UNIVERSITY OF CALGARY

The Effect of Snow on Solar Photovoltaic Systems in Alberta

by

Namrata Sheth

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ABSTRACT

Alberta lies in the highest irradiance regions of Canada and has a cold climate which makes it the best candidate to expand its installed solar photovoltaic capacity. Alberta's Climate Leadership Plan to shut down coal generated electricity is another motivation to develop renewables like solar PV. However, there is a significant amount of snow in Alberta, which may hinder the electricity generation ability of photovoltaic systems. The primary objective of this paper is to find the effect of snow on electricity generation by photovoltaic systems in Alberta. A photovoltaic system is set up in Calgary for the experimental research. The result is there is a 9% loss in energy yield per year due to snow accumulation which is quite an insignificant loss considering the analysis is in the absence of bypass diodes.

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CHAPTER 1 – INTRODUCTION

Solar photovoltaic (PV) systems are made of photovoltaic diodes, which when exposed to sunlight, directly convert incident light into electricity. The electrons absorb the energy of incident photons and produce electricity. Solar PV systems are well-adept for Canada's climate, as it is a fact that solar PV systems have better efficiency in colder temperatures; however, the effects of snow precipitation have to be explored thoroughly. There is a significant amount of snow in Alberta, which may hinder the electricity generation ability of these systems. The purpose of this research project is to analyze the impact of snow on electricity generation by solar PV systems in Calgary, Alberta. Additionally, the environmental benefits of solar PV systems as a renewable energy source and the implications of the technical analysis in terms of promotion of solar PV in Alberta are also discussed in this paper. The result of this analysis can be used in planning solar energy strategies for regions in Canada that receive heavy snow precipitation, and also to plan and devise strategies for installing and maintaining solar PV systems in regions of Canada (and the rest of the world) that normally receive heavy snow precipitation.

1.1 Background

Understanding and improving the efficiencies of solar photovoltaic systems is important, since investment into these systems can address two of the most significant issues that exist in the world today – growing energy demand and increasing greenhouse gas emissions.

1.1.1 Energy Demand

The world's energy demand has been growing since the Industrial Revolution. It will only multiply as the population increases and as the standard of living improves among all populations of the world. Moreover, this demand in energy is strongly driven by economic growth. The U.S. Energy

Information Administration (EIA) predicts that world energy consumption will grow by 56% between 2010 and 2040, from 153 million gigawatt hour (GWh) to 240 million GWh (U.S. Department of Energy, 2013). Out of all, electricity is the fastest growing form of energy. However, electricity production contributes least to the reduction in fossil fuel consumption in the global energy mix. To keep up with the electricity demand, especially from developing countries, a total of 7,200 gigawatts (GW) of capacity needs to be built by 2040 (International Energy Agency, 2014).

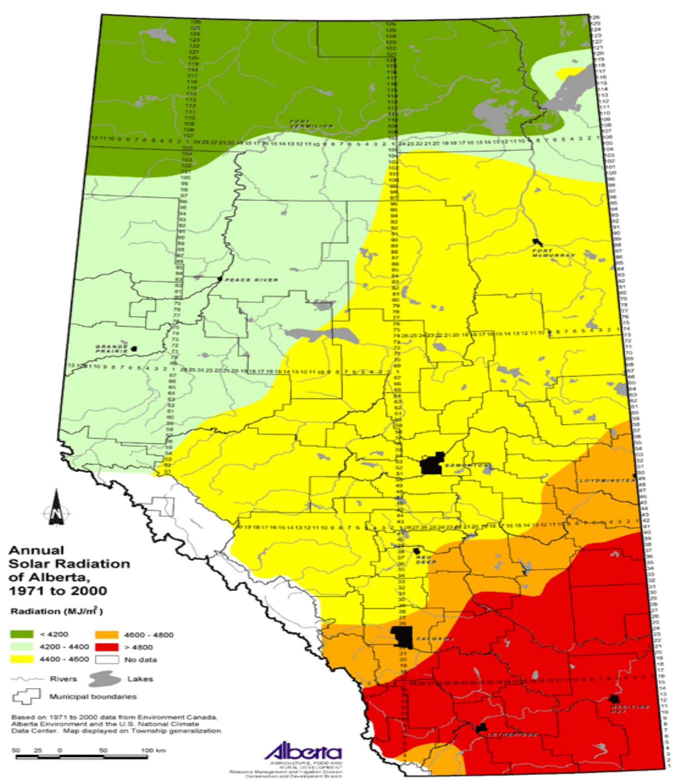
1.1.2 Climate Change

Greenhouse gas (GHG) emissions is one of the leading anthropogenic factors that is causing climate change. Alberta has the highest GHG emissions in Canada. In 2013, the province emitted 250 mega tonnes of carbon dioxide equivalent (Mt CO_2e) of GHG emissions, which represents 36.8% of the country's total emissions (Environment and Climate Change Canada, 2016). In Alberta, the electricity generation sector had the highest share of GHG emissions at approximately 35.4 % of the total emissions (Alberta Government, 2013). Coal is still the dominant source of electricity generation in Alberta, with 55% of power production emanating from this resource, followed by natural gas at 35% (Alberta Energy, 2014). The rest originates from renewables which is a mere 10%, comprising hydro, wind, and biomass (Alberta Energy, 2014). One of the specific goals of Alberta's Climate Leadership plan is to phase out coal-generated electricity and developing more renewables (Alberta Government, 2015). Not only does coal contribute to global GHG emissions, it is also detrimental to human health. This indicates that the current energy mix of Alberta has room of diversification from conventional energy sources to include alternatives and renewables, such as solar power given its abundance and advantages over fossil fuels.

1.2 Solar Resource in Alberta

Solar energy is an abundant resource in Alberta. Southern Alberta has a very high solar resource compared to the rest of the country. As shown in figure (1), the average annual solar energy is greater than 4800 Mega-joules per square metre (MJ/m^2) in Southern Alberta. Solar PV systems directly convert solar energy into electricity, thus the mechanical energy conversion losses are avoided. The solar PV system can be flexible such that it can either be grid tied or off-grid depending on the requirements. A significant amount of fall is seen in the prices of solar PV systems in last three decades. Since 1977 to 2013 the module prices have fallen down from $76.67/watt to $0.74/watt which is a more than 10,000 times of price reduction (British Columbia Sustainable Energy Association, 2015). It is predicted that this trend in price drop will continue with technological advances in solar PVs.

Figure 1Alberta Solar Energy Resource



Source: (Agriculture Alberta, 2016)

The yearly photovoltaic (PV) potential in Calgary is 1,292 kilowatt-hours per kilowatt (kWh/kW), which is much higher than a city like Berlin, Germany, that has a potential of 848 kWh/kW (Natural Resources Canada, 2015). Germany is a leading country in installed PV capacity, which was at 35 GW at the end of 2013 (Solar Energy Industries Association, 2014). Comparatively, Alberta has an installed solar PV capacity of only 9.3 MW (Solar Energy Society of Alberta, 2016), which is 3,700 times less than Germany. Moreover, Alberta has a land area which is twice that of Germany. The reason for such little installed PV capacity is low motivation for installing solar PV systems in Alberta. One of the objectives of this paper is to look into technical causes for the same. For instance, in Calgary, the annual average snow precipitation is about 150 cm per year (Calgary Weatherstats, 2016) and in Germany it is about 50 cm –100 cm (Current Results, 2016), which could be a justification for a low installed capacity. Another purpose of this paper is also to find the factors behind low motivation in people regarding solar PV systems.—This suggests that there is room for significant growth of solar power in Alberta. Therefore, understanding how snow may affect solar PV systems is an important step to exploiting its full potential of solar energy in Alberta and Canada.

1.3 Three Dimensions

The three disciplines discussed in this paper are – energy (technical), environment and socio-economical dimensions. For technical dimension, losses due to snow on solar PVs are studied. In the environmental dimension the GHG emissions offset from replacing an amount of coal powered electricity by Solar PVs is discussed. Lastly, for the socio-economical aspect, the factors behind motivating people to install solar PVs are explored.

It is understood that the government plays an important role in promoting any energy technology. Provided, Alberta has an abundant oil and gas resource, other energy sources were not really developed until so-far. However, with the current economic condition in Alberta, it is important to look into other energy resources, especially renewables for their benign pollution free qualities relative to fossil fuels. Another reason to develop renewables is to become more energy independent in terms of the fuel source and to diversify the economic sector so when difficult times arise for the province's economy, it is not so dependent on a single resource.

In the technical (energy) dimension, the losses due to snow on solar PV systems are analyzed. The results from the analysis are used to discuss its implications on the socio-economic dimension. For instance, the consequences of energy loss due to snow on the PV market in Alberta and also its importance on promoting solar PV in Alberta are discussed. In the socio-economic dimension, results of a survey of approximately 300 Calgarians about their perspective on Solar PV investment are also examined.

For the environmental dimensions, the advantage of solar PV systems replacing a percentage of fossil fuel for electricity generation in Alberta is discussed. The advantages are in terms of reducing GHG emissions in the electricity production process. This analysis shows how both the issues of energy demand and increasing GHG emissions can be combatted using renewable energy, and especially solar PV in this case.

Hence, the results of this paper can be used in the industry and by the government to make strategic decisions about the future energy mix of the province.

1.4 PV in Cold Climate Regions

The term 'cold climate' can have many connotations, but for the purpose of this paper it is defined as climate which has freezing temperatures, snow, ice, dark winters and long summer days for more than a few months per year. These factors are important to consider while designing a PV system. Normally, the general masses believe that PV systems do not work well in cold climates due to low temperatures. On the contrary, the fact is that the efficiency of PV systems increases in cold weather, as the heating losses are reduced at low ambient temperatures. The efficiency of PV systems not only depends on the ambient and module temperature, but also on the irradiance reaching the solar panel's surface, along with the mounting design, shading on the panel and precipitation among other factors.

Thus, Alberta has an advantage both in terms of cold temperatures and high irradiance numbers all over the year. So, on a cold sunny day, the energy yield of PV systems increases significantly. The purpose of this research is to explore the effect of precipitation and snow accumulation on electricity yield from solar PVs.

CHAPTER 2 - CONCEPTUAL FRAMEWORK & LITERATURE REVIEW

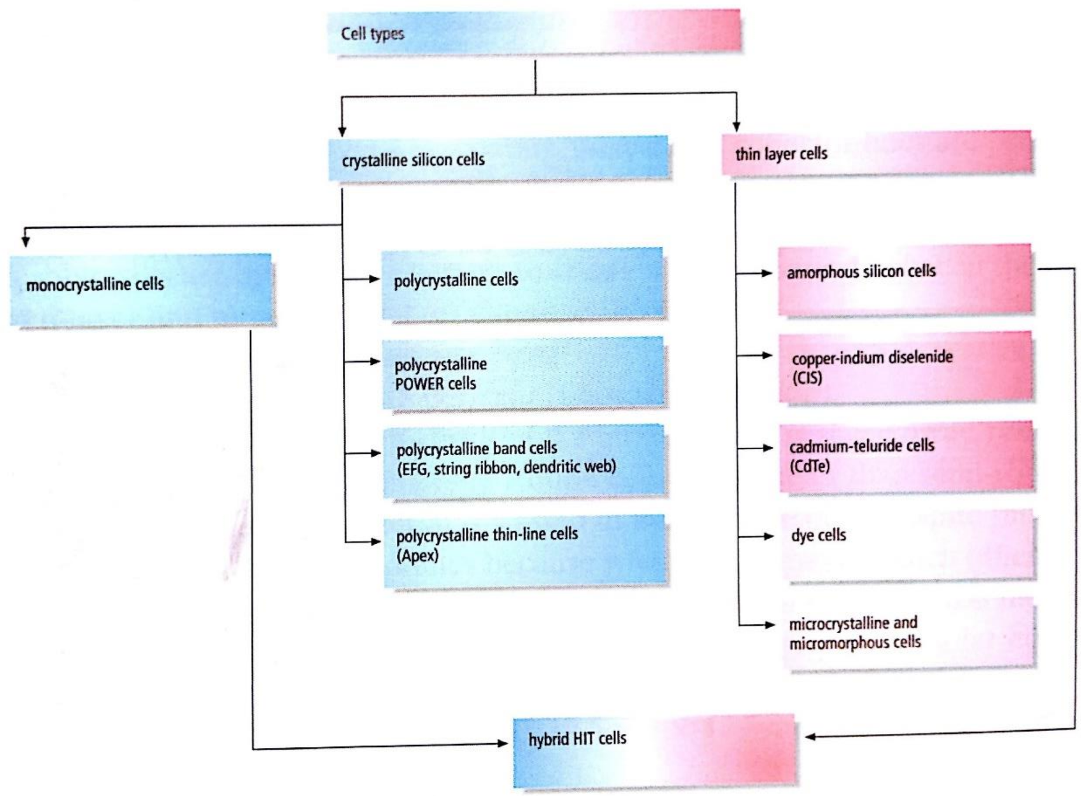
2.1 Photovoltaic Systems

The basic building block of a solar photovoltaic system is a solar cell. A solar cell is a PN junction diode, which produces electricity when exposed to sunlight. A particular number of solar cells are connected together in series or parallel to form a string. Then, a few or many strings are connected in series or parallel to form a solar panel depending on the power requirement. Then, to form a solar PV system a number of modules are connected together determined by its power requirement. Along with the solar cells, a PV system is composed of many other components like invertors, battery storage etcetera.

