DALHOUSIE UNIVERSITY

The effect of snowfall on the power output of photovoltaic solar panels in Halifax, NS

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Abbreviations

Btu: British thermal unit (equal to 0.293 watt hours or 1055 joules of energy)

CO_2: Carbon dioxide

HRM: Halifax Regional Municipality

IPCC: Intergovernmental Panel on Climate Change

NS: Nova Scotia

PV: Photovoltaic

W: Watts (measurement of power output); W-h refers to Watt-hours

1.0 Introduction

1.1 Background

The issues of global warming and climate change and how we reduce the global impact of these problems have been at the forefront of many discussions between government bodies, world organizations and the general public. According to the Intergovernmental Panel on Climate Change, one of the main drivers of climate change is carbon dioxide emissions (IPCC, 2007). Since an anthropogenic source of CO_2 emissions is the combustion of fossil fuels, the Government of Canada, as well as many other government bodies, have developed multiple strategies to combat the problem of climate change, one of which being substituting conventional energy production, usually in the form of fossil fuels, for clean and renewable energy technologies such as solar power (IPCC, 2007; Environment Canada, 2010). Further, the Nova Scotia Department of Energy has committed to increasing the electricity created by renewable energy to 25 percent of the total electricity use by 2015, and to 40 percent by 2020 (Nova Scotia Department of Energy, 2010). Although there are many different forms of renewable energy such as wind, biomass and geothermal, it is expected that solar energy will play a prominent role in providing both developing and developed countries with clean and renewable energy (Sen, 2004; IPCC, 2007).

When looking at Canada, issues such as snow accumulation on PV panels need to be addressed before concluding that solar power is a viable alternative to conventional energy production. The design of these panels allows the PV arrays to withstand harsh environmental conditions such as extreme heat or cold, but during the winter season, build-up of snow and ice can occur on the PV panels. Although the PV arrays are not physically damaged by the severe winter conditions, accumulation of snow or ice could lead to decreases in energy output as long as the panels are covered by precipitation. This is because the build-up of snow or ice on the PV panels could prevent the incoming solar radiation from penetrating the PV arrays (Usher et al., 1994; Ross, 1995; Powers et al., 2010). To date, there are few studies that have investigated the issue of snow cover on PV panels, especially in Nova Scotia. This study will help to fill this knowledge gap in Nova Scotia. The following section will provide background information on previous research in this area, providing justification for this study.

1.2 Literature Review

1.2.1 Overview

Even though Canada has a relatively small population size, it is one of the world's leaders in energy consumption (Usher, Jean & Howell, 1994; EIA 2008). In 2005, the Canadian population consumed a total $1.50\text{x}10^{17}$ Joules of energy, ranking it fifth in the world in terms of total energy consumption (EIA, 2008). Presently, as the total energy demand in Canada continues to increase at a rate of 1% per year (EIA, 2008), PV panels are one of the sources of renewable energy that may develop into an economically viable means of supplying Canada, and most regions of the world, with the necessary amount of energy. (Usher et al., 1994; Dresselhaus & Thomas, 2001). Cold climate areas in particular are presented with the difficult task of developing new energy systems due to the fact that any energy generation methods, such as photovoltaic arrays, must be functional under harsh winter conditions that include snow, freezing rain and hail. Advancements in the design of the PV systems have been made so that they are physically capable of capturing solar radiation in the winter conditions described above, but one area that needs to be addressed is the reduced ability to generate electricity from the PV systems due to an accumulation of snow on the panels (Usher et al., 1994). It is crucial that the effect of snow accumulation on PV electricity generation be explored in order to validate its use as an effective alternative energy source in Canada in the coming years.

In order to determine the effect of snowfall on PV performance there are many variables that require analysis: precipitation characteristics, humidity, ambient temperature, building features and the distance between the roof and the PV array (Becker et al., 2007; Powers, Newmiller & Townsend, 2010). These factors could all influence if or how snow accumulates on the panels and for how long it remains. For instance, variables that are associated with weather such as temperature and humidity could have a negative correlation with the accumulation of snow on the panels and could reduce the amount of time it remains on the panel since warmer temperatures will allow snow to melt quicker than cold, dry temperatures. Relative humidity and ambient temperature refer to the temperature (°C) and humidity at that given temperature (%) around the experimental setup. Building features can be described as structures or multi-level roofs that could cause shading or prevent snow from falling on the panels. The distance (cm) between the roof and the PV array is important because drifts from the ground could overtake the entire setup. Finally, precipitation characteristics include but are not limited to wet snow, dry snow and freezing rain (Ross, 1995). Different snow types could all affect the time that the snow remains on the panel. For example, wind could easily blow dry / fluffy snow off the panels.

1.2.2 Snow Accumulation & PV panels

The effect of snow accumulation on the reduction of power output from PV arrays during the winter months in Nova Scotia has yet to fully be determined. Although it has not been studied in detail in Nova Scotia, research has been conducted in other regions of the world such as California, USA and Munich, Germany. An idea that had been proposed was to install the panels at a very steep angle in order to make it very difficult for snow to accumulate (Powers et al., 2010). Although snow accumulation was little to none, steep angles were shown to be less effective in generating energy, as steep angles prevent high amounts of radiation absorption (Powers et al., 2010). For fixed-angle PV arrays, it is most effective for panels to sit at an optimal angle, which varies depending on latitude (Calabrò, 2009). Optimal angle refers to the angle at which PV panels must be installed in order to achieve the maximum amount of solar radiation. The optimum angle varies depending on a given location's latitude and the time of year (Calabrò, 2009). Refer to section 2.1 for the optimum angle value for PV arrays in Halifax, NS.

Through studies conducted in Germany and the United States, it has been observed that snow accumulation does affect PV performance (Becker et al., 2007; Marion et al., 2009; Powers et al., 2010). Powers and colleagues (2010) analyzed the effect of different tilt angles on the percent loss in energy generation of un-cleaned PV panels compared to those that were regularly cleared of snow. Using three different tilt angles: 0°, 24° and 39° relative to the horizontal, it was found that the energy losses generated from November to May were 42%, 33% and 25% respectively. Annual energy loss values were also estimated as being (in the same order) 18%, 15% and 12% (Powers et al., 2010). The major finding from this study was that percent loss of electricity generation is a function of the snow depth on the PV panels and tilt angle of the PV array. Knowing that steeper panels are unable to collect as much radiation as more shallow sloped panels, it is concluded that the midsize tilt angles are the most effective year-round compared to the other tilt angles used.

Although Powers et al. (2010) demonstrated that tilt angle is a major factor in determining loss of energy power generation due to snow accumulation on PV panels, snow type is another factor that could influence the amount of energy output, where snow type is defined as the physical appearance and structure of the precipitation such as fluffy/dry snow (Becker et al., 2007; Powers et al., 2009). A study in Munich, Germany found that daily energy output by PV panels is directly related to the amount of fresh snow that fell on the panels that given day (Becker et al., 2007). On fresh snow days, the total energy to the grid decreased to zero (Becker et al., 2007). Since there were no controls in this experiment, it is impossible to say that fresh snow was the only factor that induced a zero energy output reading.

Another consideration to look at is how the power output increases over time and as snow melts off the panels. One study found that snow on unmodified solar panels will start to melt at temperatures as low as -3°C for a snow depth of 10cm (Ross, 1995). Ross (1995) used computer modelling tools to determine the melting rate of snow on PV panels in four different sites in northern Canada. From the four sites, it was concluded that the time it took for all the accumulated material to melt off the PV panels was 2019 hours at Prince George BC, 2566 hours at Norman Wells NWT, 1775 hours at Daniel’s Harbour NFL and 1364 hours at Bagotville QC (Ross, 1995). From this information, it is evident that snow cover on PV panels could affect their power output over numerous days. This model included a number of assumptions: that the initial precipitation accumulation was 5cm on each panel, that the ambient temperature will always be less than 0°C and that no snow will accumulate on the panels apart from the initial 5cm. These assumptions are not likely to occur in field studies; therefore these results can only be used as a rough comparison for other data collected in real world settings which will aim to study in more detail the correlation between energy output and snow melting rate (Ross, 1995).

Currently, there is research being conducted at Queen’s University in partnership with St. Lawrence College in Ontario, Canada that is aiming to develop a better understanding of how snowfall affects the power output of PV panels in Canada (Pearce & Andrews, 2011). A second goal of the study is to discuss some possible solutions that could be used to mitigate the losses in energy output over the winter months (Pearce & Andrews, 2011). This research involves two study locations: Queens Innovation Park, and the roof of the Wind Turbine and Trades building at St. Lawrence College. Both sites will test the effect of snow accumulation on PV panels of varying tilt angles between 0° and 70° from the horizontal (Pearce & Andrews, 2011). Since this project is only in the preliminary stages, no results have been presented to date.

1.2.3 Particulate Matter &PV panels

Although there have been very few studies that analyse the effect of snowfall on PV performance, there is research that describes how dust and other particulate matter reduce the power output of PV systems. Asl-Soleimani, Farhangi & Zabihi (2001) were able to collect energy output values (W-h) over the winter season, but it was not the main focus of their study. In this study, it was found that energy output in winter at any tilt angle was much lower than energy output in spring, summer or fall (Asl-Soleimani et al., 2001). In this study, the panels were only cleared once a season to allow for particulate matter to accumulate. Out of the all the tilt angles tested, a 29° angle was the most effective at avoiding particulate matter build up and at generating energy in winter compared to angles with degrees of zero, 23, 35 and 42 from the horizontal (Asl-Soleimani et al., 2001). Again, as with Powers et al. (2010), Asl-Soleimani et al. (2001) show that shallower angles are more effective at producing electricity than steeper angles, even during winter months. Particulate matter and snowfall would reduce power output in the same way by preventing solar radiation from penetrating the PV panels, but the amount of power reduction could be dependent on type of accumulated material and their associated characteristics. In addition, it was apparent that as dust and other particulates accumulate on the panels, the PV performance decreases (Mani & Pillai, 2010; Asl-Soleimani et al., 2001; Kaldellis

& Kapsali, 2011). From a review on the effects of particulate matter on PV performance (Mani & Pillai, 2010), it is evident that dust characteristics such as size, shape and weight are important factors in determining how much energy output will be lost based on their ability to restrict the amount of solar radiation reaching the PV panel’s surface (El-Shobokshy & Hussein, 1993; Mani & Pillai, 2010). From these findings, it could be expected that snow type, defined in the previous section, will affect the amount of power output generated by the PV panels. Furthermore, research shows that as dust starts to be deposited and remain on the panel it becomes easier for additional amounts of dust to accumulate (Mani & Pillai, 2010). Finally, it was shown that shallower tilt angles allow for more particulate collection than panels that are installed at a steep angle (Mani & Pillai, 2010).

Similar results can be expected for snow as were presented for particulates because they both accumulated on the panels over time and blocked incoming solar radiation from penetrating the PV arrays. For example, shallow angles would theoretically allow more snow to accumulate on the PV system just as was the case with particulate matter. In addition, as with dust, it is expected that as a thin layer of snow falls and remains on the panels, it will become increasingly easier for snow to accumulate on the panels. However, it is not sufficient to assume that snow will act in the same way as particulate matter because their physical characteristics, such as composition and particle size, are different. Also, the ability to accumulate and remain on the panels could vary between the two substances because snow can be melted off the PV panels whereas particulate matter can only be washed away or removed by the wind. Therefore the effects of snow accumulation on PV systems must also be analyzed in as much depth as the correlation between particulate deposition and PV performance has been studied.