A solar cell is made from a semiconductor material which is generally silicon. Sunlight is composed of tiny particles called photons, and when it hits the surface of the diode, the electrons of the diode absorb these photons from sunlight and get loose from their valence shell to move throughout the free region, giving the diode a potential difference thus producing a flow of electrons, which is electric current. This energy in the form of electricity can be collected in a battery or can be used to run appliances.

PV systems can be standalone or grid tied. A major advantage of such systems is they can be used to produce electricity in remote areas and when necessary the excess electricity can be supplied to the grid. PV cells can be made from different elements and in different ways. The classification of different types of PV cells is shown in figure (2). Different types of PV cells have various efficiencies and have different costs.

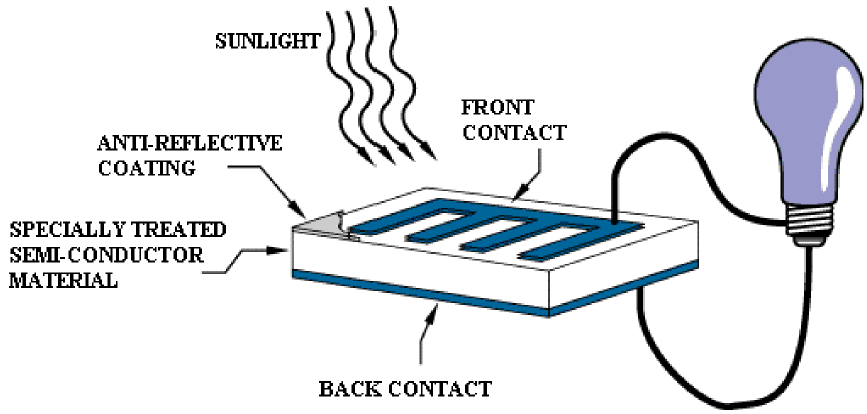
Figure 2 PV Classification



Source (The German Energy Society, 2008)

A typical solar cell is constructed in a way that the p doped layer is at the bottom and the n doped layer is on the top. The top layer is generally coated with an anti-reflective coating to prevent reflection losses. Both the n and p type semiconductors are connected with front and back contacts which act as anode and cathode respectively (The German Energy Society, 2008). To collect the electricity, the front and back contacts are connected with an appliance or a battery as shown in figure 3.

Figure 3 Solar cell Construction

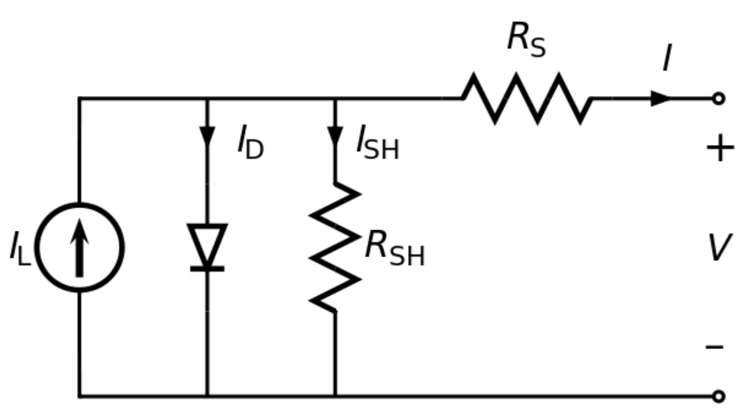


Source (Toothman & Aldous, 2016)

2.1.1 Solar cell – Electrical Properties

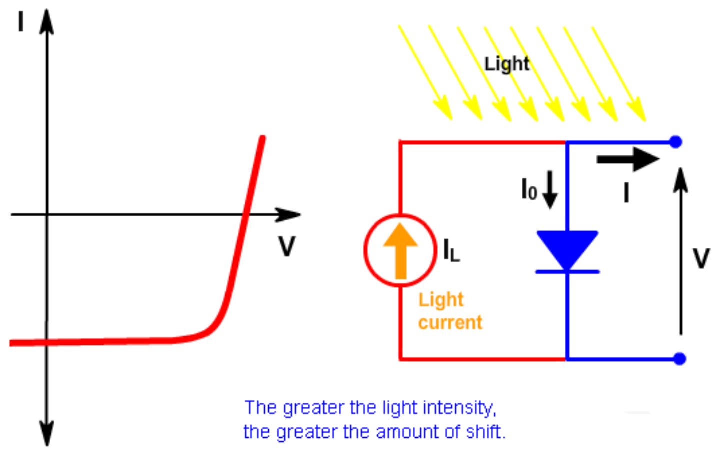
The electrical equivalent circuit of a typical solar cell is shown in figure 4. When sunlight strikes the diode, total current produced by the solar cell is I_L. I_D is the current passing through the PN junction diode and I is the current passing through the external load (any appliance or a resistor). Ideally, R_S (series resistance) and R_{SH} (shunt resistance) should be zero and infinity respectively so that all the current passes through the diode and the appliance. Due to parallel connection between the appliance and the diode, the voltage across all the components is same.

Figure 4 Equivalent circuit of a Solar cell



Source: (Lorenzo, 1994)

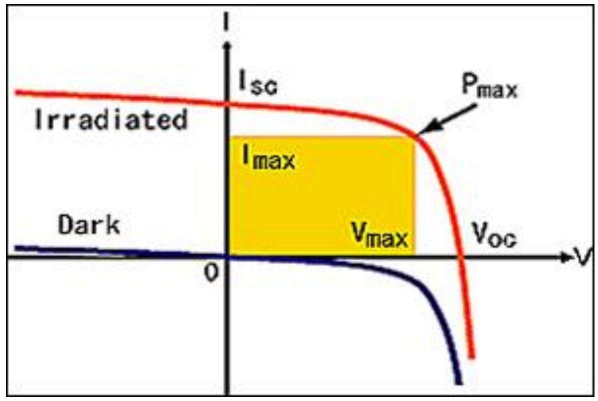
Figure 5 I-V Characteristics -1



Source: (Honsberg & Bowden, IV Curve, 2013)

The Current-Voltage (I-V) characteristic of a solar cell is shown in figure 5. It is similar to that of the PN junction diode, only difference being, in forward bias condition there is a negative current flowing even when the voltage is zero. But generally the graph is mirrored and reversed on the axis and is represented as shown below in figure 6. I_{SC} is the short circuit current when the circuit is closed and the voltage is zero. V_{OC} is the open circuit voltage, when the circuit is open and the voltage is maximum across the diode with no current flowing through the circuit. Generally, the I_{SC} and V_{OC} of a panel are specified on the data sheet of the solar panel. I_{max} and V_{max} are the maximum current and voltage respectively that the panel can attain under standard test conditions (STC). For that particular condition the power (P_{max}) = I_{max} * V_{max} obtained is the maximum power point of the panel.

Figure 6 I-V Characteristics - 2



Source: (Solar Central, n.a)

The fill factor shows the quality of solar cells. It can vary between 0 and 1, the closer to 1, better the quality of the solar cell (The German Energy Society, 2008). Generally, the fill factor can vary between 0.5 to 0.85. Fill factor is given by,

$$FF = \frac{V_{MP} I_{MP}}{V_{OC} I_{SC}} \qquad - (1)$$

Efficiency of a solar cell or a panel is the most important characteristic in determining its quality. It is the fraction of power generated to the power incident on the area of the panel. Thus, it depends on the area and the irradiance incident upon the solar cell. It is given by the formula (The German Energy Society, 2008),

$$Ŋ = \frac{Imax * Vmax}{Area(A) * Irradiance(E)} \qquad - (2)$$

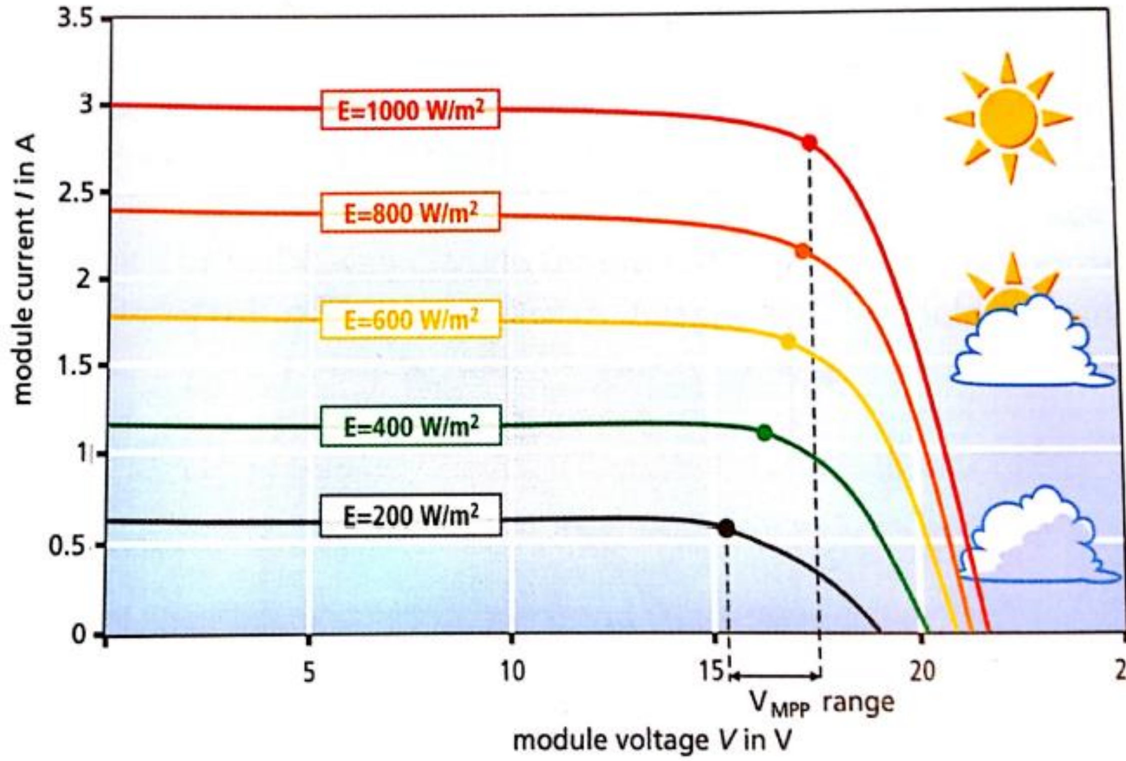
Moreover, efficiency on data sheet by manufacturers is given at STC where the temperature is 25 °C and irradiance is 1000 watts per square meter (W/m^2).

2.1.2 Solar PV Panel – Irradiance dependence

Generally, most PV manufacturers indicate all important technical characteristics of the panel on its data sheet. Parameters like efficiency are generally given at STC but in real life STC occurs rarely. Moreover, the power output varies depending on a number of variables like irradiance reaching to the panel, cell temperature and shading on the panel. All these factors are necessary to consider while designing a PV system.

Irradiance is the power from the sun that is incident upon the solar panel. It is measured in Watts/square meter (W/m^2) and irradiance at STC is 1000 W/m^2. Current produced in the solar cell is dependent on this irradiance. However, it does not have a direct effect on the voltage induced in the photovoltaic panel. However, if the irradiance is halved, the current is also halved. Thus, the power produced is also halved. As shown in the figure 7, current and thus produced power are directly proportional to the power incident on the solar cell (The German Energy Society, 2008). As irradiance changes throughout the day, the power produced also varies throughout the day. Hence, it is an important factor to consider for the technical analysis in this paper.

Figure 7 Effect of Irradiance on Solar cell

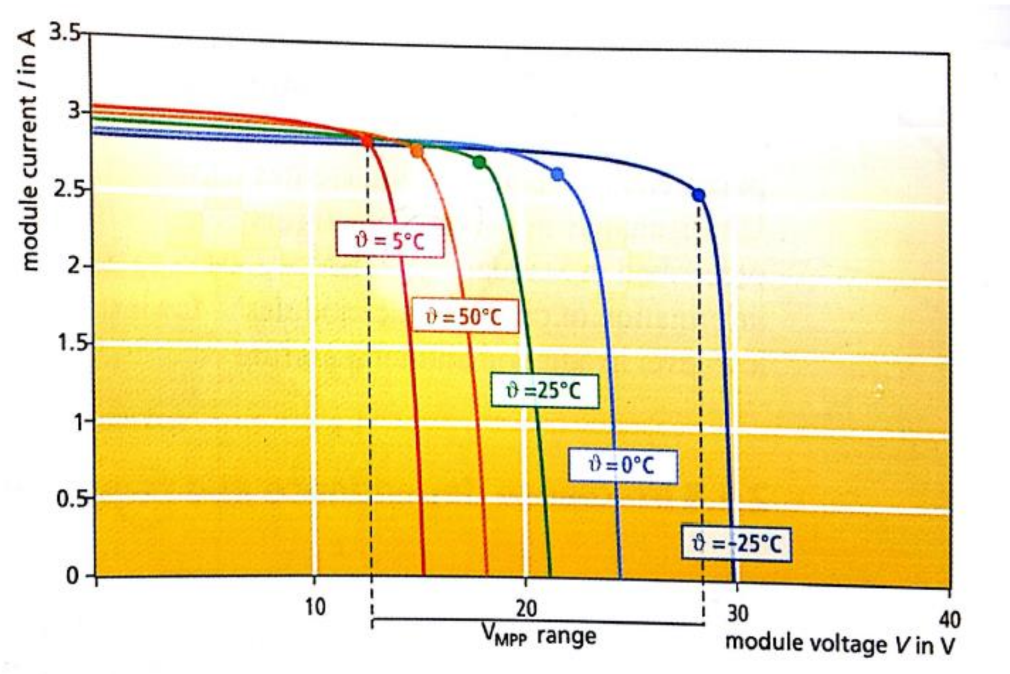


Source (The German Energy Society, 2008)

2.1.3 Solar PV Panel – Temperature dependence

Voltage induced in the panel is not affected by the irradiance. However, the cell temperature and thus the ambient temperature significantly affect the voltage across the panel. As shown in figure 8, the maximum voltage induced in a solar module, is decreased by half as the temperature increases from -25°C to +50°C. But there is no significant effect on the current produced by the module due to temperature change. Thus, even in this case the power produced by the module is directly affected due to the increase in temperature. This is relevant for Alberta because as it has a cold climate, the power production in the panels should increase, compared to sunny, tropical, equatorial regions if all other conditions are constant. Thus in a strict comparison where temperature is the only parameter affecting the efficiency of a solar module, the efficiency would increase in cold climates such as Alberta.

Figure 8 Temperature dependence of a solar cell



Source (The German Energy Society, 2008)

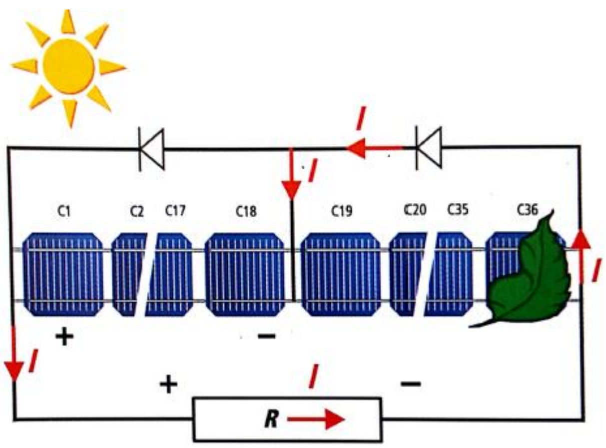
2.1.4 Solar PV Panel – Effect of Shading

As discussed in the previous chapter, irradiance is an important factor that directly affects the power generation from a solar panel. Shading on the panel can obstruct sun's radiation to fully reach the panel. The energy reaching the panels from the sun depends on a number of factors like the angle of elevation of the panel, orientation of the panel, shading due to the surroundings and also climatic factors like dust, snow and precipitation. There is a technical problem that occurs due to shading on the panels. For instance, a leaf like object lying on the panel produces shade and stops the light from reaching the panel's surface. This disables that particular part of the panel to produce electricity and starts consuming the current and acts like a load. The reverse current flows only when a breakdown voltage is achieved in the panel, and it is dependent on the position of the shaded cell(s) on the panel.

Due to the reverse current a hot spot is developed and if the heat is high, it can cause damages to the entire panel (The German Energy Society, 2008).

To prevent such damages, bypass diodes are inserted in the panels so that it does not become a load and the excess reverse current is diverted and passed through these bypass diodes instead of the particular shaded cells.

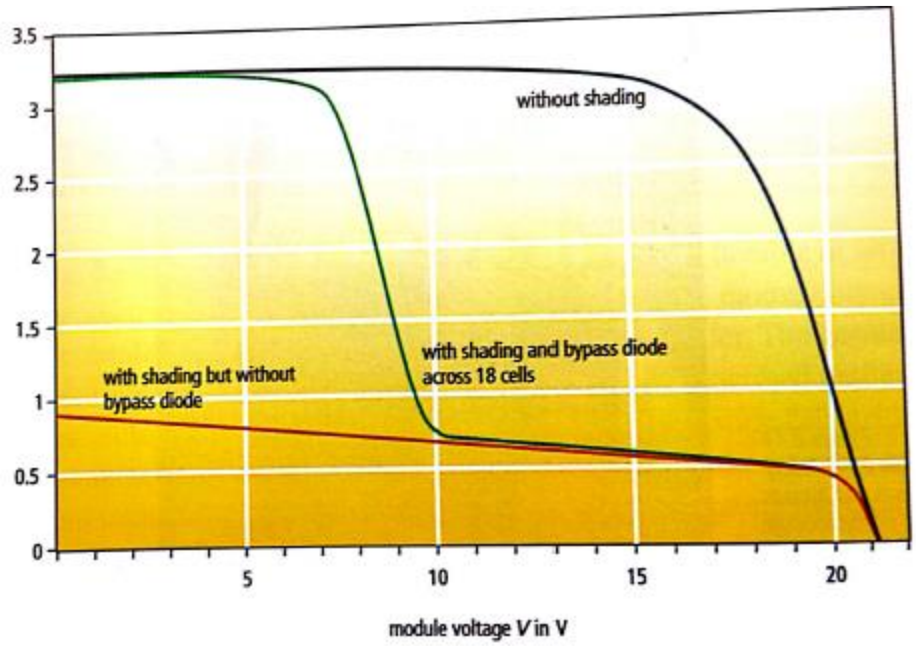
Figure 9 Effect of Bypass diodes



Source (The German Energy Society, 2008)

As shown in figure 9, it can be seen that the excess current is diverted and thus the damages to the panel are avoided by introducing bypass diodes. The effect of the presence and absence of bypass diodes in case of shading on the I-V curve is shown in figure 10 and it can be seen that power losses due to shading are prevented by introducing the bypass diodes.

Figure 10 Effect of Bypass diodes on I-V curve



Source (The German Energy Society, 2008)

2.1.5 Snow

In cold climates, snow accumulation acts like a shade on the panel. It obstructs full irradiance from reaching the surface that would normally reach, in case of absence of snow. For cold climate regions like Calgary, where winter lasts for about 5 months a year, the effect of snow accumulation and melting behavior on solar panels is important to explore, as solar PV market is on the rise.

Snow is interconnected to all the three factors mentioned above - temperature, irradiance and shading. Hence, it is a complex phenomenon and necessary to study to know its effect on electricity generation. As snow generally precipitates at low temperatures, the efficiency is effected positively due to the temperature dependence factor. However, snow also acts as a shade on the panel due to which the efficiency is affected negatively as the irradiance reaching the panel is reduced. The results of this experiment specifically deal with the snow accumulation on the panel. Thus, for Alberta as solar market is rising rapidly and as the Alberta's Climate Leadership Plan is also about increasing the renewable energy installed capacity, it is important to examine the technical dimensions of the effect snow on PV performance in cold climates.

2.2 Literature Review

2.2.1 Technical Dimension – Energy

Previous studies have shown that electricity generation from PV systems depends on factors such as the orientation, tilt angle of the PV modules, and meteorological factors. In snowy conditions, energy inflow to the PV modules can occur by diffusion of short wave radiation through the snow layer, albedo reflection to the exposed rear of the module, or by conduction from other parts of the PV array that are not covered with snow (Andrews, Pollard, & Pearce, 2013). It should be noted, however, that albedo reflection effect is highly dependent on the orientation and mounting of the modules. There is virtually zero albedo reflection effect on a mounted roof top system (Andrews, Pollard, & Pearce, 2013).

Power generation losses of PV systems due to snow is dependent on the snowmelt behavior on the panels and the degree to which snow accumulation occurs. Snow accumulation is dependent on the inclination of the modules, ambient temperature, wind speeds, and surface properties (Andrews, Pollard, & Pearce, 2013). The electricity generation losses due to snow can be as high as 24-34 % in Michigan, USA (Heidari et al., 2015) for modules having comparably very less tilt angle to the losses ranging to as low as 0.3-2.7 % in Germany for a highly tilted roof mount system (Andrews, Pollard, & Pearce, 2013).

There have been studies of the effects of snow on PV systems in different places, such as USA, Germany, Ontario (Canada). According a study done in Edmonton, Alberta, at the Northern Alberta Institute of Technology, the amount of losses due to snow in winter months for three consecutive years from 2012 to 2014 in the best to worst optimum angles is between 0.88% to 19.33% (Northern Alberta Institute of Technology, 2015). To calculate the amount of loss due to snow, two different scenarios were analyzed in the NAIT experiment. First scenario incorporated the manual removal of snow and on the other the snow was allowed to melt naturally. In addition, numerous panels at different mounting angles were observed to measure the amount of loss in different cases.

According to one study (Andrews, Pollard, & Pearce, 2013), the amount of losses due to snow ranged from 1% to 3.5% but the level of snowfall was low during the winter that the experiment was conducted. It was also concluded in the same research that albedo effect can be a major cause in the difference in amount of losses from snow on the PV panel in different systems. Thus, it is also important to consider the system topology while calculating the snow losses (Andrews, Pollard, & Pearce, 2013). At different mounting angle of the panels, different amounts of losses are seen. This conclusion matches with the results of the NAIT study that there are different amounts of losses at different angles. It is not necessary that the optimum angle for that region for sunny conditions, would coincide with the optimum angle for snowy conditions. Thus while designing the system, it is important to consider both the sunny and snowy optimum angles such that maximum power output can be gained.