1.2.4 Summary of Limitations & Gaps in Existing Literature

The following gaps need to be addressed before the effectiveness of PV panels during a Canadian winter can be understood. Firstly, the effect of snow on PV panels in Nova Scotia, HRM in particular have yet to be determined. Due to its unique weather and climate characteristics explained in the next section, the results gathered in previous studies cannot be just simply applied to this region since the weather at these study areas is much different than in Halifax. Secondly, snow melting rate has only been studied using computer modeling software which included many assumptions that are not likely to occur in field studies (Ross, 2005). It would be beneficial to study the effect of snow melting rate on power output of PV panels in a real-world setting to determine the length of time that un-cleared PV panels would be affected by snow cover.

Additionally, both Powers et al. (2010) and Becker et al. (2007) used only one study location in their design: a backyard in Truckee, California and a building roof in Munich, Germany respectively. Installing identical set-ups on two different roofs would add validity to the findings, especially if they show similar patterns and results. Building design could be a factor because roof structures and multi-level roofs would cause shading of the panels. Study location is also a factor because surrounding buildings could shade the panels, preventing snow from accumulating.

Only Powers et al. (2010) used a side-by-side experimental set-up where some panels are manually cleaned of snow and others are left to allow snow accumulation. While this was an effective design because power output loss could be determined by comparing the cleared and un-cleared PV panels, the panels were situated very close to the ground. Since they were on the ground, surrounding snowfall covered the entire set-up thus interfering with the cleared panels (Powers et al., 2010). It would be beneficial to install the PV arrays high enough off the ground to avoid covering of the control panels by drifts as much as possible.

Finally, Powers et al. (2010) noted that the PV panels were installed too close to each other in the experimental set-up. This caused some panels to shade others and for some of the snow on un-cleared panels to be carried by wind onto the cleared panels. In order to avoid panels interfering with one another, each panel should be situated at a far enough distance away from the adjacent panels.

1.3 Proposed Research

The purpose of this study is to determine the impact of snowfall and other winter weather such as freezing rain on the power output (W) of PV panels. Power output is defined as the amount of electricity in watts that the PV array will generate. The research will look at the effect of winter conditions such as ice accumulation and snowfall on photovoltaic solar panels in an attempt to answer the question: “does snowfall significantly reduce the output power of south-facing photovoltaic solar panels in Halifax, Nova Scotia, Canada?” Additional objectives include:

1) To determine the length of time that the panels were affected by snow accumulation, and how snow melt affects the power generation of these PV panels.
2) To determine the effect that solar radiation has on power output. And,
3) To determine the effects of additional variables such as snow type, percent cover and snow depth on the power output of PV panels

Due to the insulating properties of snow, it was hypothesized that as the depth of snow increases on the treatment (un-cleared) panels, there would be a decrease in the amount of solar radiation reaching the PV solar panels and thus a decrease in the power output of the snow-covered panels would be witnessed. In addition, when the snow has melted off the control panels, it was predicted that the power readings would increase until they were equal to those of the treatment panels.

The results of this study will have many applications and could be used by a variety of organizations or people who are looking to incorporate renewable energy in their homes or offices as will be discussed in section 4.0. Additionally, the results gathered from this study will provide opportunities for further research, which will be explained in more detail in section 4.0.

This is the first study to look at the effects of snowfall on PV performance in Halifax, Nova Scotia, Canada. The study will include aspects of previous research such as side-by-side design and specific instrumentation, while improving upon their limitations, gaps and errors.

1.4 Thesis Outline

The thesis follows the outline discussed in this section. Firstly, the methods section describes the experimental design and provides justifications as to why it is the most effective set-up. Quantitative analysis procedures for the various variables are discussed in detail, and the limitations and delimitations of the study are described. The results are then presented and statistical significance is calculated in order to validate the data collected. The results in the light of existing research, opportunities for future research and possible additions/changes to methodology are discussed. Any inconclusive results, errors/issues associated with the methodology, and changes to the methodology are explored. This study highlights certain questions that need to be addressed prior to the acceptance of solar panel as an important alternative to fossil fuels. Conclusions are drawn to establish a link between this study and the future use of solar energy in Canada as one of many initiatives to reduce the country's impact on climate change and global warming. Images, tables or sets of data that are referred to in this paper appear in Appendices A-E.

2.0 Methods

The following section will describe the instrumentation used to perform the study and the data collection and analysis procedures. The majority of the experimental design, including the side-by-side setup and the instruments used (pyranometer, image capturing software and humidity/temperature gauges) is derived from standards determined by the National Renewable Energy Laboratory (Marion et al., 2009).

2.1 Study Location

The city that served as the study location is the Halifax Regional Municipality (HRM) in Nova Scotia, Canada (*Figure 2.1.1)*. Halifax is located on Canada's Atlantic coast at latitude 44° north, at longitude 63° west and at an elevation of 145 metres above the mean sea level (Environment Canada, 2011). Two locations served as the study sites for the research: the Kenneth Rowe Management building on Dalhousie University's Studley Campus (GPS coordinates: 44.636906; -63.588172) and a residential neighbourhood site in HRM (GPS coordinates: *44.673273; -63.567525)* (*Figure 2.1.1)*. Since both locations are situated at the same latitude, if the results are similar, that is a good indication that the results are accurate and valid. Also, any outliers or skewed results can be then attributed to either faulty equipment or specific conditions at the given location. Both sites were purposely chosen because of their ease of access. Since the control panels needed to be cleared off immediately following a snowfall, it is necessary that the panels were situated close to the researchers' place of residence or study.

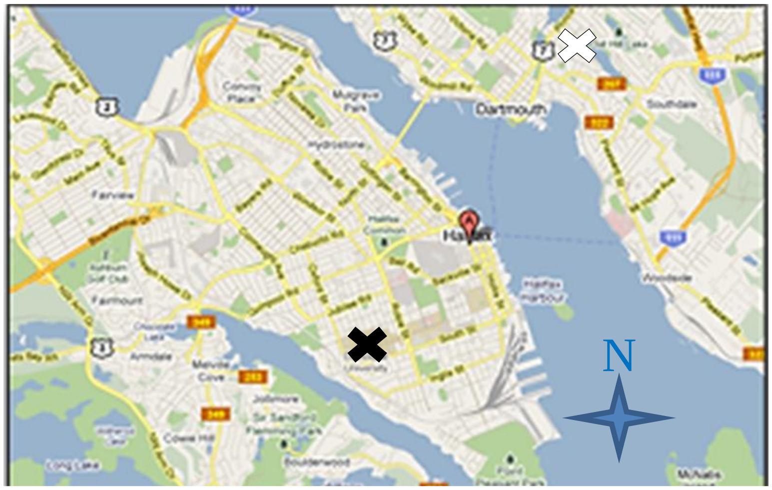

***Figure 2.1.1*:** Map of Halifax Regional Municipality in Nova Scotia, Canada. The black "X" shows the Dalhousie University study location and the white "X" shows the residential neighbourhood study location.

The climate for Halifax, NS displays weather characteristics pertinent to both a maritime and a continental climate making Halifax a unique study location in Canada because most regions do not have this combination of weather (*Table 2.1.1;* Environment Canada, 2008). Weather and climate information were gathered from Environment Canada's historical weather database and were used as comparisons between the amount of snowfall that was received this winter and snowfall received in previous years in order to determine if the snow received this year is comparable to average winter weather in Halifax.

***Table 2.1.1*:** Climate data for Halifax, Nova Scotia between 1971 and 2000 presented based on yearly averages. Measurements were obtained from the Halifax Citadel weather station.
Source: modified from Environment Canada (2011)

HALIFAX, NOVA SCOTIA (1971-2000)	**Yearly**
Average high (°C)	11.2
Average low (°C)	3.2
Average high Dec-Mar (°C)	1.5
Average low Dec-Mar (°C)	-6.5
Precipitation (mm)	2,875
Rainfall (mm)	1,356
Snowfall (mm)	1,519
Average Precipitation days (≥2.0mm)	152
Average snowy days (≥2.0cm)	24
Prevailing winds	Westerly

2.2 Experimental Design

At each location, eight PV panels were installed (*Figure 2.2.1),* half of which served as treatment panels and were manually cleared off following a snow event. The other half remained untouched and served as the control panels (*Figure 2.2.2; Appendix D).* For the purpose of this research, a snow event is defined as a period of snowfall greater than 2 cm. In order to achieve the maximum amount of energy generation for studies that are performed in the Northern Hemisphere, the PV system should face in a due-south direction (Marion et al., 2009). The PV panels were mounted at an angle of 45°, the optimal angle for the latitude at which Halifax, Nova Scotia is located. The optimal angle refers to the tilt angle at which the potential energy output is the highest. They were installed at this angle to reflect how PV panels would be installed in a residential setting.

Sunwize (SC3-12V) 3-watt solar panels with dimensions of 9.4 cm x 5.6 cm were used, which are much smaller than PV panels that would be used in a typical residential setting. These panels produced useful amounts of power but are low-voltage and are safe for experimental use.

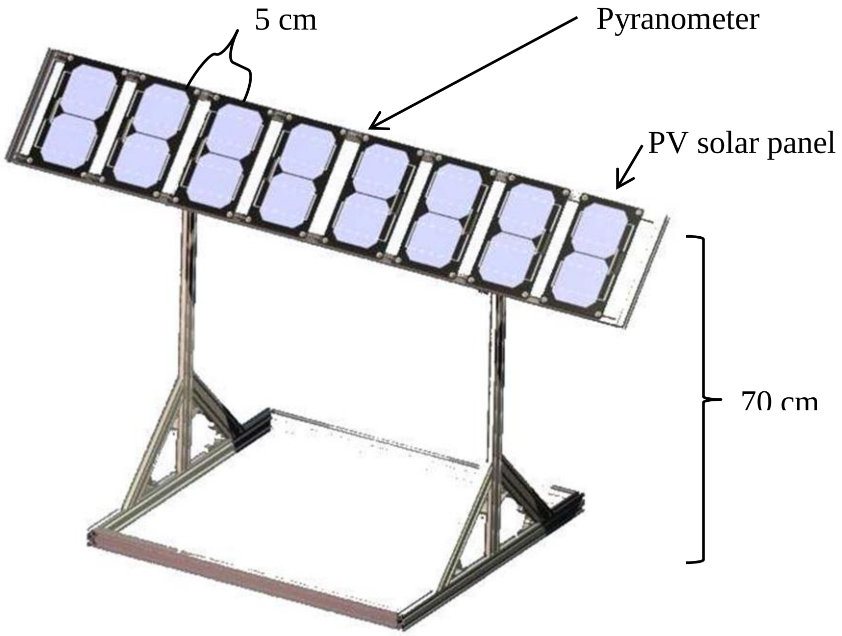

Figure 2.2.1**:** Schematic of the experimental design. Parts that are associated directly with the physical set-up are labelled. Photo equipment was mounted separately. Image: Alain Joseph (2012).

The panels were mounted in a horizontal linear fashion in order to avoid the shadowing of some of the panels by the others. The base of the panels was attached to an aluminum frame and situated at 70 cm above the ground to reduce the chance of snow drifts overtaking the entire set-up (*Figure 2.2.1)*. Since it is important to achieve randomness in this experimental design in order to avoid the alignment of panels so that some receive more snow cover than others and thus skewing the results, a random number generator was used to determine the order of the panels (*Figure 2.2.2).* In addition, each panel was separated at a distance of 5cm from the adjacent panels to reduce the chance of one panel affecting the others.

In order to achieve consistency in the results, the same Sunwize 3-watt solar panels, SP-215 Apogee amplified pyranometer and Wingscapes 4-megapixel TimeLapsePlantCam camera and video recording software was used at both locations. This camera was installed across from each of the PV setups and would take a picture every minute during daylight hours. The purpose of the camera was to have image evidence of what is occurring at the study sites without requiring constant monitoring. It was useful in determining how long it took snow to melt off the panels. Also, when any unusual results were observed, it was possible to reference these images to see if there were any obvious reasons why these abnormalities were occurring.