According to another study in Japan (David & Pelland, 2011), snow losses can count for up to 0.7% and 3.5% of the total energy collection. There are various parameters that play an important role in accounting for the losses. The type of snowfall (heavy or light), age of snow, irradiation, temperature which are climatic factors and other technical parameters include the type of mounting system, distance of modules from the ground, tilt of the module for snow to melt and fall. The complex interactions between these phenomena make it difficult to generalize the conclusions for the exact number for snow loss (David & Pelland, 2011).

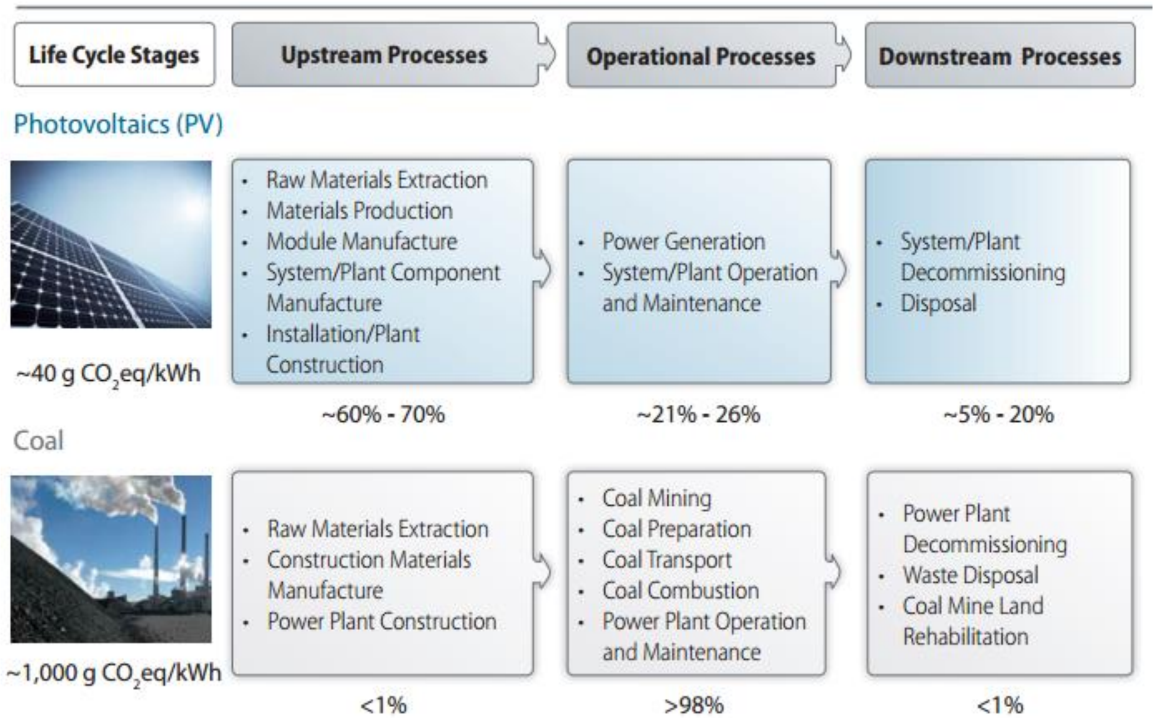
Therefore, it is important to explore the possible methods to deal with the snow accumulation. There can either be manual or automated methods to deal with the issue of snow accumulation to avoid losses due to snow. The problem of snow accumulation can be dealt with in different ways such as:

1. Letting the snow to melt naturally, and optimize the design so that the snow melts with minimum losses to the system.
2. Manually removing the ice and snow using cleaning tools, which may break or scratch parts of the system connections between the cells.
3. Sealing the panels with a transparent film to form a protective layer against ice and snow. It should be noted that this is not a permanent solution and this protective layer has to be applied every two to three years, which may reduce the economic appeal of the entire system (Husu et al., 2015).
4. Defrosting the panels by applying heat on the entire surface area using a 220 V electric field to the foil, leading to rapid melting and removal of the ice or snow (Husu et al., 2015).

2.2.2 Environmental Dimension

Solar PV is a relatively environmentally friendly technology compared to fossil fuel resources. There is minimum amount of environmental impact in its life cycle and especially during the operation stage of electricity generation from PVs as shown in figure 11. Although the use of PV systems emits GHG emissions, it is mostly in the upstream manufacturing stage. However, there is an issue of disposal of PV panels. The life-time of a typical PV system lasts anytime between 25-30 years. Despite the fact that there has not been much advancement in the disposal and end of life cycle phase of PV systems, there has surely been good progress in the life cycle impact from the use of PV systems (Fthenaki, Kim, & Alsema, 2008).

Figure 11 LCA Stages of PV and coal

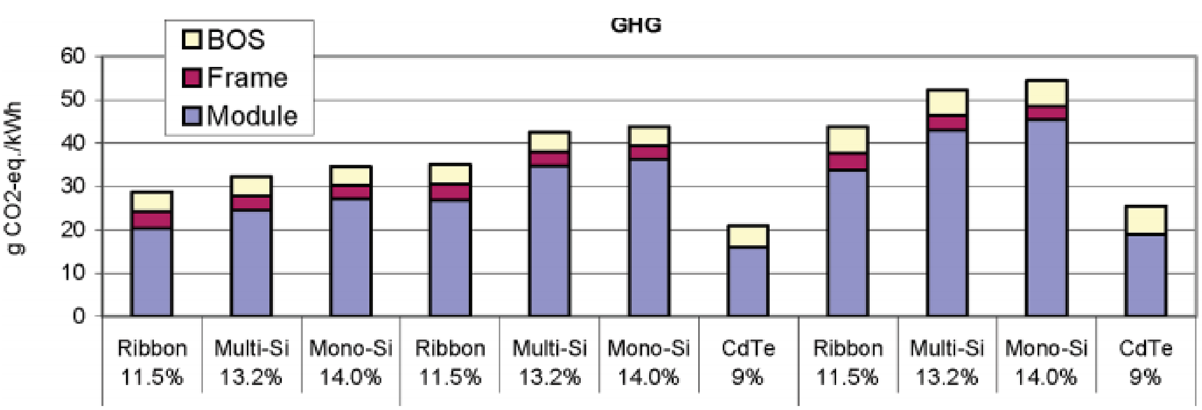


Source (Natural Resources Canada, 2015)

In a report from National Renewable Energy Laboratory (National Renewable Energy Laboratory, 2012), as shown in figure 11 there is a major difference in GHG emissions in the operation stage of the Life Cycle Assessments (LCA) of PV systems and fossil fuel based sources like coal. In a coal based system, 98% of the GHG emissions are produced in the operational phase of its LCA. A Life Cycle Assessment is a fair method to compare holistic environmental impacts of any two technologies or process. According to this report (National Renewable Energy Laboratory, 2012), the amount of GHG emissions from PV systems and Coal based system is 40 g CO_2 eq/kWh and 1000 g CO_2 eq/kWh respectively. Out of those 40 g CO_2 eq/kWh for PV systems, 70% of the emissions are only from the upstream processes of making the solar panels. Manufacturing of solar panels is a very energy intensive process, but it is important to keep to note that that this number can vary depending on the energy source used to manufacture the panels. As the current energy mix is still dominant by fossil fuels, this number is high. But in the future, as the ratio of clean energy will increase, GHG emissions from PV systems will decrease. Today, GHG emissions from solar PV is 25 times less than coal even while fossil fuels dominate the general energy mix.

Energy Payback is another important parameter to consider in terms of environmental impacts. It is defined as the period required for a renewable energy system to generate the same amount of energy (total primary energy equivalent) that was used to produce the system itself (Environment Canada and Canmet Energy, 2012). A report by Environment Canada states that payback period for PV systems can vary from 0.8 - 3.6 years depending on various factors such as the energy mix in the manufacturing process, the performance ratio of the system, and the type of solar panel material and manufacturing process (Environment Canada and Canmet Energy, 2012).

Figure 12 GHG emissions from production various PV systems



Source (Fthenaki, Kim, & Alsema, 2008)

According to another research at Brookhaven National Laboratory, different types of PV systems have different energy requirements and thus different GHG emissions. The GHG emissions for PV systems can vary from approximately 20 g CO_2 eq/kWh to 54 g CO_2 eq/kWh and these systems can vary in efficiencies as shown in the figure 12 (Fthenaki, Kim, & Alsema, 2008).

This is an important factor to consider for Alberta, as majority of the province's electricity comes from coal. Moreover, with the Alberta Climate Leadership Plan in initial stages, the goal to reduce GHG emissions and phase our coal can be achieved by implementing Solar PV in the electricity sector.

2.2.3 Socio – Economic Dimension

As mentioned before, countries like Germany have made a lot of progress in making their energy mix greener in the last few decades. Today, Germany has more than 22% of its energy deriving from renewable sources (Curry, 2013). Out of this, solar makes about one quarter of the renewable energy share. It is one of the leading countries in installed PV capacity despite its cloudy and cold climate. The factors behind such successful implementation of a renewable energy technology is not only the technical feasibility of PV systems. It took conscious efforts by the country's government and motivating public to promote this technology.

For instance, the Ontario government has taken similar steps. Despite its solar resource being much less, it has much more installed PV capacity than Alberta. The government needs to have strong reasons to promote a technology. They could be - to strengthen the economy, to promote a new policy or for the benefit of the environment. So far, Alberta did not have enough economic motivation to delve into renewables because of its strong fossil fuel natural resource based economy. However, today as the oil and gas economic sector is on the fall (Financial Post, 2015), it is necessary for the province to diversify its economic resources and energy mix due to environmental disadvantages of fossil fuel based energy systems. From a sustainability perspective it is absolutely necessary for the province to not go about the business as usual path and transform slowly to a more sustainable path as the energy demand grows, fossil fuel based resources diminish and as the problem of climate change increases. Thus, it has become more pertinent now to promote a renewable energy like solar PV than ever before.

There are a number of socioeconomic factors that affect the promotion of a renewable energy technology. Policies that induce a positive market for solar panels are needed because subsidies and incentives are not healthy for an unregulated market for any technology. The prices of the panels are on a decrease because of the market and not the subsidies (Rodriguez, 2012). Moreover, this is only possible if there is public awareness about solar PV, so the demand grows and the prices fall. Thus, the subsidy programs, if there are any, have to be reviewed from time to time. Another reason that Germany has been successful in solar because it has democratized its grids so all people – rich or poor are alike with an equal advantage.

According to an article (Dubey, Jadhav, & Zakirova, 2013), the key drivers to a successful penetration of the solar technology are mainly markets that are sustained without subsidies because as it is seen in the past, heavy subsidies on renewables have led to mask up their actual costs. Another driver is reduced manufacturing cost and this can happen with a healthy competition in international markets that are deregulated. As countries like China have figured out a way to decrease the panel costs day by day, the competitors are forced to develop their research and development capabilities to bring down the costs of panels internationally. The success of solar in Alberta in the long run, would not be due to just subsidies and incentives, but a healthy market for the solar technology needs to exist (Rodriguez, 2012)

Apart from the free markets, the government can do what countries like Germany have done. Economic policies like feed-in-tariff (FIT), net metering etc. can be implemented to encourage the installation of solar PVs. Such policies tend to encourage improvement of energy efficiencies based on the economies of scale. Programs such as FIT, increase public participation in implementing renewable energy, and also allow the public to economically benefit from the technology. FITs are programs that allow common people to generate electricity that is produced from renewable sources and they can sell it to the grid for which they get paid according to the cost of the technology. The payment varies depending on the cost of the technology (Ontario Power Authority, 2014).

CHAPTER 3 - RESEARCH METHODOLOGY

This research project examines the impacts of snow melting and snow accumulation on electricity generation by solar PV systems. It is an experimental work for which the data was collected from November 2013 to May 2014 by Dr. Anis Haque from Schulich School of Engineering at the University of Calgary. The PV system was located on main campus, with a capacity of 140 W. Photographs of the PV panel were taken every 10 minutes on a daily basis. These images are used to examine the effect of snow accumulation and melting behavior on the PV panel.

3.1 Technical Analysis - Methodology

3.1.1 Experimental Set up and Data Collection

The block diagram of the hardware set up is shown in figure 13. The system was set up in the winter of 2013 – 2014 with the purpose of analyzing snow melting behavior on solar PV, along with the losses in power generation. The solar panel used for this experiment is KYOCERA KDSX140 – UPU, with a power capacity of 140W,

$V_{max.}$ = 17.7 V

I_{max} = 7.91 A

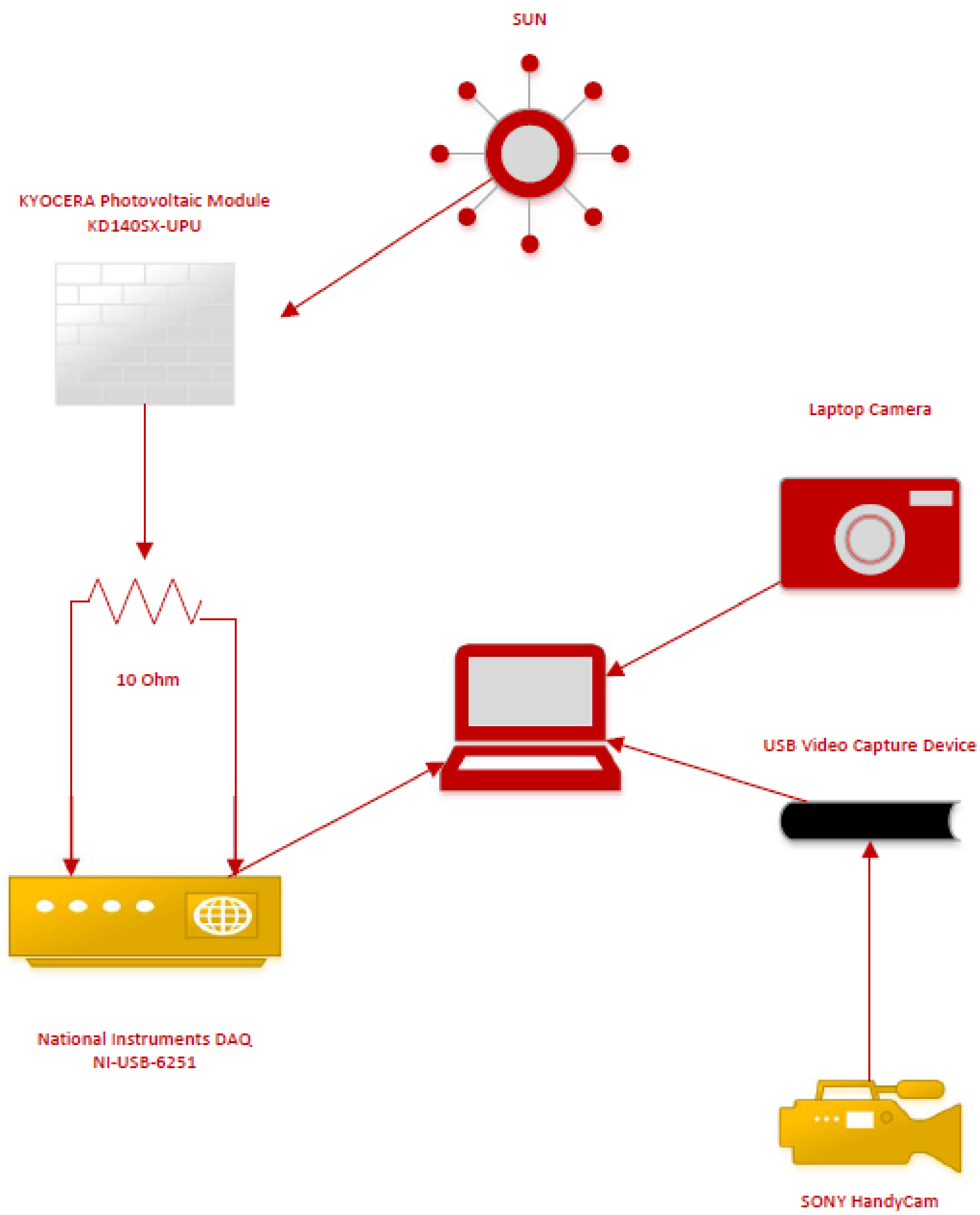
V_{OC} = 22.1 V, and

I_{SC} = 8.68 A.

In this experiment, bypass diodes which are generally used to prevent shading losses are removed from the panel to know the actual loss because of snow. From the above mentioned values for current and voltage, the optimum load (resistor) value to generate maximum power from the panel is 2Ω. However, the load used for this set up is 10Ω which is obtained using a rheostat. The system is set up in a way that the images of the panel and its surroundings are captured every ten minutes. A

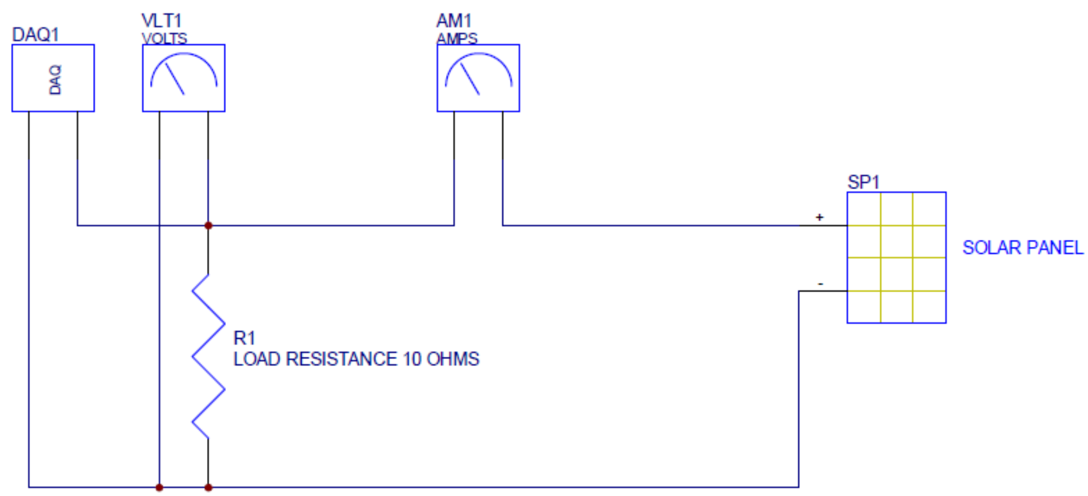
SONY handy camera and the data acquisition system computer's inbuilt camera are used to click pictures. LabVIEW is used to design the system software for the data acquisition system. The software flow of the set-up is found in Appendix A and the datasheet of the solar panel is found in Appendix B.

Figure 13 Block diagram- Experimental Set up



The circuit diagram for the system set up is shown in figure 14. As shown, the load is connected in parallel with the panel. Voltage is measured across the load using a voltmeter in Volts, and the current flowing into the load is measured using an ammeter in Amperes. The voltage and current are both measured every ten minutes, over the course of 6 months, along with the images. The power across the load is calculated by multiplying the voltage and current which is the practical power (P_{PR}) across the load at any given time.

Figure 14 Circuit diagram – System setup



The irradiance and weather data for the analysis are collected from the University of Calgary weather station. The weather data includes irradiance in W/m^2, ambient temperature in °C, and precipitation in millimeters (mm). Additionally, it has information about the date and time for cleaning and brushing of the radiometers. Radiometer is an instrument used to measure the incoming irradiance on the earth. According to the University of Calgary's weather station data sheet, errors can occur in irradiation measurement due to precipitation, dew, birds resting on incoming instruments, contaminants deposited on the sensors, shadows cast on the sensors, rabbits resting on the outgoing sensors etc. Moreover, there is a known issue caused by an instrument tower which casts a short duration of shadow across the sensors in the morning during winter months (University of Calgary, 2016). Hence, early morning data of winter months is not included in the analysis. The pyranometer used at University of Calgary is Eppley PSP. A pyranometer is also an instrument used to measure the sun's irradiance According to the datasheet of the Eppley PSP, there is a system accuracy of ±1.6% of the reading (Campbell Scientific Inc, 1992), which is taken into account in the data analysis.

3.1.2 Data Filtration

The voltage and current are measured on a daily basis in ten minute intervals for six months and collected in excel sheets by the data acquisition system. Firstly, the useful data for the analysis is filtered and sorted for all the months. P_{PR} is calculated in excel sheet using the measured voltage and current values. The everyday data from sun rise to sun set are considered for the analysis for all months. The monthly average of sun rise and sun set for each month is calculated separately and the data from two hours of before and after the sun rise and sun set is also included to get a better understanding of the everyday P_{PR} values. This is repeated for all months except November and December due to technical issues in the data collection system. Thus, the data analysis for snow losses is done for the months of January 2014 to April 2014. The month of May is not included due to lack of snow precipitation in that period. The panel images for all the months are sorted, such that only the daytime images are used for the analysis.

3.1.3 Data Analysis

For the data analysis, firstly graphs are plotted for voltage, current and power versus time, on a daily basis for the months between January 2014 and April 2014. This is done to see the trends in measured Voltage, Current and Power. Secondly, the panel images are observed to distinguish snowy days from non-snowy days. 'Snowy day' for this paper means here is at least 10 % snow accumulation on the PV panel on that day for any amount of time. Next, all snowy days for each month are separated. Along with this, information about durations of snow accumulation on the panel is also journaled. The objective is to find the effect of *only snow* accumulation, so the effect from all other factors is discarded. Performance ratio of the panel on any non-snowy day is calculated to separate the loss due to factors other than snow. This is done by calculating the performance ratio or K factor which, for the purpose of this paper is found by dividing the P_{PR} to the theoretical power (P_{TH}) at any instant.

The performance ratio is calculated by:

$$K = \frac{\text{POWER pr}}{\text{POWER th}} \qquad - (3)$$

Where P_{PR} = V*I (V and I is the data measured from the system set up) - (4)

The Theoretical Power (P_{TH}) is found using formula 5:

$$P_{TH} = \eta_{cell} * \text{Area of the panel} * S_{mod} \qquad - (5)$$

In the above formula S_{mod} is given by: (Honsberg & Bowden, 2014)

$$S_{mod} = \frac{\text{Shori} * \sin(\alpha+\beta)}{\sin(\alpha)}, \text{ where} \qquad - (6)$$

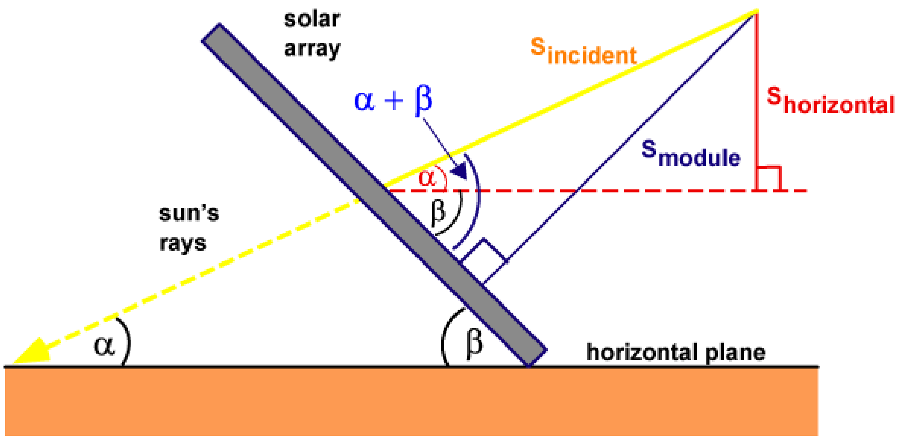
$$\alpha = 90 - \varphi + \delta ; \qquad - (7)$$

φ is Calgary's altitude = 51° ;

$$\delta = 23.45° * \sin\left[\frac{360(284+D)}{365}\right]. \qquad - (8)$$

The panel is fixed and mounted at an angle of β = 44° (used for formula 6) which is the optimum angle for Calgary for best irradiance throughout the year. S_{hori} is the irradiance reaching the pyranometer lying horizontally on the surface of earth. S_{hori} is known from the data collected by the University weather station. The actual irradiance reaching the panel is different from the irradiance reaching the pyranometer (S_{hori}) because they are mounted at different angles. So, S_{mod} that is the actual irradiance (in W/m^2) reaching the panel is calculated using formula 6. In formula 6, α is the elevation angle and β is the tilt angle of the module. D is the day of the year which is used in formula 8 to calculate δ that is the declination angle. Maximum power from the module can be obtained when the panel is lying perpendicular to the incoming radiation as shown in the figure 15.