Ambient temperature and humidity were recorded using a Honeywell thermocouple. Solar panel power output was measured as voltage using Dataq USB data loggers (EL-USB-1-LCD) with WinDaq/Pro software. The amplified pyranometer was used to measure the amount of solar radiation penetrating the panels; to avoid skewed results, the pyranometer was maintained free of snow and debris at all times using the same process as removing snow from the treatment panels. It was also installed in the middle of the setup on the same angle of the PV panels to achieve the most accurate readings (Becker et al., 2007; Marion et al., 2009).

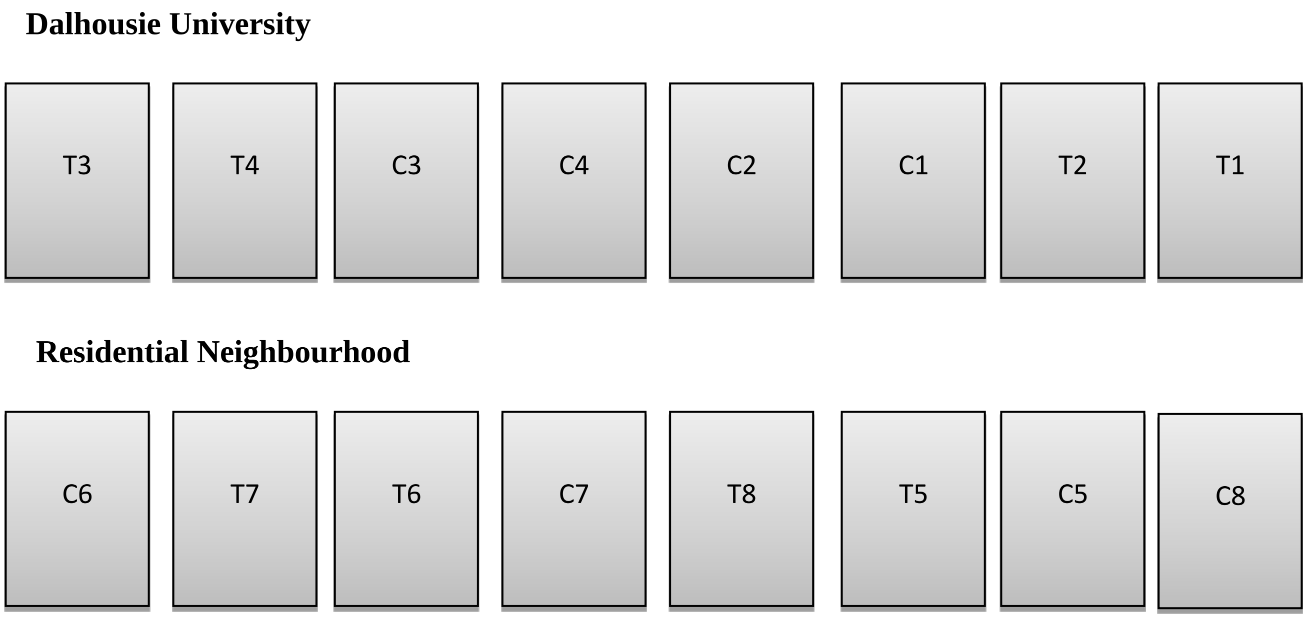

Figure 2.2.2: Schematic of the PV set-up on both locations: Dalhousie University & Dartmouth Residential Neighbourhood. Note the figure is not to scale; it is showing the location of the control and treatment panels where T= treatment and C=control

2.3 Data Collection

The data collection period ran from January 5th 2012 until March 5th, 2012. Due to the fact that it is impossible for the panels be maintained free of snow all day, every day, the most effective method of collecting data was to use targeted snowfall events. When weather forecasts from Environment Canada depicted a snowfall for a specific day, the following day was used as a test day. Prior to sunrise, a manual snow gauge was used to determine whether the snowfall was greater than 2 cm. If so, the PV set-up was checked for snow accumulation. If there was snow accumulation, the percent snow cover per panel and snow type was estimated and the snow depth on each panel was measured using a ruler (*Appendix B).* Snow depth was measured at the side of each panel at mid-length in order to avoid interfering with the snow on the treatment panels. Snow depth was measured on the controls before snow removal was completed. Following these measurements, the control panels were manually cleared of snow using an automotive snow brush/scraper. If there was obvious variability in the snow depth, multiple measurements were taken and the average was calculated.

Once the snow was removed from the controls, the pyranometer measured how much solar radiation was reaching the solar panels. Data was automatically recorded for voltage of each panel every 16 seconds for a 24 hour period and then transferred to an excel spreadsheet where the data set was manually compressed to every ten minutes. With remote capabilities on the two sites, the data logger was able to be remotely shut off, instead of manually. Using the TimelapsePlantCam camera combined with this data, the time it took the snow on the treatment panels to melt off (hours) was determined. The power output (W) and the associated variables such as snow type, percent cover and snow depth were then analyzed to determine if there was a correlation between snow accumulation and the overall performance of the solar panels. The following section provides details on how the data was analyzed.

2.4 Data Analysis

After all the data had been gathered, energy output was analyzed over time. In addition, power loss (W-h) was determined by comparing the power generated by both the control and treatment panels. From analyzing the differences in power output and pyranometer readings from PV panels installed at the Dartmouth location for both a sunny day and a cloudy day, it was expected that control panels will display data similar to the sunny day and the treatment panels will display data similar to the cloudy day but with greater differences because the snow is directly covering the panels.

The data collected was statistically analyzed using R software in order to determine whether or not the results are significant. In order to determine if the differences in power output between the control and treatment panels were in fact statistically significant, a matched pair t-test was completed. The following hypotheses were tested: H_o: $\mu_1 = \mu_2$ and H_a: $\mu_1 - \mu_2 > 0$. Where H_o means that there is no significant difference between the control and treatment panels whereas H_a means that there is some degree of significance. The test was run at an $\alpha = 0.05$ level which means that in order for the differences to be significant and in order to reject the null hypothesis, the p-value obtained must be less than 0.05. If the p-value is not less 0.05, it is possible that there is slight significance, just not at the 0.05 level. A 95% confidence interval was also performed for the differences (Equation 1):

$$95\%\ CI = \bar{y}_d \pm t_{\alpha/2,\ n-1}(s_d/\sqrt{n}) \tag{1}$$

where: $\bar{y}_d$ is the mean difference (between the cleared and un-cleared panels)

“n” refers to the sample size

s_d is the standard deviation and,

$t_{\alpha/2,\ n-1}$ is the t-value at 0.05/2, sample size-1.

If all the variables gave correct results and there were enough snow days with different snow types, a linear regression analysis could be completed in order to determine what measured variables significantly affected power output of the PV panels. Variables that could be analyzed are snow type, snow depth, temperature, humidity, percent cover and time of day. Since not enough data was collected for each of the variables, the linear regression was not performed in this study. For example, certain snow types only occurred on one day; multiple days with the same snow type would be needed in order to attribute any differences in the results to this variable. In addition, any outliers were removed before statistical analyses were completed.

A comparative analysis of power output was also conducted between the two study sites. Both snow days and non-snow days were used as comparison. Power output was calculated per panel at each location and was then graphed with the results for each location side by side. It was anticipated that both study locations would display similar results since they are both in the same city, at the same latitude, and had similar snowfall. Some factors that may be different between the two sites are the amount of time the panels are shaded or the amount of time that the panels are exposed to direct sunlight, and buildings or other obstacles that could prevent snow from falling on the panels. Although these factors could cause differences in the results, the locations chosen were the best possible sites that satisfied the criteria of being easy to access in morning by the researchers. Extrapolating the results from the sample population allowed for conclusions to be drawn for the target population of HRM, Nova Scotia.

2.5 Limitations & Delimitations

Due to time constraints, data was only collected over one winter season (January 2012 - March 2012). This study will serve as the first phase of a longer study which will collect data over a multi-year period.

Another limitation to this study is the type of weather that Halifax received during the 2011-2012 winter season. Although the archival climate data has been more or less constant for the amount of snowfall (cm) and number of snow days in the past ten years, it was impossible to determine, prior to data collection, the number of snow days Halifax would receive during the study period (Environment Canada, 2011). Even though this variable is uncertain, it was expected that enough snow would fall to gather meaningful results.

There are also delimitations, deliberately imposed limitations, associated with this research. Due to financial constraints and safety precautions, only 16 solar panels were used in total. Since only 16 panels were used, the study did not include variations in tilt angle or in panel orientation. It was important to develop a method that was electrically safe in order to ensure the experimental design was safe for the experimenter. Another imposed limitation is that the study was only conducted at two locations with the same latitude. Since the optimum angle differs as latitude changes, conclusions could only be drawn for places located at the same latitude as Halifax, and that display similar temperature averages and a comparable quantity of snowfall, but this methodology can be applied anywhere.

2.6 Summary

It has been shown that a side-by-side panel set up with half the panels being regularly cleared of snow and the other half left to accumulate snow as being the most effective set-up in determining the effect of snowfall on PV panels because you can determine the power loss associated with snow cover by comparing the results from the un-cleared and the cleared panels (Marion et al., 2009; Powers et al., 2010). Through implementation of the proposed methodology, the question “does snowfall significantly reduce the power output of PV solar panels in Halifax, Nova Scotia” was determined. The melting rate of snow on the PV treatment panels was also determined through the use of cameras and the power data.

3.0 Results

3.1 Weather Characteristics

In order to draw conclusions regarding the effects of snowfall on PV panels in Halifax, Nova Scotia, it is important to first look at the weather characteristics of the study year compared to those of previous years. This is necessary in order to determine whether or not the meteorological conditions that occurred in the study year were representative of typical Halifax weather. From referencing the historical weather database from Environment Canada it was possible to retrieve weather data as far back as 1971.Through calculating average snowfall between January and March for each year, it was concluded that the total snowfall that took place in 2012 between January and March was approximately 50% of the average snowfall received during that period between 1971 and 2011 (*Figure 3.1.1).* Also, comparing the average number of snow days of previous years with the number of snow days this year, it is evident that less snow days occurred over the 2012 winter season (*Figure 3.1.2).* Therefore, it can be concluded that the snow received during the study period was much less than the average winter in Halifax (Environment Canada, 2012). Since less snow days occurred here than in previous winters, these results are conservative estimates of the power loss associated with snow accumulation and it is expected that more days will be affected in future winters.

A slight increase in average daily temperature (from -4.2°C to -3.7°C) between January and March was also observed in the 2012 study period when compared to the average daily temperature between 1971 and 2011 (*Figure 3.1.1).* Given this warmer temperature, it is possible that some of the precipitation days that were comprised of rainfall could have been snowfall had the temperature been colder.