Figure 15 Solar Radiation on a tilted surface



Source (Honsberg & Bowden, 2014)

Temperature effect on efficiency is taken in account because of low temperatures in Calgary to improve the accuracy of the analysis. The efficiency of solar cell accounting in the temperature effect is given by (Dubey, Sarvaiya, & Seshadri, 2012)

$\eta_{cell} = \eta_{STC} [\, 1 - \beta_{REF} (T_{cell} - T_{ref})]$ - (9)

Area of the panel = 0.8649 m^2 is obtained from the data sheet of the panel.

In formula 9, η_{cell} is the cell or panel efficiency at a given cell temperature. η_{STC} is the efficiency of the panel at Standard test conditions of 25°C temperature. As panel efficiency is dependent on the temperature of the module it is necessary to calculate η_{cell}. From equation (2) for η and substituting the value of E with 1000 W/m^2,

$\eta_{STC} = \frac{17.7*7.9}{0.8649*1000} = 0.16$ - (10)

In formula 9, β_{REF} is the temperature coefficient of the panel (Dubey, Sarvaiya, & Seshadri, 2012), T_{ref} is the reference temperature that is 25°C in this case. T_{cell} is the temperature of the module at a given ambient temperature and time where it is given by,

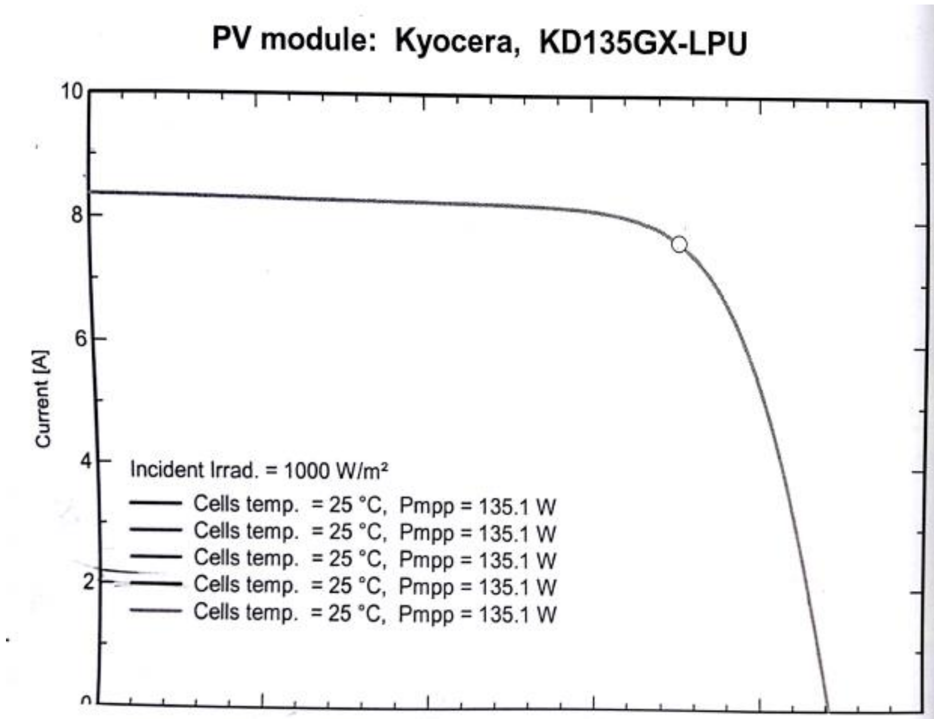
$T_{cell} = T_{Am} + [\frac{(Noct-20)}{8} * S_{mod}]$ - (11)

In formula 11, T_{Am} is the ambient temperature which is known from the weather station data at any instant. NOCT is the nominal temperature which is 45°C and S_{mod} as mentioned previously is the irradiance reaching the module.

Using the formulas above, the performance ratio of the panel at any instant is found. The performance or K factor for approximately 20 non-snowy days from all four months is calculated first using equation (3) and is averaged for that period. Next, using the same formula K factor for approximately 20 snowy days from all four months is calculated and averaged for that period. Then, the performance factor of snowy days is compared to the non-snowy days and the percentage loss in the performance due to snow accumulation on the panel is calculated.

It is necessary to note that the current measured in this system is the current from resistor (load) and not from the solar cell. Thus, the practical power P_{PR}, is the power across the load. But the theoretical power P_{TH} that is calculated from the formula (5) is the theoretical power of the solar cell. Thus, modifications are made such that the formula to calculate performance ratio can be used correctly. Furthermore, the load used in this experiment is not optimum, rather it is 5 times more than the optimum value, so the current passing through the load is less than maximum. The I-V curve in figure 16 for KYOCERA panel is retrieved from PVsyst Software. According to this curve, for a load value of 10 Ω, maximum theoretical power value for the resistor is calculated to be 47 W. Therefore, to have a valid comparison of powers in the performance ratio equation, whenever P_{TH} value calculated from formula 5 goes above 47 W, the denominator in the K factor's formula is taken as 47 W so that calculation in the analysis are fair and accurate. Consequently, both practical and theoretical powers calculated in the equation are for the load.

Figure 16 I-V Curve for KYOCERA Panel



Source (PVSyst Software, 2016)

Errors are minimized as much as possible. Hence, the performance factor of snowy days is calculated only after the radiometers at the weather station are cleaned and brushed off in the mornings. If the radiometer is not brushed on the same day, then the values for K are taken into account only after an hour of the sunrise. Also, the evenings values are considered only up to an hour before the sunset.

The performance loss of the panel (power output) is not enough to know how much electricity is exactly lost due to snow. Thus, loss in energy for the 20 snowy days is calculated using the practical power, theoretical power and performance ratio. The practical energy yield E_{PR} for 20 snowy days is calculated by summing the area under the power v/s time curve, using the trapezoid area method. The theoretical energy yield for 20 snowy days is calculated by first finding the theoretical power under no snow scenario which is denoted as $Power_{No\ Snow}$. The area under this curve - $Power_{No\ Snow}$ v/s time gives the theoretical energy yield E_{TH} which is calculated using the same method as above. E_{TH} is the energy that would be ideally produced by the panel under hypothetical non-snowy conditions.

The actual energy yield E_{PR} and theoretical energy yield E_{TH} are then summed up for all the twenty snowy days. Next, the difference is compared to find the energy loss for those particular twenty snowy days. Lastly, this loss is extrapolated to an average energy loss for a year. This energy loss per year is the number that could be useful in system designing and in economic analysis for a particular PV system. While interpreting this energy loss per year, it is necessary to acknowledge the fact that there are no bypass diodes in place, so that the actual loss due to *snow only* is known.

3.2 Environmental Dimension

One of the main goals of Alberta's Climate Leadership Plan is to phase out coal fired emissions in the province by 2030. In 2014, 55% of the province's electricity was generated using 18 coal fired power plants (Alberta Government, 2016). There are 5 mines in Alberta where coal is produced which is used in the province and also exported. Under current federal regulations 12 coal power plants are to be phased out by 2030 due to strict imposition of GHG emission regulations by the federal government. The rest of the plants were expected to operate past 2030, but under the new plan, policies will be implemented to phase out all coal units. In 2015, coal generated electricity was 41,378 GWh which constituted 51% of the province's electricity supply (Alberta Energy, 2015).

For the environmental dimension, the GHG emissions in different scenarios where coal fired power plants are replaced by solar PV systems to generate electricity are analyzed. The GHG emission analysis is done for various scenarios to have a broader and practical picture of the emissions offset.

In the methodology used to calculate emissions offset, the GHG emission numbers in terms of per kWh of electricity produced are used from the National Renewable Energy Laboratory (NREL) study for both PV and coal based systems. These numbers are then used to calculate the amount and percentage of GHG emissions that could be offset using solar PV systems in a cradle to grave scenario. Cradle to grave in this context means, from the manufacturing to disposal of the systems. The different scenarios analyzed are to replace 10%, 20% and 30% of the coal generated electricity with solar PVs.

3.3 Socio-Economic Dimension

Public participation and awareness is another important factor in how successfully a technology penetrates unregulated markets. Surveys are excellent tools for collecting research data especially when people's perspectives are of a major concern. Sometimes, installing solar PV in cold climates can be a subject of uncertainty for general masses. Thus, a survey is discussed in this paper to know the viewpoint of local people on solar PVs.

The survey was conducted by a graduate student at the University of Calgary under the supervision of Dr. Haque in 2013-2014, to assess how informed Calgary public is about the solar PV technology. Approximately 300 residents of Calgary were surveyed with three major question. The questions are based on:

1. Interested to invest in Solar PV technology.
2. Quality of information available to the public.
3. Awareness in the people about the fact that PV systems work better in cold temperatures.

CHAPTER 4 - ANALYSIS, FINDINGS AND INTERPRETATION

4.1 Technical Analysis

The primary objective of the technical analysis is to find energy loss per year due to *snow only*. The first step is to calculate the average performance ratio of non-snowy day which is found as:

Average Performance Ratio for non-snowy days $\mathbf{K_{non\text{-}snow} = 0.78}$

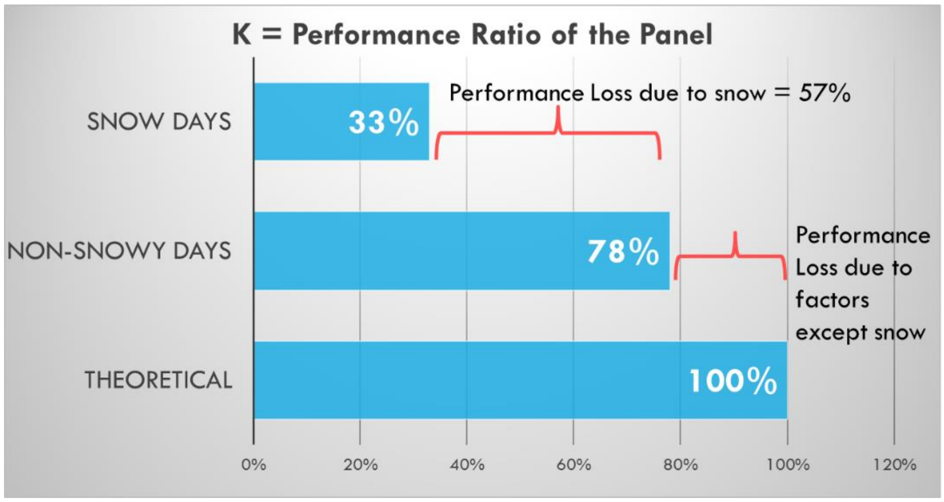
To calculate $K_{non\text{-}snow}$ - Approximately 20 non-snowy days in the period of four months of the analysis are considered. $K_{non\text{-}snow}$ is calculated for each of those days and averaged to find the performance ratio of the panel under non-snowy conditions. It means that on any non-snowy day the solar panel gives an average performance of 78% of its efficiency. Such low performance ratio could be due factors like external shadow on the panel and other technical losses (The German Energy Society, 2008). Moreover, the efficiency formula used in the analysis does not consider the effect of irradiation, which can also cause the low performance ratio of 78%.

In the next step, the performance ratio of the panel in presence of snow K_{snow} is found. Approximately twenty snowy days are selected between January to April with various thickness of snow accumulation. Same method as above is used for calculations.

The average performance ratio for snowy days, $\mathbf{K_{snow} = 0.21}$ **and 0.33**

0.21 indicates performance of the panel only for the particular period when there is snow present on the panel (30%-100% of panel covered with snow). 0.33 indicates the performance of the panel for the entire day on which there is any amount of snow accumulation. Snowy days are selected by looking at the images captured from the setup. This could be interpreted as the performance of the panel (in absence of bypass diodes) decreased from 78% to 33% in presence of snow in the winter of 2013-2014 in Calgary. Thus, it could be said that the loss in performance of the panel due to snow specifically is 57%. This loss is calculated by normalizing K_{snow} to $K_{non\text{-}snow.}$ The representation of the results of performance ratio of the panel in different scenarios is shown in figure 17.

Figure 17 Performance Ratios – different scenarios



The final step is to calculate energy loss per year due to *snow only*. Any other losses due to factors other than snow are eliminated. Hence, two different energy yield are found – Actual and Theoretical energy yield. Actual Energy yield is calculated by integrating practical power values over time. So basically it is the area under the power v/s time curve which is found using the trapezoidal formula in MS excel.

To find the theoretical energy yield, theoretical power (under no snow scenario) Power $_{\text{No Snow}}$ is found using the formula (12). Then, the Theoretical Energy yield for snowy days is found using the same trapezoidal method in Excel as mentioned above.

$$\text{Power}_{\text{No Snow}} = \frac{0.78 * \text{POWERpr}}{K\ Snow} \qquad \text{-(12)}$$

Next, the actual energy yield and theoretical energy yield are then summed up for all the selected snowy days. Then the difference is compared to find the loss in energy yield which is calculated as 61%. It means that there is **a** 61% loss in the actual energy is delivered to the load, for those 20 snowy days**.** This loss can be attributed mainly to snow, because other losses are already eliminated as much as possible. Despite this there can be other unknown factors that cause losses to the system, but they are minor due to which a small error is estimated in the analysis. So far, energy loss is calculated for 20 snowy days. An average year in Calgary experiences 54.2 snowy days (Current Results - Weatehr and Science Facts, 2016). So, energy loss is extrapolated from 20 days to a whole year. **The final result is, Energy loss per year due to *snow only* in absence of bypass diodes is approximately 9%.**

Three cases are considered to put the 9% loss number in perspective. – Theoretical case; Non-snow Calgary operating condition; Actual Calgary Operating condition. Non-snow Calgary operating condition is a hypothetical case where there is no snow precipitation all around the year. Assuming the capacity factor in Calgary is 15%, the calculations for all three cases are done based on the results of this research paper. Amount of energy yield for the 140 W panel is calculated for all three cases as shown in table 1. Detailed calculations are shown in Appendix D. Therefore, the amount of energy loss per year due to snow is 13 kWh out of a total of 143 kWh energy yield per year from the KYOCERA 140W panel which accounts for an annual 9% loss in energy production. Losses due to snow are calculated by comparing case C to case B.

Table 1 Three Cases for energy loss per year

Case	Energy yield per year (kWh)	Energy Loss Amount per year (kWh)	Energy Loss% per year
A. Theoretical	184	0	0
B. Hypothetical Non-Snow Calgary Operating Condition	143	41	22
C. Actual Calgary Operating Condition	130	54	29
LOSS DUE TO SNOW	**-**	**13**	**9**

An interesting phenomenon is observed in the data analysis. In the month of February due to both high irradiation and snow on the panel, when snow is melted off the panel, immediately there is high amount of power delivered to the load. This phenomenon can be caused as a result of very low panel temperature due to snow accumulation on the panel's surface which increases the efficiency of the panel temporarily. This phenomenon is shown in table 2. Moreover, the resistance of the load decreases due to low temperature, thus leading to increase in current flow and hence, the increase in power.

Table 2 Effect of Temperature on Power yield

TIME	POWER (W)	Ehori (W/m^2)	Tamb	Spanel W/m^2)	Spamel in kw/m2	Tcell (C)	ŋStc	ŋReal	K
11:35	26.88996	314	-20.2	757.40	0.757403	3.448842	0.16	0.175517	0.572127
11:45	31.21526	309	-20.0	745.34	0.745342	3.271949	0.16	0.175644	0.664154
11:55	**27.98229**	**324**	**-20.4**	**781.52**	**0.781524**	**4.042627**	**0.16**	**0.175089**	**0.595368**
12:05	**47.11535**	**273**	**-20.4**	**658.51**	**0.658506**	**0.178325**	**0.16**	**0.177872**	**0.645202**
12:15	45.97212	347	-20.5	837.00	0.837003	5.656332	0.16	0.173927	0.97813

Figure 18 Effect of Snow Melting on the panel

From figure 18, it is seen that with decreasing temperature, the power delivering capacity of the panel increases because of the increase in efficiency. Another interesting observation in the analysis, is that the snow melting behavior on the panels is a complex phenomenon. For instance, it is seen that complete snow melting on the panel can take any time between 30 minutes to 2 hours. Two different scenarios are shown in figure 19. In case 1, the snow accumulation has light to medium thickness and it is patchy. It melts in an uneven way and complete melting takes 30 minutes. On the other hand, in case 2, snow accumulation is very thick and non-patchy. The melting of snow occurs in slabs and it takes 45 minutes for the snow to melt completely. Snow melting behavior on the panel is dependent on various factors. The factors observed are:

1. Ambient temperature
2. Module temperature
3. Snow thickness on the panel
4. Type of snow material
5. Irradiance

It is a complex phenomenon because the above mentioned factors are interdependent. Ambient Temperature, Irradiance and Module temperature are dependent on each other as mentioned in the literature review.

Figure 19 Snow Melting Case 1(Patchy) and 2(Slab)

In terms of Alberta, given that it has a significant amount of snow, the results of this research are important to consider while installing Solar PV systems. The 9% energy loss per year without bypass diodes is not a significant loss because in real life scenario, by pass diodes are always present in the system, which prevent shading loss from happening.

4.2 Environmental Analysis

Alberta is planning to phase out coal by 2030, to reduce GHG emissions of the province. Hence, the environmental viability of PV systems is compared to business as usual fossil fuel based systems. The scenarios considered here are kept as practical as possible. The scenarios are for replacement of coal with solar PV by 10%, 20% and 30% in terms of energy generation.

Table 3 Results of Environmental Analysis

Scenarios	10%	20%	30%
Amount of electricity replaced (GWh)	4137.8	8275.6	12,413
GHG Emissions offset ton CO2 eq/kWh	3972	7944	11916
% of GHG emissions offset	**9.6%**	**19.2%**	**28.8%**

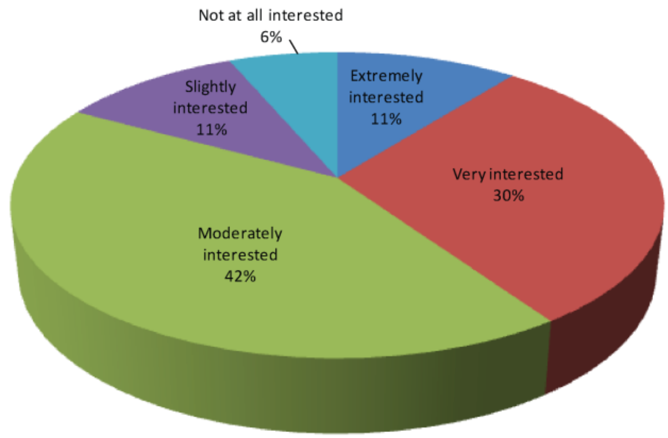
The result of this analysis in table 3, shows that even for the 10% scenario, which actually means 5.5% of the total energy mix of the province, the percentage of carbon offset is 9.6%. Whereas, for maximum scenario, the carbon emissions offset is 28.8%. Offset GHG emission amount is found in terms of ton CO_2 equivalent per KWh of electricity produced by solar PV instead of coal.

Thus, given how the energy efficiency of solar PVs increase in cold temperatures, and Alberta's high solar irradiance relative to the rest of Canada, solar PV is an option that should be explored to look for replacements of coal when the province is transitioning to a cleaner energy supply. The economic analysis is out of the scope of this paper but it has to be done to know the full feasibility of implementing and promoting this technology in Alberta. However, this analysis is sufficient to prove that solar PV is environmentally and technically feasible to promote on a large scale in Alberta.

4.3 Socio-Economic Dimension

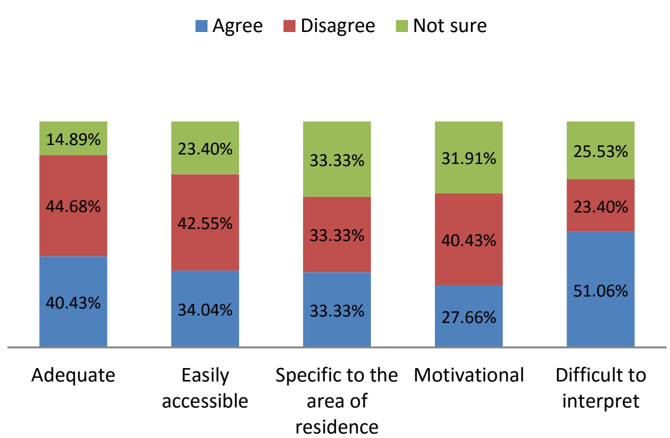
Public participation is absolutely necessary to implement solar PV on a broader scale in Alberta. The results of the survey by Dr. Haque show the perspective of Calgarians with regards to solar PV. The results show that more than 85% of the people are at least moderately interested in investing in PV systems as shown in figure 21. People were also surveyed on the quality of information available in terms of adequacy, easy access, specificity to the area of residence, motivation and difficultly of interpretation. As shown in figure 22, more than 50% of the people surveyed either disagreed or were not sure whether the information available to them was adequate. Less than 35% of the people said that the information available was easily accessible. To less than 30% of the people the information is motivational and to more than 50% the information is difficult to interpret.

Figure 20 The outcome of the survey for the interest of people to invest in photovoltaic systems.



Another question of the survey was about how much do people know about the fact that cold climates have an advantage over hot weather for better PV performance. More than 85% of the people surveyed did now know that low temperatures are actually beneficial for the performance of PVs.

Figure 21 The outcome of the survey for the amount of information available to the people.



The results of the survey demonstrate that people of Calgary are interested in knowing more about PV technology, but the problem is that there is not enough user friendly information which is easily accessible. So, it is necessary to dispose such quality information to the people to equip them with right tools to make decisions about installing PV systems in their homes. Moreover, this could also affect the growth of PV markets in the long run. The better access to a user friendly information availability, the more motivated people could be to install solar PVs.

CHAPTER 5 - LIMITATIONS and FUTURE RESEARCH

Limitations of this research are due to various technical factors. In the experimental set up, the current from the load is measured and not from the diode. Due to this, a problem is faced in the data analysis for calculating the performance ratio K, which is the ratio of practical power and theoretical power. However, the practical power measured is across *the load* and theoretical power calculated from theory and formulas is the power from the *solar cell*. So, to make a fair comparison both numerator and denominator need to have power across the same component that is either load or solar cell. So, modifications are made to have a valid calculation of K factor which are explained in the methodology section. Hence, theoretical power across the load is calculated. Moreover, the load used in the setup is 10 Ω instead of the maximum power point load of 2 Ω. Thus, calculations are revised again to avoid errors as much as possible.