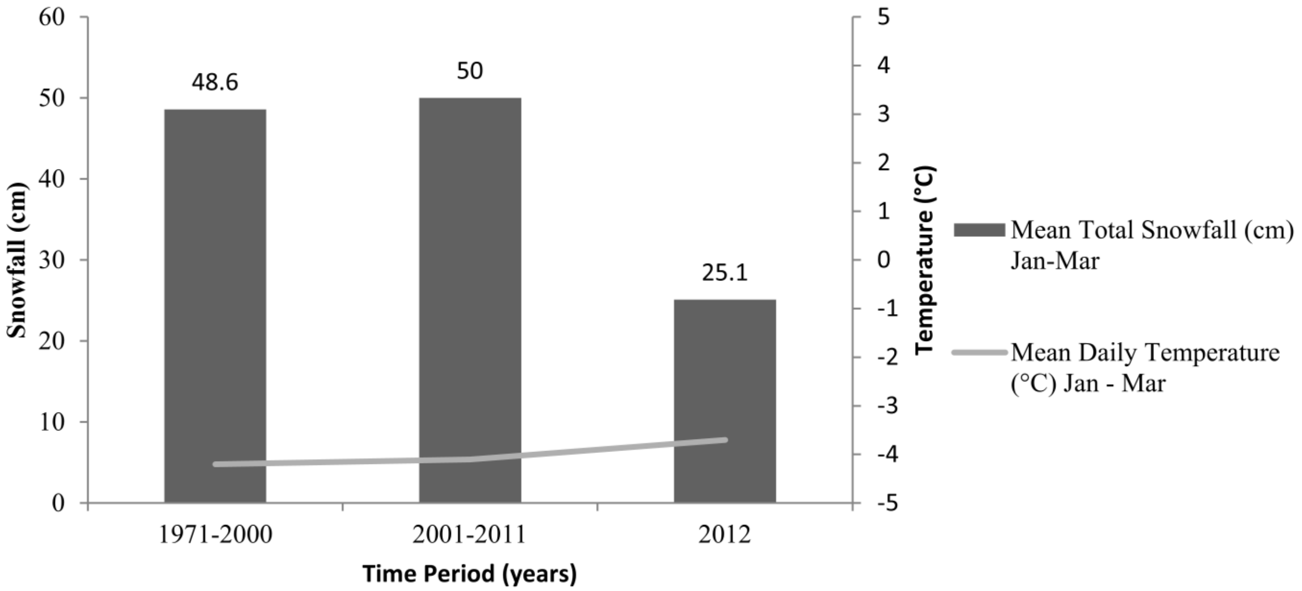

Fig 3.1.1: Snowfall (cm) and temperature (°C) averages between January and March from 1971 - 2012 for Halifax, Nova Scotia. Note data missing for 2003.

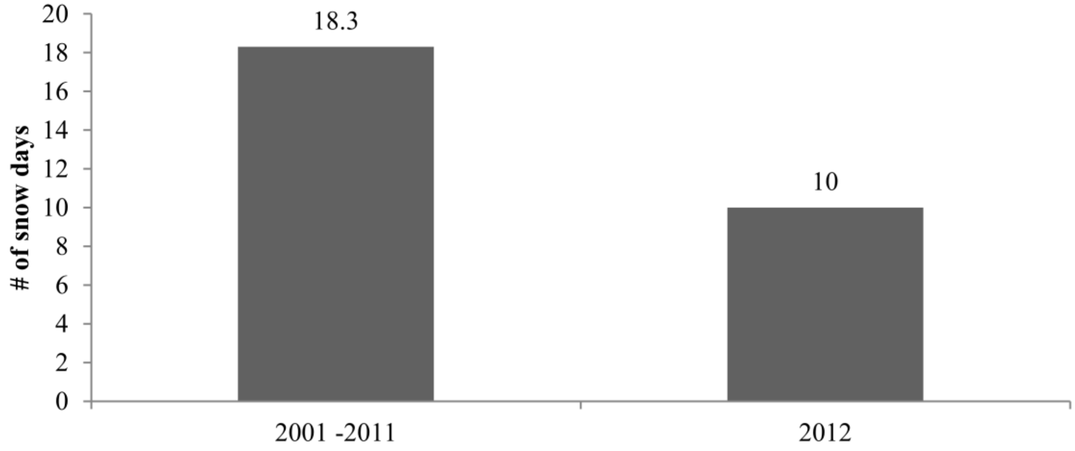

Fig 3.1.2 Number of snow days (≥2cm) between January and March in Halifax, NS. Measurements taken at Stanfield International Airport

3.2 Cloud Cover and PV performance

One objective of this study was to analyze the effect of solar radiation on PV performance since cloud cover prevents solar radiation from reaching the PV panels and therefore decreases their power output. Comparing the power readings from a mainly clear day and a mainly sunny day allowed for the effect of cloud cover on the power output of PV panels to be determined. From looking at pyrometer readings obtained for each day and descriptive weather characteristics from Environment Canada's historical weather database, two days were determined to be accurate representations of a clear day and a cloudy day: February 10th, 2012 and February 6th, 2012 respectively (*Figure 3.2.1; Appendix A*). February 10th was a good representation of a clear day because the pyranometer readings were constantly high (500 + W/m^2). February 6th was used because the pyranometer readings for the day were consistently low (<100 W/m^2). The clear day shows what the total capacity of these PV panels is in the winter with minimal obstruction (no snow or clouds). It was determined that cloud cover reduces the amount of power output (W-h) by approximately 77% (*Figure 3.2.1*). It is evident that long periods of cloud cover will have a large effect on the ability of the PV panels to produce power at their full capacity.

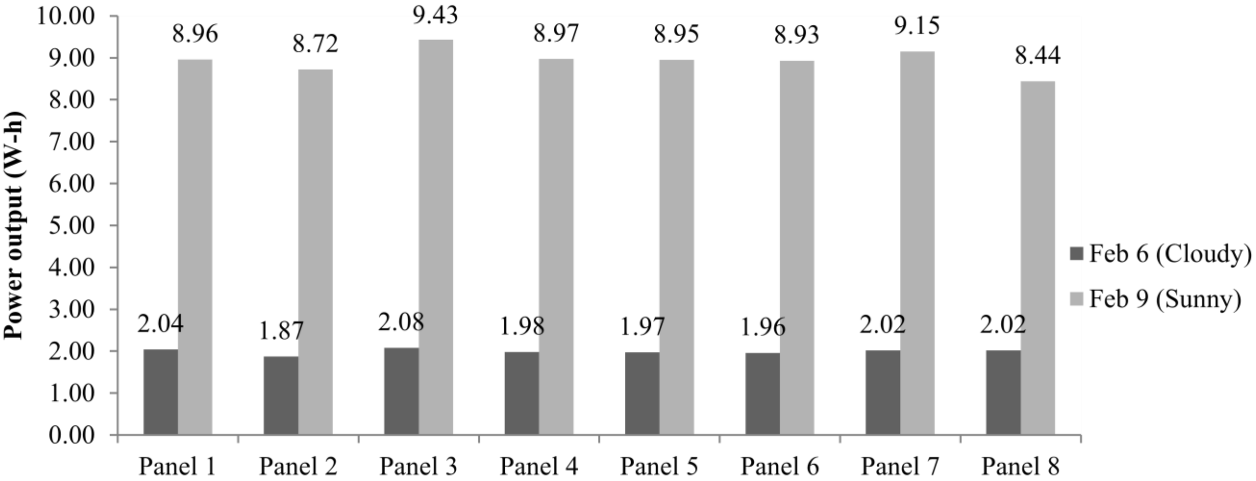

Fig 3.2.1: Power output (W-h) over a nine hour period for the PV setup on the Rowe Building at Dalhousie University in Halfiax, Nova Scotia.

3.3 Snow Accumulation and Power Output

Location One: Kenneth Rowe Building

According to Environment Canada's historical weather data, there were a total of ten significant snowfall days (greater than 2cm) during the study period (Environment Canada, 2012; *Appendix C*). Two of those days were in January, six in February and two in March. Of those ten snowfall days, two of the days were accompanied by rainfall and therefore there was no net snow accumulation by the next morning as the rain melted the snow that had previously fallen. Of the remaining eight days, snow accumulated on the PV set-up for five of the days. Possible reasons why snow did not accumulate on three of the days will be discussed in section 4.0. From the data collected on the five days where snow accumulation on the PV panels did occur, there was an obvious difference in the power generated by the PV panels that remained covered with snow and those that were manually cleared of snow in the morning.

In total, three different snow types were observed over the five measured snow days at the Rowe building location: wet / compact snow, dry / fluffy snow and ice buildup. Both wet / compact snow and dry / fluffy snow occurred on two days each whereas ice buildup was only observed on one of the snow days (*Table 3.3.1; Appendix B).* The day where the ice buildup occurred (January 21st, 2012), the snow remained on the panels the longest (until about 3:30 pm). Also, the snow depth per panel was small on each of the five snow days, ranging from 0 cm to only 2 cm, even if there was more snow that had accumulated on the ground (*Table 3.3.1; Appendix B).* Generally, percent cover and snow depth were similar across the eight panels at this location (*Table 3.3.1; Appendix B).*

Table 3.3.1: Summary characteristics for each of the five snow days analyzed at the Rowe building location in Halifax, NS

Date & Location	Peak power output (watts)	Percent Cover	Snow Type(s)	Average Snow Depth (cm)	Weather (Environment Can.)	Approx. time when snow melted off the panels
Jan 21st 2012 – Rowe	2.05 W	5 % to 70 %	Compact snow and ice buildup	Ice layer to 20 mm	Mainly clear Low temp. Moderate humidity	3:00 pm
Jan 31st 2012 - Rowe	1.82 W	All 100%	Light / fluffy snow	17 mm to 18 mm	Mainly clear Low temp. Moderate humidity	12:00 pm
Feb 2nd 2012- Rowe	0.06 W	All 100%	Light / fluffy snow	3 mm to 4 mm	Cloud cover Rainy / fog periods Moderately low temp.	1:00 pm
Feb 28th 2012- Rowe	1.10 W	50 % to 100 %	Compact / wet snow	4 mm to 6 mm	High humidity Showers Fog + 0°C temp .	Before sunrise
Mar 2nd 2012 – Rowe	0.36 W	80 % to 95 %	Compact / wet snow	All 2 mm	Cloud cover Low temp. Moderate humidity	1:30 pm

For each of the five snow days, power output was measured per panel. Upon comparing the panels that were covered with snow and those that were cleared of snow it is evident that the treatment panels displayed higher power output readings than the control panels until the snow had completely melted off the controls (*Figure 3.3.1; Appendix E*). From the example below, it is clear that the treatment panels (in blue) have higher power outputs until early to mid-afternoon when the snow melts off the control panels (*Figure 3.3.1).* The figure displayed below is the power output (watts) versus time data for February 2nd, 2012; the rest of days are similar to this example (*Appendix E).* It is also important to note that some of the days showed much lower power readings overall, regardless of whether snow accumulated on the panels (*Table 3.3.1; Appendix E).* This is because those days were comprised of cloud cover, which, as shown in section 3.2, reduces the overall power output potential of the PV panels.

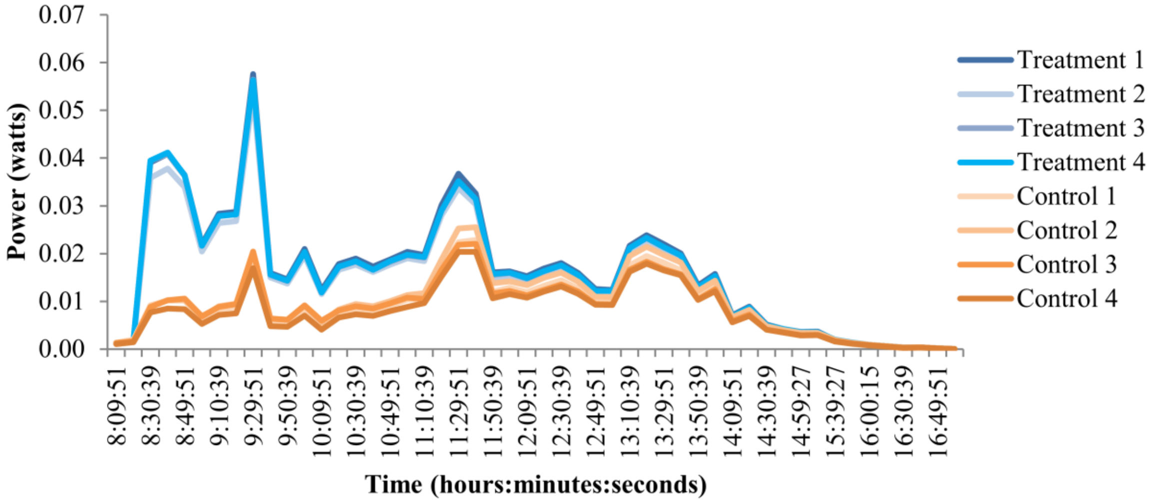

Fig 3.3.1: Power data (watts) for the PV setup on the Rowe Building at Dalhousie University in Halifax, Nova Scotia on February 2nd, 2012. Note control means that the panels were left covered in snow and treatment means that the panels were cleared of sno

As stated above, there were three days, in addition to those where snow accumulated on the PV panels, where there was no accumulation on the PV panels the morning after a snowfall (February 5th, February 25th and March 5th). Due to this fact, all of the eight panels display very similar power readings throughout the entire day. From this data it is possible to conclude that snow accumulation was one of the main factors contributing to the loss of power output by the control panels. Reasons as to why snow did not accumulate on these panels will be discussed in section 4.0.