The results of this research would be more accurate if the experimental set up had two different scenarios - 1. Panel with bypass diodes 2. Panel without bypass diodes. Errors would be minimal in that case.

The data from the University's weather station had errors in winter mornings. Due to this, 8 snowy days out of 28 snowy days had to be discarded from the analysis. Furthermore, there were technical issues in the months of November and December due to problems in the system set up so those months are eliminated from the analysis. Additionally, the data analysis is done only for one winter in Calgary hence, the results are specific and accurate for that particular year. The result for the energy loss would be more generalized if the data were collected and analyzed for more than one winter.

Moreover, due to the lack of measurement of the thickness of snow accumulation on the panel, a relationship between the snow thickness and energy losses is not established. Errors are estimated due to issues mentioned previously. In the efficiency formula used in the analysis, the effect of change in temperature is taken into account but the effect of change in irradiation is not considered, which might affect the accuracy of the calculated performance ratio K. This can be attributed to the low value of performance ratio K for sunny days - 78%.

As a part of future plans for this research, it will be an application for a formal publication. The scenario in which extrapolation of energy losses with the presence of bypass diodes with current findings will be explored.

Moreover, the snow melting behavior is a very interesting and complex phenomenon. There is lack of research on this topic and it is an important subject to explore which could reveal the effect of snow melting behavior on energy losses in PV. Furthermore, it is important to look into feasible solutions that are environmentally and economically viable to find ways to melt or remove the snow from solar panels. As mentioned in the literature review, only few researches are done on finding solutions for snow accumulation, but they are not yet feasible to implement on a large and real life scenario. Hence, there is a lot of room for research on this topic. A bigger system with various scenarios – like different angles of the panels, with and without bypass diodes, can be analyzed for more than one winter and in various places.

CHAPTER 6 - CONCLUSION

The result of this analysis – 9% loss in energy yield per year, is without bypass diodes in the system. 5% of error is estimated because of faults in weather data, power measurements and the modifications used for calculations. It is important to acknowledge the fact that this energy loss per year is without bypass diodes in place. Hence, it is not a significant energy loss in real life scenario when bypass diodes are always present. To compare an area close to Calgary, a research about energy loss due to snow was conducted in Edmonton. Where Edmonton is a colder region than Calgary and with more snow precipitation, the study about energy losses due to snow in PV systems was analyzed for four years and the losses accounted for 0.82% to 5.24% depending on the tilt of the module (Northern Alberta Institute of Technology, 2015). It is necessary to note that Edmonton study had bypass diodes present in the panel that prevent power losses due to shading. Thus, the result of this paper is comparable to other studies in areas geographically close to Calgary. Hence, snow causes energy losses per year to a small extent which can be avoided with no maintenance requirement if the panel tilt is as high as possible along with maintaining the optimum irradiance incidence angle for that place.

Taking into account that Alberta lies in the highest irradiance region of Canada and has cold climate, it has an underlying advantage compared to other regions of Canada - to have a high installed PV capacity. Even though solar capacity is increasing day by day, Alberta is not tapping into the full potential of the solar resource it has. Thus, this paper would help motivate Canadians and more Albertans to invest further in Solar PV as it proves to be an environmentally and practically viable technology despite the small amount of losses due to snow on the panels. It is established that people are clearly interested to invest in PV but in reality the actual investment is trivial, therefore, access to correct and straightforward information about PV is necessary. The government or not for profit educational organizations can take up this opportunity to spread quality and user friendly information so that the citizens of Calgary and Alberta can make right decisions for PV investments.

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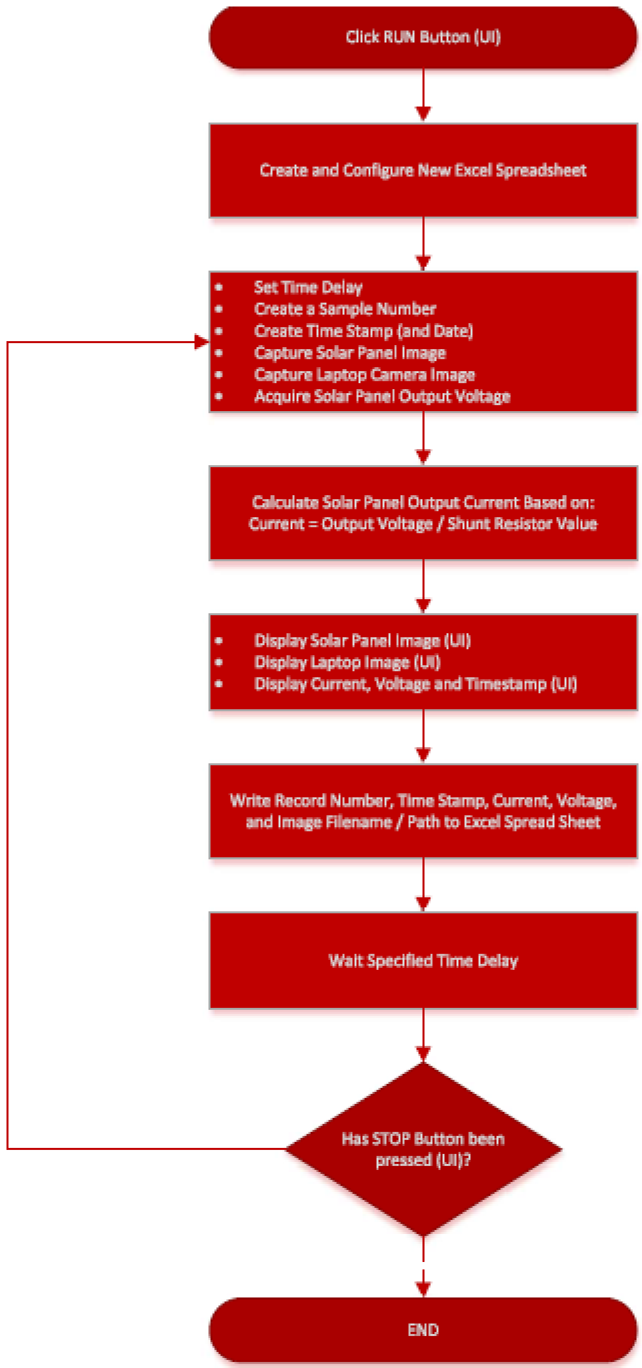
Appendix A – Software Flow



Appendix B – Data Sheet KYOCERA Panel

Figure 22 KYOCERA Datasheet

ELECTRICAL SPECIFICATIONS

Standard Test Conditions (STC) STC = 1000 W/M² irradiance, 25°C module temperature, AM 1.5 spectrum*	KD135SX-UPU	KD140SX-UPU	
P_{mp}	135	140	W
V_{mp}	17.7	17.7	V
I_{mp}	7.63	7.91	A
V_{oc}	22.1	22.1	V
Is_c	8.37	8.68	A
$P_{tolerance}$	+5/-5	+5/-5	%
Nominal Operating Cell Temperature Conditions (NOCT) NOCT = 800 W/M² irradiance, 20°C ambient temperature, AM 1.5 spectrum*			
T_{NOCT}	45	45	°C
P_{max}	97	101	W
V_{mp}	16.0	16.0	V
I_{mp}	6.10	6.33	A
V_{oc}	20.2	20.2	V
I_{sc}	6.78	7.03	A
Temperature Coefficients			
P_{max}	-0.45	-0.45	%/°C
V_{mp}	-0.52	-0.52	%/°C
I_{mp}	0.0066	0.0066	%/°C
V_{oc}	-0.36	-0.36	%/°C
I_{sc}	0.060	0.060	%/°C
Operating Temp	-40 to +90	-40 to +90	°C

System Design	
Series Fuse Rating	15 A
Maximum DC System Voltage (UL)	600 V
Hailstone Impact	1in (25mm) @ 51mph (23m/s)

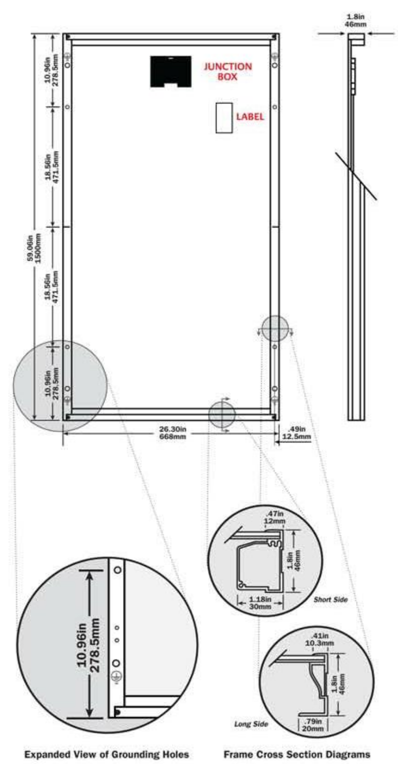
* Subject to simulator measurement uncertainty of +/- 3%.
KYOCERA reserves the right to modify these specifications without notice.

MODULE CHARACTERISTICS

Dimensions: *length/width/height*	59.06in/26.30in/1.8in (1500mm/668mm/46mm)
Weight:	27.6lbs (12.5kg)

PACKAGING SPECIFICATIONS

Modules per pallet:	20
Pallets per 53' container:	54
Pallet box dimensions: *length/width/height*	63.19in/27.56in/49.02in (1605mm/700mm/1245mm)
Pallet box weight:	617lbs (280kg)



NEC 2008 COMPLIANT
UL 1703 LISTED
CERTIFIED IEC61215 ED2 IEC61730 BY JET

Registered to ISO9001-2000

WARNING: Read the instruction manual in its entirety prior to handling, installing & operating Kyocera Solar modules.

Legend
O MOUNTING HOLES .35in (9mm) ◖ DRAINAGE HOLES ⊕ GROUND SYMBOL .35in (9mm)

041212

OUR VALUED PARTNER

Source (Kyocera, 2013)

Appendix C – Environmental Analysis Calculations

Method 1

Suppositions: [NREL]

- GHG emissions from a typical PV system per kWh - 40 g CO_2 eq/kWh
- GHG emissions from a typical coal system per kWh - 1000 g CO_2 eq/kWh

Data:

- Electricity generated from coal in 2015 = 41,378 GWh

Scenarios	10%	20%	30%
Amount of electricity replaced (GWh)	4137.8	8275.6	12,413
GHG Emissions offset CO2 (ton eq/kWh)	3972.288	7944.576	11916.864
% of GHG emissions offset	9.6%	19.2%	28.8%

Appendix D – Three Cases for Energy Yield Calculations

For the panel used in this experiment, which has a capacity of 140 W, the three cases calculated are: Theoretical case; Non-Snow Calgary Operating conditions and Actual Calgary operating condition (includes snow).

Assumption: The capacity factor for the panel in Calgary is 15% (conservative number)

Theoretical Case: There are No losses in this case, for which energy yield per year using the KYOCERA 140 W panel is –

Energy Yield per year = 140 * 24 * 365 * 0.15

= 184 kWh

Non-Snowy Calgary Operating Condition: A hypothetical case where there is no snow in Calgary all around the year for which energy yield per year using the KYOCERA 140 W panel is –

Energy Yield per year = 140 * 24 * 365 * 0.15 * **0.78**

= 143 kWh

0.78 is the performance ratio of the panel used under non snowy conditions, which is found from the result of this research analysis.

Actual Calgary Operating Condition: This is the real case where there are on average 54 snowy days all around the year in Calgary, for which energy yield per year using the KYOCERA 140 W panel is calculated as:

Energy Lost due to snow = Total Energy in Non-snowy condition - Energy yield Non-snowy days

= 143 – (0.91*143)

= **13 kWh**

Energy yield Snowy days = Energy Yield per year - Energy yield Non-snowy days

= (0.91 * 143) - (140 * 24 * 311 * 0.15 * 0.78)

= 8 kWh

Above calculation is based on the 9 % energy loss per year due to snow from this research analysis.