Location Two: Residential Neighbourhood

An additional PV setup was installed in a residential neighbourhood in Dartmouth, part of HRM, on February 2nd, 2012. As stated above, the second location was added in order to determine to what degree the study locations within HRM impact either the amount of snowfall that accumulates on the panel or how much power is generated by the PV setup and to validate the results since they both should show similar power readings. At this location, February 2nd and March 2nd were the only days on which snow accumulation was observed on the PV panels. February 2nd was a very cloudy day with low power output readings, peaking at 0.06W in the early afternoon. Differences in the control and treatment panels are noted until shortly after 2:15pm when the snow had melted off the panels (*Table 3.3.2; Appendix E*) .March 2nd was somewhat cloudy and therefore the power output readings are relatively low compared to the actually capacity of the solar panels used in this study (*Appendix E*). From analyzing the power data for this study day, it is clear that the snow covered panels display lower power readings than the panels that were manually cleared of snow. As the snow melts off the control panels, between 1:00-1:40pm, the power readings quickly increase until they become equal to the values of the treatment panels (*Figure 3.3.2).* The power output (watts) versus time data is shown below as an example of the results obtained for the residential neighbourhood location. The rest of the results can be found in *Appendix E.*

Table 3.3.2: Summary characteristics for the two snow days analyzed at the residential neighbourhood location in HRM, NS

Date & Location	**Peak power output (watts)**	**Percent Cover**	**Snow Type(s)**	**Weather (Environment Can.)**	**Approx. time when snow melted off the panels**
Feb 2nd 2012- Residential Neighbourhood	0.10 W	All 100%	Light / fluffy snow	Cloud cover Rainy / fog periods Moderately low temp.	2:15 pm
Mar 2nd 2012- Residential Neighbourhood	0.50 W	All 100 %	Compact / wet snow	Cloud cover Low temp. Moderate humidity	1:00 pm – 1:40 pm

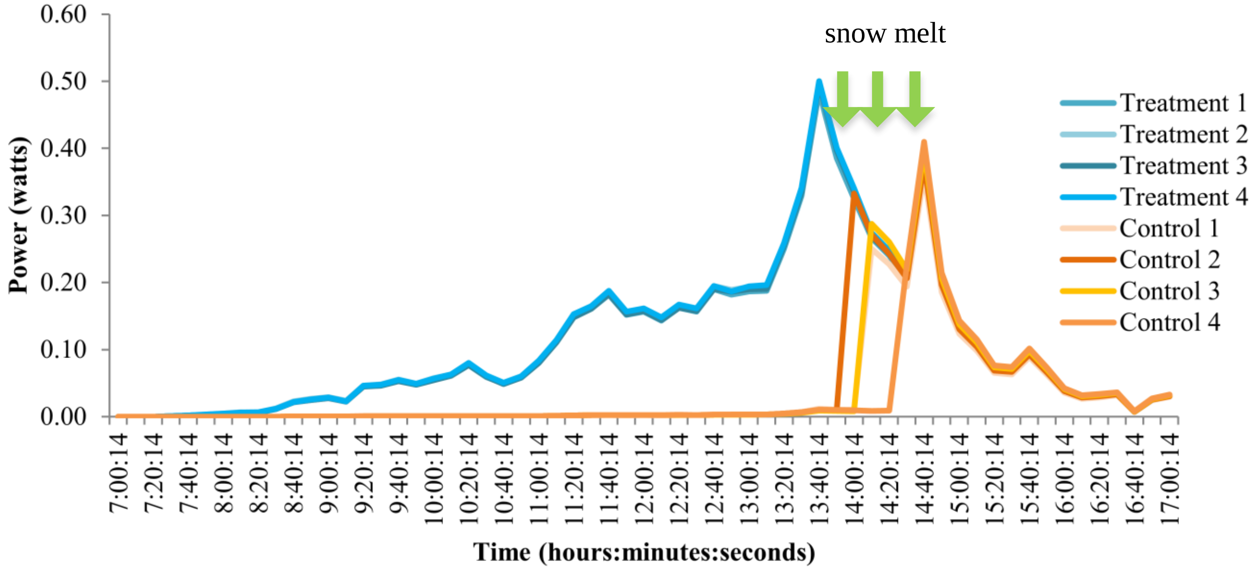

Fig 3.3.2: Power data (watts) on March 2nd, 2012 at the residential neighbourhood location, HRM Nova Scotia. Note: Control panels are those which remain covered with snow.

3.4 Snow accumulation and power loss

Location One: Kenneth Rowe Building

The five days on which there was snow accumulation on the PV panels were analyzed to determine the amount of power loss (W-h) associated with the build-up of snow on certain panels. It was concluded that snow accumulation on PV panels does decrease their power output when compared to PV panels whose snow was manually removed. Although it is evident that snow cover decreases power output, the amount of power loss appeared to vary greatly among the five snow days. On January 21st and February 28th there were two panels that produced much higher power readings than the other panels and therefore, the power reduction was determined excluding these outliers (*Figure 3.4.1).* The day on which there was the largest power reduction was January 21st. The power output by the panels covered by snow was reduced by approximately 46% on this day. Power readings were also observed for January 31st, February 2nd, February 28th and March 1st. The percent reductions between the clear PV panels and the snow covered panels were 22.2%, 37.5%, 3.2% and 28.7% respectively (*Figure 3.4.2*).

From referencing historical weather data from Environment Canada, it becomes clear that when the study day was generally cloudy, the power readings were much smaller for both the control and treatment panels compared to the power readings on the days that were mainly sunny. This shows that both cloud cover and snowfall have effects on power output of PV panels.

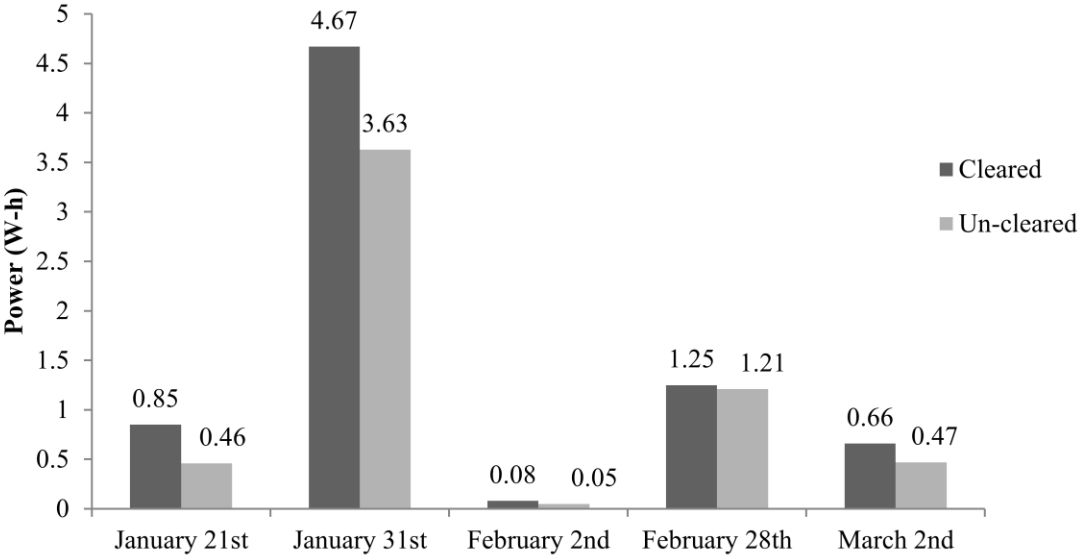

Fig 3.4.1: Differences in power output between cleared and un-cleared PV panels on Rowe Building, Dalhousie University in Halifax, Nova Scotia

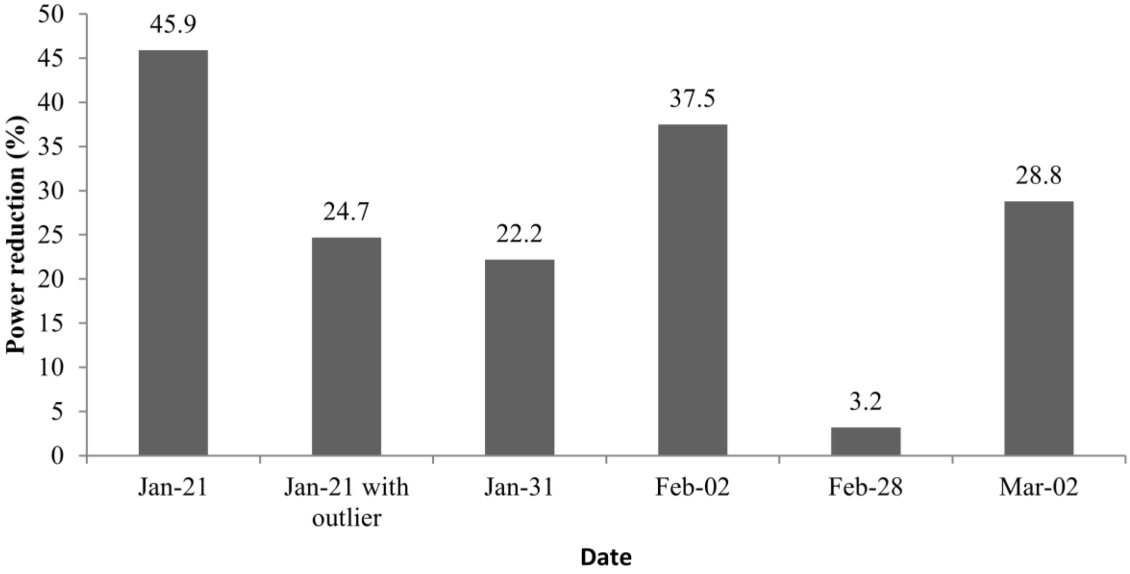

Fig 3.4.2: Power reduction (%) between control and treatment panels on the Rowe Building at Dalhousie University, Halifax, Nova Scotia

Location Two: Residential Neighbourhood

As stated previously, February 2nd and March 2nd was analyzed for power in order to determine to what degree snow accumulation on PV panels affects their power output. From analyzing the power readings (W-h) for these study days, it becomes clear that snow accumulation negatively affects power output as expected. Through calculating the average power output of the four control and four treatment panels, there is evidence of a 60% decrease, from 0.15W-h to 0.06 W-h on February 2nd, and a 69.0% decrease, from 1.10 W-h to 0.34 W-h on March 2nd, in the amount of power generated by the snow-covered panels when compared to the cleared panels (*Figure 3.4.3)*.

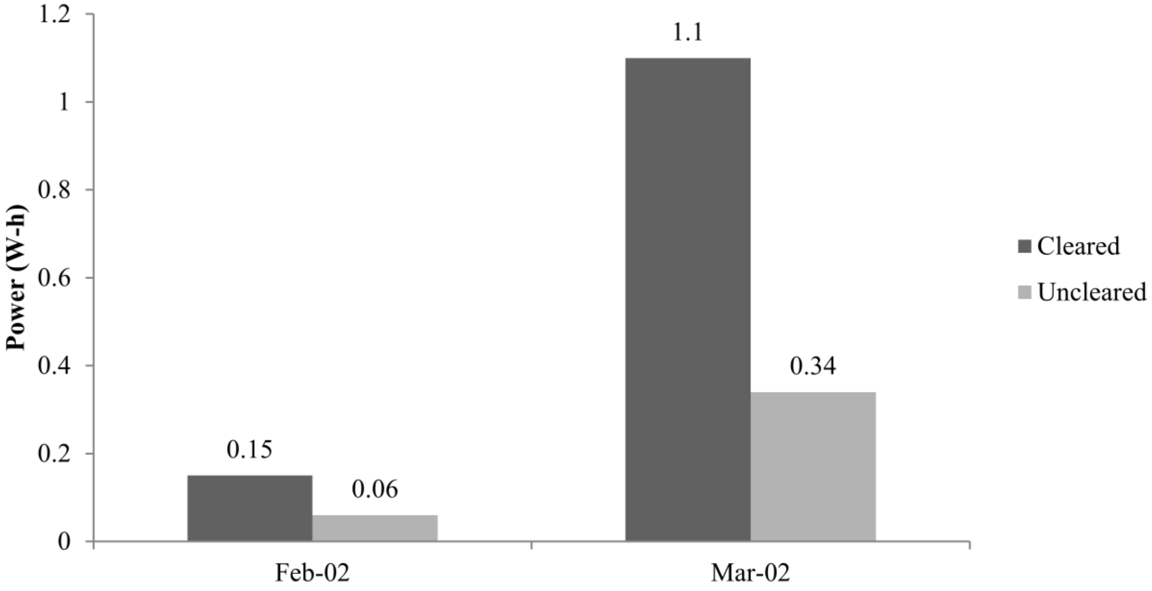

Figure 3.4.3: Differences in power output (W-h) between cleared and un-cleared panels in the residential neighbourhood, HRM

Combined analysis of study locations

As stated in section 2.0, a matched pair T-test and a 95% Confidence Interval were performed using R statistical software. The two study locations were grouped together because the values obtained were similar. Any days where there was overlapping data, the mean was taken of the two study sites. This was used to determine whether or not the difference in power output between the control and treatment panels was significant. The p-value obtained through the matched pairs test was p=0.046, which means that the difference is slightly significant at α=05 level. This result was expected since the differences in power output varied and since the percent decreases in power output were much lower for snow cover than for cloud cover. The 95% confidence interval for the difference was determined to be (-0.103565, 0.905565), which means that 95% of the time the true mean difference will lie within this two points. This shows that it is possible for there not be a net difference overall and therefore confirming the "slight significance" that was found through the matched pairs t-test.

3.5 Solar Radiation & Power Output

From comparing the power output data to the pyranometer readings for each day, it is possible to attribute any spikes or drops in the data to changes in the amount of solar radiation reaching the panels. Pyranometer readings can be affected by weather features such as cloud cover that reflects incoming solar radiation. Power output and solar radiation have a positive correlation, meaning that as solar radiation increases so does the power output of the PV panels. This was accurately represented on all of the test days. The graph presented below is an example of the correlation between power output and the pyranometer readings. There was no solar radiation data for January 21st, 2012 because the device had yet to be installed on the setup.

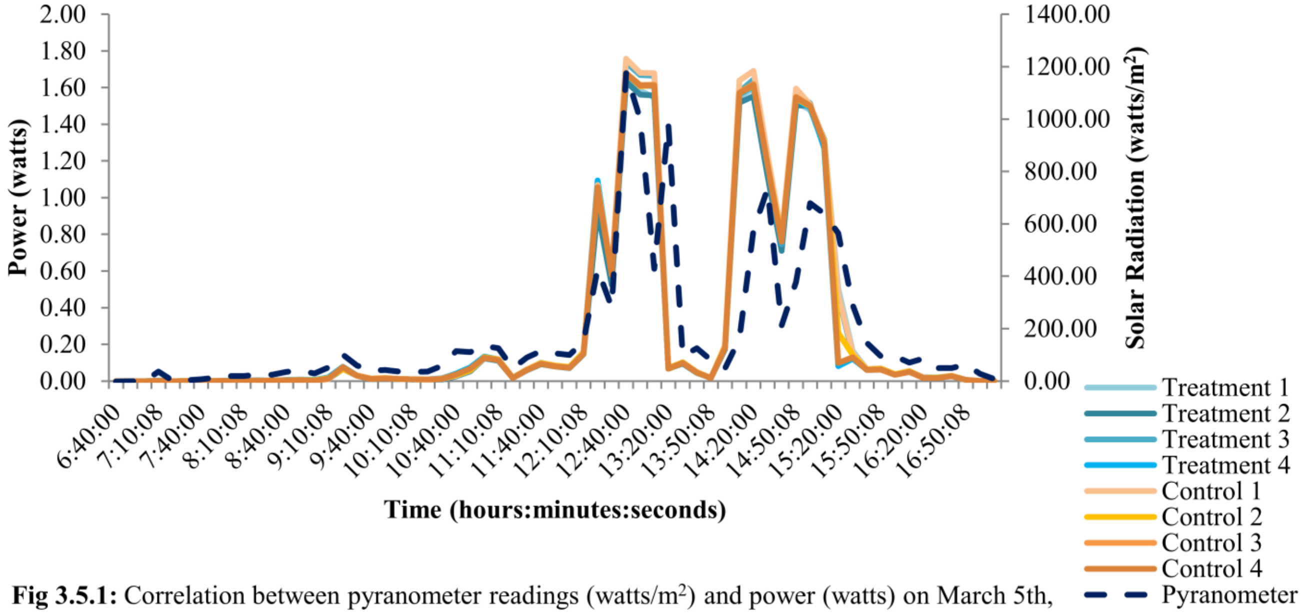

Fig 3.5.1: Correlation between pyranometer readings (watts/m^2) and power (watts) on March 5th, 2012 for the PV setup on the Rowe Building at Dalhousie University, Halifax, Nova Scotia

3.6 Location Comparison

As hypothesized, both study sites displayed similar results since they are both in the same city, at almost the same latitude. A day where snow accumulation occurred and a day without snow were compared between the two study sites (*Figure 3.6.1).* Although they are not exactly the same, there are no large inconsistencies between the two sites. The data gathered on February 2nd, 2012 shows that the difference between the two locations for the un-cleared panels is only 0.01W-h and the difference between the same study sites for the cleared panels is 0.07W-h. In addition, on February 14th, 2012, the difference in power output between the two sites was 0.14W-h (0.87W-h & 0.73W-h). Since the two locations gave similar readings, the likelihood that these results are accurate is strengthened.

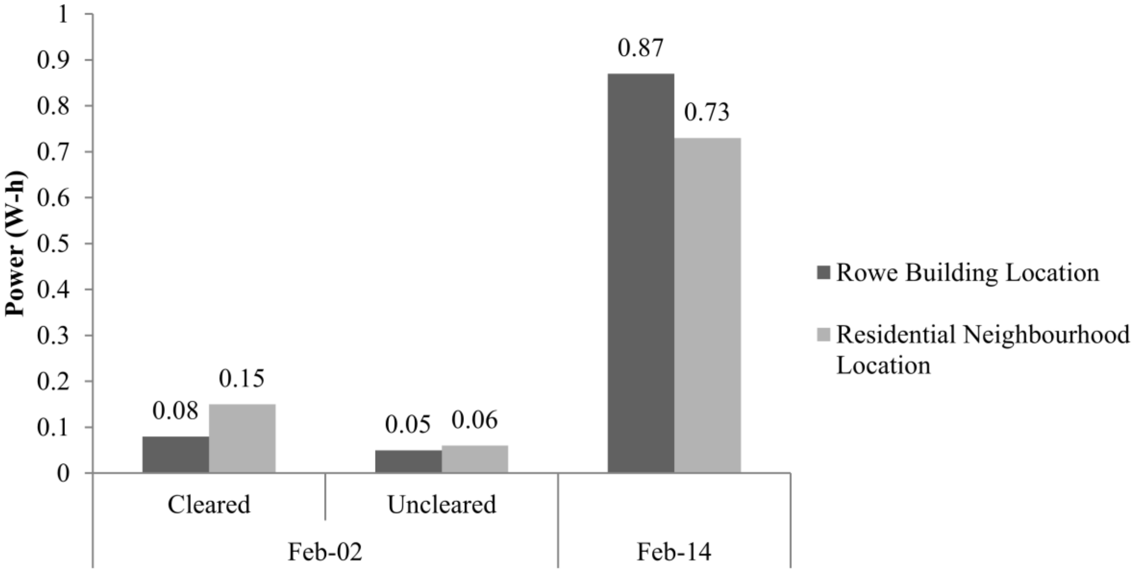

Fig 3.6.1 Power output (W-h) comparison between the two study locations: Rowe Building, Halifax and the Residential Neighbourhood location, in HRM

3.7 Other factors influencing power output

Although temperature and humidity sensors were located at the PV setup at both locations, the values collected were inaccurate and thus were not used in this study. When it was first observed that the sensors installed were not providing accurate values, additional sensors were ordered but were not received in time. Upon receiving the new sensors they were tested for their accuracy. Since they appear to function well, they will be used in in the subsequent study years. It is suggested that these measurements be included in future studies to determine whether or not there is a correlation that exists between either of these two variables (temperature and humidity) and power output of the PV panels.

As presented in subsection 3.4, additional factors such as snow depth, percent cover and snow characteristics were also analyzed. Since snow accumulation on the PV panels was only observed for five snow days, it is difficult to draw meaningful conclusions about each of these factors since the sample size is so small. For example, an accumulation of ice only occurred on one day. Also, since there were no large snow storms (≥ 15cm) that occurred during the study period, and most of the snowfalls were combined with rain, all of the recorded snow depths are very small (≤ 2cm) (Environment Canada, 2012). There was only one panel, on one day, which displayed a snow depth equal to or greater than 2cm (*Appendix B).* This makes it difficult to determine what effect different snow depths have on power output using just this one study period.

4.0 Discussion

4.1 Weather Characteristics

Although it was expected that there would be a total of 16 significant snow days (> 2 cm) during the study period since that was the average number of snow days that had occurred during this period in previous years, the actual number of testable days was much lower (eight days). For this reason, the results presented here can be considered to be a conservative indication of the amount of power loss that would be observed due to snow accumulating on PV panels. Due to this fact, it is suggested that this study be performed in following years in order to achieve results for the average amount of snowfall occurring in Halifax, Nova Scotia in a given winter. If a similar or a smaller number of snow days occur in following years, it is likely that snow accumulation on PV panels will be less of a problem for the simple fact that less snow events are happening. In addition, although an additional snowfall occurred after the study period ended, it could not be analyzed due to time constraints and removal of some of the setup.

4.2 Snow Accumulation

The panel setup was effective because it only allowed for atmospheric deposition of snow on the panels and it prevented snow drifts overtaking the setup. Although there were no snow storms that caused large drifts at the study site, installing the panels at 70 cm above the surface was still a good precautionary action. This was a suggestion described in Powers et al. (2010) and it is recommended that this be continued in the subsequent years of study. Although these panels were much smaller than ones that would be used in residential settings, validation tests were conducted with pre-existing PV arrays located at the NSCC Waterfront campus. These tests showed comparable power output readings with the only difference being that snow lasted slightly longer on these larger panels, but it all melted off within a 24-hour period.

Compared to the results documented by Powers et al. (2010), it appears that the average percent losses in power generation for each month were much greater for January than for the same month in this study: 80% decrease in Truckee, CA compared to a 35.3% reduction in NS. February data for the studies were similar whereas the losses observed during this study were greater in March than in the study completed by Powers et al. This could be because only one snow day was analyzed in March in NS whereas multiple snow days were documented in the California study. The percentage losses shown here do not include the days where snow accumulation did not occur on the panels A possible reason for the smaller percent reductions observed here could be due to tilt angle. It was noted that steeper tilt angles cause less snow to accumulate and therefore less power loss due to snowfall (Powers et al., 2010). The tilt angle used in this study (45° from the horizontal) was greater than the steepest tilt angle used in Power et al. (39° from the horizontal). Therefore, if the conclusions by Power et al. are valid, it would be expected that the 45° panels would cause less power loss than the 39° panels and thus justifying some of the differences noted between the two studies. Tilt angle was not analyzed here because the quantity of panels used was too small and because it was decided that the year-round optimal angle would be the most representative of how solar panels would be installed in this region.

In addition to the five documented snow days where there was accumulation on the panels, there were additional days when a significant snowfall occurred but the panels were not covered with snow. It is difficult to speculate on the reasons why this occurred, but since it happened at both study locations, it appears as though the site would not have had an influence on the amount of snow that accumulated, or that did not collect on the panels. It was also observed that snow did build up on the surface around the setup, which would again rule out the location as being the main factor. It could have been a combination of temperature, humidity and snow type that played a role in how the snow accumulated on the panels, but since the temperature and humidity sensors were faulty, it cannot be concluded for certain that these were contributing factors. The same general snow types occurred on both days where snow did accumulate on the panels and those days where it did not and therefore making it difficult to say that the snow type hindered the build-up of snow on the panels. The final factor that could inhibit snow build up on the PV panels would be tilt angle. It is possible that the angle at which the panels were installed prevented the accumulation of snow under additional specific conditions, but as discussed above, tilt angle was not analyzed here because a 45° tilt angle is the optimal angle for PV installations at this latitude. None of the previous research analyzed here discussed snow days on which there was no snow accumulation and therefore these are potential factors that will need to be studied in more detail in order to determine why snow build-up was prevented on certain days.

4.3 Cloud Cover versus Snow Cover

Although it was hypothesized that snow cover would have a similar but greater effect on power output than cloud cover, it was determined that snow accumulation actually causes smaller and shorter lasting effects. The reduction observed between a cloudy day and a sunny day was 77% whereas decreases in power output due to snow accumulation were as low as 3.2% and as high as 69%, and it was only that high on one occasion. Even though cloud cover was not a focus of this study in the beginning, it was realized throughout the study period that it caused drastic drops in the power generated. On a cloudy day, snow covering PV panels will have a less crucial impact since the power generated is already so low due to decreased solar radiation reaching the panels due to cloud cover. Snow cover becomes more of a problem on clear, sunny days where there is the potential to generate a lot of energy. In addition, cloud cover can have an impact throughout the entire day or for multiple days at time whereas snow accumulation only seems affect the PV panels for about half of the day.

Since it would take multiple cloudy days to equal the power generated by one sunny day, it is important to ensure that PV panels are free of snow on sunny days. This is especially important for residential systems or any system relying on solar power in an off-grid, battery based application, to generate electricity because it would be detrimental to the system to lose that potential power needed to either run the system or charge the battery due to a build-up of snow on their panels.

4.4 Snow melt

An additional objective of this research was to determine what effect the snow melting off the panels had on the power output. Although Ross (1995) had modelled that it could take anywhere from 1364 hours to 2019 hours for the snow to melt off panels at locations across Canada, the results of this study were different. The time at which the panels were completely cleared of snow varied between noon and 3:00pm of the same day that the treatment panels were removed of snow. This means that it only took between three and six hours for all the snow to be removed from the treatment panels. A possible factor that caused this large discrepancy between the two studies is that Ross (1995) assumed that there was an accumulation of 5cm of snow on the panel and that the temperature remained below 0°C. Neither of these standards was achieved in this study; the largest snow depth recorded was 2cm on the panels and there were many instances when the temperature was above 0°C (Environment Canada, 2012).

Throughout the data collection period it was also noted that snow on the treatment panels melted off some of the panels faster than others. Usually, the snow on each panel melted off within minutes of each other, but there were a few exceptions. The first day that this occurred was on January 21st at the Rowe Building location. Since snow type, coverage and depth varied across the panels it is presumed that these were the reasons why the snow melted off some of the panels faster than others. Some of the treatment panels had patches of a thin ice layer whereas others had thicker ice build-up on top of which was a layer of snow (*Appendix D)*. It is possible that the larger the amount of snow on the panel, the longer it took the panels to be cleared of snow. The second day was on March 2nd at the residential neighbourhood study location. From analyzing the camera images, it appears as though shading of certain panels cause them to melt at a slower rate. Since the impact of shading was not analyzed in this study, it cannot be concluded with absolute certainty that this was the main reason why some panels were covered with snow for longer periods of time.

It is also important to note, that once the panels starting melting, the snow was rapidly removed from the panels, it did not occur gradually over time. For example, on January 31st, panel four began losing snow at approximately 11:45am and was completely cleared of snow by 11:55am (*Appendix D).*

There are many other factors that could influence the melting of the snow on the treatment panels. Upon collection of more data in subsequent winters, these factors will be better analyzed to determine relationships between them and the snow melting rate. Firstly, had the temperature and humidity sensors functioned properly, those factors could be analyzed in attempt to determine why the snow melted off the panels so quickly. Secondly, from looking at the current data set, snow type seems to have some effect on the snow melting rate. The day on which the snow lasted the longest on the panels was on January 21st, 2012. On this day an ice layer had formed underneath the snow whereas on all the other test days, no ice formed. Again, significant conclusions cannot be drawn with regards to whether or not snow type has an effect on the melting rate due to the fact that the sample size is low for some of the snow types (ex. Ice layer only formed on one day). Finally, although tilt angle was not studied here due to the quantity of equipment used, it could also be a factor in the high rate of snow melt observed in the study.

As noted in subsection 4.2, when the results of these panels were compared with larger arrays from the NSCC campus, it was shown that snow lasted slightly longer on the larger panels. Even though snow remained longer, it was still completely melted away in one day. This result shows that surface area of the panels could have some impact on how long snow remains on the panels. Surface area will be an additional variable analyzed in future study periods.

5.0 Conclusions & Recommendations

After analyzing the data collected in the 2011-2012 winter season, the question “does snow accumulation significantly reduce the power output of PV solar panels?” was answered with a high degree of certainty. It is evident that snow accumulation on PV panels does in fact decrease their power output, but these results suggest a reduction only for about half of a post-snowfall day for a collector facing due south at a 45 degree tilt angle. It was concluded that the differences in power output observed between the control and treatment panels were slightly significant and therefore the null hypothesis was rejected. In addition, it was concluded that overall, the issue of snow accumulation has more of an impact on clear, sunny days. This is because cloud cover drastically reduces the amount of power output much more than snow does. This will have implications for residential solar panel systems insofar as it is more important for the panels to be cleaned of snow if it is a clear day in order to generate the most energy possible for the system. It is less urgent on cloudy days, since the amount of energy generated on these days is much smaller in comparison to sunny days. Therefore, for systems that depend completely on solar power, this is a problem, especially when snow is covering PV panels on sunny days, since the system would lose a significant amount of power potential.

The additional objectives were also addressed in this study. Firstly, the time it takes for the panels to be completely cleared of snow was determined to only be between three and six hours. This was a much shorter time frame than what was suggested by previous studies. Although the factors contributing to snow melt on the control panels were not identified due to small sample sizes and equipment errors, some factors seem favourable such as snow type and temperature. Additional study periods are required in order to draw conclusions regarding these two objectives.

The results observed throughout the study period will serve as good preliminary results for a multi-year study. Since this experiment was developed from the ground up beginning in September 2011, it is imperative that this research be continued while making corrections and adjusting for issues that presented themselves in this first winter season. Having acquired temperature and humidity sensors that work as expected, these factors will be analyzed in future years. If more equipment is incorporated, it would be interesting to look at different tilt angles in order to determine which one allows for the most power output and which ones cause the most snow accumulation at this location. Finally, if more snowfall occurs in the following winters, there is the possibility of developing or testing automatic snow removers that would clear the panels as the snow falls.

As the concerns about climate change continue to grow and as countries are looking for ways to reduce their global environmental impact, it is important that the effect of snowfall on PV panels continue to be studied, especially in Canada where snow is a factor for a significant portion of the year. As research in this area continues, the viability of solar power as an alternative to conventional modes of electricity production will be determined.

6.0 References

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Appendix A – Environment Canada Historical Weather Data (Feb 6th & Feb 10th 2012)

Hourly Data Report for February 6, 2012

Time	Temp °C 📈	Dew Point Temp °C 📈	Rel Hum % 📈	Wind Dir 10's deg	Wind Spd km/h 📈	Visibility km 📈	Stn Press kPa 📈	Hmdx	Wind Chill	Weather
00:00	-14.5	-15.9	89	24	9	24.1	99.50		-20	Clear
01:00	-12.7	-14.7	85	26	9	24.1	99.45		-18	Mainly Clear
02:00	-11.7	-14.0	83	21	9	24.1	99.39		-17	Cloudy
03:00	-12.1	-14.4	83	20	9	24.1	99.39		-17	Cloudy
04:00	-11.3	-13.7	82	18	19	24.1	99.25		-19	Mostly Cloudy
05:00	-11.0	-13.0	85	20	19	24.1	99.23		-19	Mostly Cloudy
06:00	-9.4	-11.5	85	23	22	24.1	99.20		-17	Mostly Cloudy
07:00	-7.3	-10.3	79	23	22	24.1	99.12		-15	Mostly Cloudy
08:00	-6.4	-9.5	79	23	20	24.1	99.10		-13	Mostly Cloudy
09:00	-3.7	-6.8	79	24	24	24.1	99.07		-11	Cloudy
10:00	-2.7	-6.5	75	23	28	24.1	99.02		-10	Mostly Cloudy
11:00	-0.4	-4.2	75	24	24	24.1	99.00		-6	Cloudy
12:00	-0.1	-3.9	76	24	32	24.1	98.93		-7	Cloudy
13:00	1.2	-3.6	70	23	19	24.1	98.86			Cloudy
14:00	2.4	-3.4	65	23	26	24.1	98.79			Mostly Cloudy
15:00	1.8	-3.1	70	23	24	24.1	98.77			Cloudy
16:00	2.2	-2.7	70	24	13	24.1	98.75			Cloudy
17:00	1.8	-2.5	73	23	7	24.1	98.72			Mostly Cloudy
18:00	1.6	-2.7	73	25	11	24.1	98.79			Mostly Cloudy
19:00	1.5	-2.6	74	23	13	24.1	98.82			Cloudy
20:00	1.6	-2.6	74	24	15	24.1	98.81			Cloudy
21:00	1.3	-2.5	76	24	15	24.1	98.85			Cloudy
22:00	1.2	-2.5	76	23	20	24.1	98.87			Cloudy
23:00	0.9	-2.1	80	24	19	24.1	98.87			Cloudy

Hourly Data Report for February 10, 2012

Time	Temp °C	Dew Point Temp °C	Rel Hum %	Wind Dir 10's deg	Wind Spd km/h	Visibility km	Stn Press kPa	Hmdx	Wind Chill	Weather
00:00	-3.0	-5.9	80	32	19	24.1	99.44		-9	Mainly Clear
01:00	-2.9	-7.4	71	31	22	24.1	99.53		-9	Mainly Clear
02:00	-3.4	-8.1	70	32	24	24.1	99.60		-10	Clear
03:00	-4.3	-8.7	71	30	13	24.1	99.68		-9	Clear
04:00	-5.0	-8.4	77	30	17	24.1	99.77		-11	Clear
05:00	-5.3	-8.8	76	31	15	24.1	99.84		-11	Clear
06:00	-7.5	-9.6	85	30	6	24.1	99.95		-11	Clear
07:00	-7.8	-9.5	88	28	6	24.1	100.02		-11	Clear
08:00	-6.8	-9.0	84	29	6	24.1	100.10		-10	Clear
09:00	-3.8	-8.4	70	25	7	24.1	100.15		-7	Clear
10:00	-1.9	-9.2	57	26	6	24.1	100.24		-4	Clear
11:00	0.8	-7.9	52	22	6	24.1	100.27			Clear
12:00	1.4	-8.6	47	20	13	24.1	100.23			Clear
13:00	2.5	-7.8	47	19	13	24.1	100.15			Clear
14:00	2.6	-7.9	46	22	11	24.1	100.08			Clear
15:00	3.5	-8.0	43	21	17	24.1	100.07			Mainly Clear
16:00	2.5	-7.1	49	19	15	24.1	100.06			Mainly Clear
17:00	0.6	-6.7	58	21	20	24.1	100.07			Mainly Clear
18:00	-1.5	-6.2	70	17	11	24.1	100.08		-5	Mainly Clear
19:00	-1.9	-5.1	79	16	13	24.1	100.07		-6	Mainly Clear
20:00	-2.5	-4.4	87	16	15	24.1	100.09		-7	Mainly Clear
21:00	-1.8	-2.9	92	15	13	24.1	100.02		-6	Mainly Clear
22:00	-0.7	-1.6	94	17	24	24.1	99.96		-7	Mostly Cloudy
23:00	0.3	-0.7	93	17	19	24.1	99.93			Mostly Cloudy

Appendix B – Data Collection Tables

DAL	Percent Cover	Average Snow Depth(mm)	Time that the panels were cleared	Type of Snow (Those highlighted were observed)	Date
Panel 3	5%	Ice layer	Not cleared	**Compact Snow** Light/Fluffy Snow **Ice Layer** Hail	January 21st, 2012
Panel 4	5%	Ice layer	Not cleared		
Panel 5	50%	10mm (ice on bottom)	Not cleared		
Panel 6	50%	10mm(ice on bottom)	Not cleared		
Panel 1	5%	Ice layer	11:20am		
Panel 2	5%	Ice layer	11:24am		
Panel 7	20%	10mm(ice on bottom)	11:25am		
Panel 8	70%	20mm (ice on bottom)	11:25am		

DAL	Percent Cover	Average Snow Depth(mm)	Time that the panels were cleared	Type of Snow	Date
Panel 3	100%	17mm	Not cleared	Compact Snow **Light/Fluffy Snow** Ice Layer Hail	January 31st, 2012
Panel 4	100%	17mm	Not cleared		
Panel 5	100%	18mm	Not cleared		
Panel 6	100%	17mm	Not cleared		
Panel 1	100%	17mm	8:07am		
Panel 2	100%	18mm	8:07am		

Panel 7	100%	18mm	8:08am		
Panel 8	100%	17mm	8:08am		
DAL	**Percent Cover**	**Average Snow Depth(mm)**	**Time that the panels were cleared**	**Type of Snow**	**Date**
Panel 3	100%	4mm	Not cleared	Compact Snow **Light/Fluffy Snow** Ice Layer Hail	February 2nd , 2012
Panel 4	100%	3mm	Not cleared		
Panel 5	100%	4mm	Not cleared		
Panel 6	100%	4mm	Not cleared		
Panel 1	100%	4mm	8:20am		
Panel 2	100%	4mm	8:20am		
Panel 7	100%	3mm	8:20am		
Panel 8	100%	4mm	8:20am		
DAL	**Percent Cover**	**Average Snow Depth(mm)**	**Time that the panels were cleared**	**Type of Snow**	**Date**
Panel 3	100%	5mm	Not cleared	**Compact Snow** Light/Fluffy Snow Ice Layer Hail	February 28th , 2012
Panel 4	50%	6mm	Not cleared		
Panel 5	50%	4mm	Not cleared		
Panel 6	100%	4mm	Not cleared		
Panel 1	100%	4mm	7:47am		
Panel 2	100%	5mm	7:47am		
Panel 7	90%	6mm	7:47am		

Panel 8	90%	4mm	7:47am		

DAL	**Percent Cover**	**Average Snow Depth(mm)**	**Time that the panels were cleared**	**Type of Snow**	**Date**
Panel 3	80%	2mm	Not cleared	**Compact Snow** Light/Fluffy Snow Ice Layer Hail	March 2nd, 2012
Panel 4	90%	2mm	Not cleared		
Panel 5	80%	2mm	Not cleared		
Panel 6	90%	2mm	Not cleared		
Panel 1	80%	2mm	11:32am		
Panel 2	90%	2mm	11:32am		
Panel 7	95%	2mm	11:32am		
Panel 8	95%	2mm	11:32am		

Appendix C – Historical Weather (January – March 2012)

Daily Data Report for January 2012

Day	Max Temp °C	Min Temp °C	Mean Temp °C	Heat Deg Days	Cool Deg Days	Total Rain mm	Total Snow cm	Total Precip mm	Snow on Grnd cm	Dir of Max Gust 10's deg	Spd of Max Gust km/h
Sum				673.7	0.0	81.7	39.6	120.7			
Avg	1.2	-8.6	-3.7								
Xtrm											
01†	8.1	-1.2	3.5	14.5	0.0	3.7	T	3.7		32	57
02†	10.7	-0.7	5.0	13.0	0.0	15.5	T	15.5		17	72
03†	4.1	-7.2	-1.6	19.6	0.0	0.0	T	T		1	35
04†	-7.2	-11.9	-9.6	27.6	0.0	0.2	0.7	0.5	T	34	50
05†	0.2	-10.4	-5.1	23.1	0.0	0.0	4.8	4.8	T	26	33
06†	-5.5	-10.3	-7.9	25.9	0.0	0.0	T	T	5		<31
07†	3.7	-6.4	-1.4	19.4	0.0	0.0	T	T	3		<31
08†	3.8	-3.4	0.2	17.8	0.0	0.0	0.3	0.3	T	31	33
09†	-2.8	-11.0	-6.9	24.9	0.0	0.0	T	T	T	28	32
10†	2.8	-11.7	-4.5	22.5	0.0	0.0	0.4	0.4	T	25	35
11†	-0.2	-13.4	-6.8	24.8	0.0	0.0	T	T	T	33	50
12†	0.5	-13.3	-6.4	24.4	0.0	0.0	12.0	12.0	T	11	69
13†	10.6	0.4	5.5	12.5	0.0	9.2	T	9.2	7	22	80
14†	2.0	-8.1	-3.1	21.1	0.0	0.0	0.4	0.2	T	22	74
15†	-7.9	-16.1	-12.0	30.0	0.0	0.0	0.2	0.2	T	32	33
16†	-4.7	-16.8	-10.8	28.8	0.0	0.0	T	T	T		<31
17†	3.1	-4.7	-0.8	18.8	0.0	0.8	0.5	1.3	T	21	48
18†	8.2	-8.2	0.0	18.0	0.0	2.1	0.0	2.1		25	59
19†	-6.9	-12.9	-9.9	27.9	0.0	0.0	0.0	0.0		34	48
20†	0.0	-11.7	-5.9	23.9	0.0	0.0	12.6	12.6	12	27	44
21†	-5.3	-13.3	-9.3	27.3	0.0	0.0	0.4	0.4	12	25	44
22†	-9.0	-15.9	-12.5	30.5	0.0	0.0	0.0	0.0	11	34	37
23†	1.8	-14.7	-6.5	24.5	0.0	T	0.0	T	10	20	32
24†	10.4	1.7	6.1	11.9	0.0	33.3	0.0	33.3	7	14	50
25†	4.8	-1.9	1.5	16.5	0.0	T	0.0	T		30	37
26†	-0.8	-8.0	-4.4	22.4	0.0	0.0	0.0	0.0		31	44
27†	3.6	-7.5	-2.0	20.0	0.0	15.6	0.3	15.9	T	11	80
28†	6.4	-4.9	0.8	17.2	0.0	0.0	0.0	0.0		29	70
29†	4.4	-3.4	0.5	17.5	0.0	1.3	0.0	1.3		26	56
30†	4.4	-9.1	-2.4	20.4	0.0	0.0	7.0	7.0	7	33	44
31†	-6.2	-11.8	-9.0	27.0	0.0	0.0	T	T	7		

Daily Data Report for February 2012

D a y	Max Temp °C	Min Temp °C	Mean Temp °C	Heat Deg Days	Cool Deg Days	Total Rain mm	Total Snow cm	Total Precip mm	Snow on Grnd cm	Dir of Max Gust 10's deg	Spd of Max Gust km/h
Sum				636.9	0.0	77.5	29.8	106.9			
Avg	0.3	-8.2	-4.0								
Xtrm	7.0	-18.2								12	78
Summary, average and extreme values are based on the data above.											
01†	1.5	-7.3	-2.9	20.9	0.0	2.7	0.3	3.0	6	13	48
02†	-2.0	-9.1	-5.6	23.6	0.0	1.0	0.0	1.0	4	36	32
03†	-6.2	-12.7	-9.5	27.5	0.0	0.0	T	T	4	34	39
04†	-6.4	-12.7	-9.6	27.6	0.0	0.0	T	T	4	34	35
05†	-9.5	-14.7	-12.1	30.1	0.0	0.0	T	T	4	30	32
06†	2.5	-12.8	-5.2	23.2	0.0	0.0	0.0	0.0	4	24	44
07†	1.4	-8.4	-3.5	21.5	0.0	0.0	T	T	2		<31
08†	-2.2	-13.0	-7.6	25.6	0.0	0.0	0.0	0.0	2		<31
09†	0.1	-8.1	-4.0	22.0	0.0	0.0	0.0	0.0	2		<31
10†	4.0	-8.4	-2.2	20.2	0.0	0.0	0.0	0.0	2		<31
11†	4.0	-1.5	1.3	16.7	0.0	46.5	T	46.5	2	35	59
12†	-0.9	-15.4	-8.2	26.2	0.0	0.0	3.2	3.2	3	34	57
13†	-7.0	-18.2	-12.6	30.6	0.0	0.0	3.4	3.4	3	23	41
14†	0.0	-12.9	-6.5	24.5	0.0	0.0	0.0	0.0	5		<31
15†	6.9	-2.0	2.5	15.5	0.0	0.0	0.0	0.0	2		<31
16†	1.6	-3.7	-1.1	19.1	0.0	0.0	0.0	0.0	1		<31
17†	2.4	-5.0	-1.3	19.3	0.0	1.5	0.5	1.8	2		<31
18†	1.4	-1.7	-0.2	18.2	0.0	0.0	9.6	9.6	5	28	41
19†	-0.7	-7.1	-3.9	21.9	0.0	0.0	0.0	0.0	6	30	50
20†	-2.8	-9.6	-6.2	24.2	0.0	0.0	0.0	0.0	6	33	37
21†	0.0	-11.5	-5.8	23.8	0.0	0.0	0.0	0.0	6		<31
22†	7.0	-4.5	1.3	16.7	0.0	8.3	3.3	11.6	5	23	41
23†	4.5	-0.7	1.9	16.1	0.0	4.3	T	4.3	2	10	57
24†	4.8	-0.5	2.2	15.8	0.0	0.0	T	T		28	61
25†	5.8	-1.2	2.3	15.7	0.0	12.7	1.6	14.3	1	12	78
26†	0.3	-6.7	-3.2	21.2	0.0	0.0	1.1	1.1	1	29	57
27†	-1.9	-9.7	-5.8	23.8	0.0	0.0	1.4	1.2	T	31	32
28†	1.9	-7.7	-2.9	20.9	0.0	0.5	5.4	5.9	5	34	54
29†	-0.9	-12.1	-6.5	24.5	0.0	0.0	T	T	5		<31

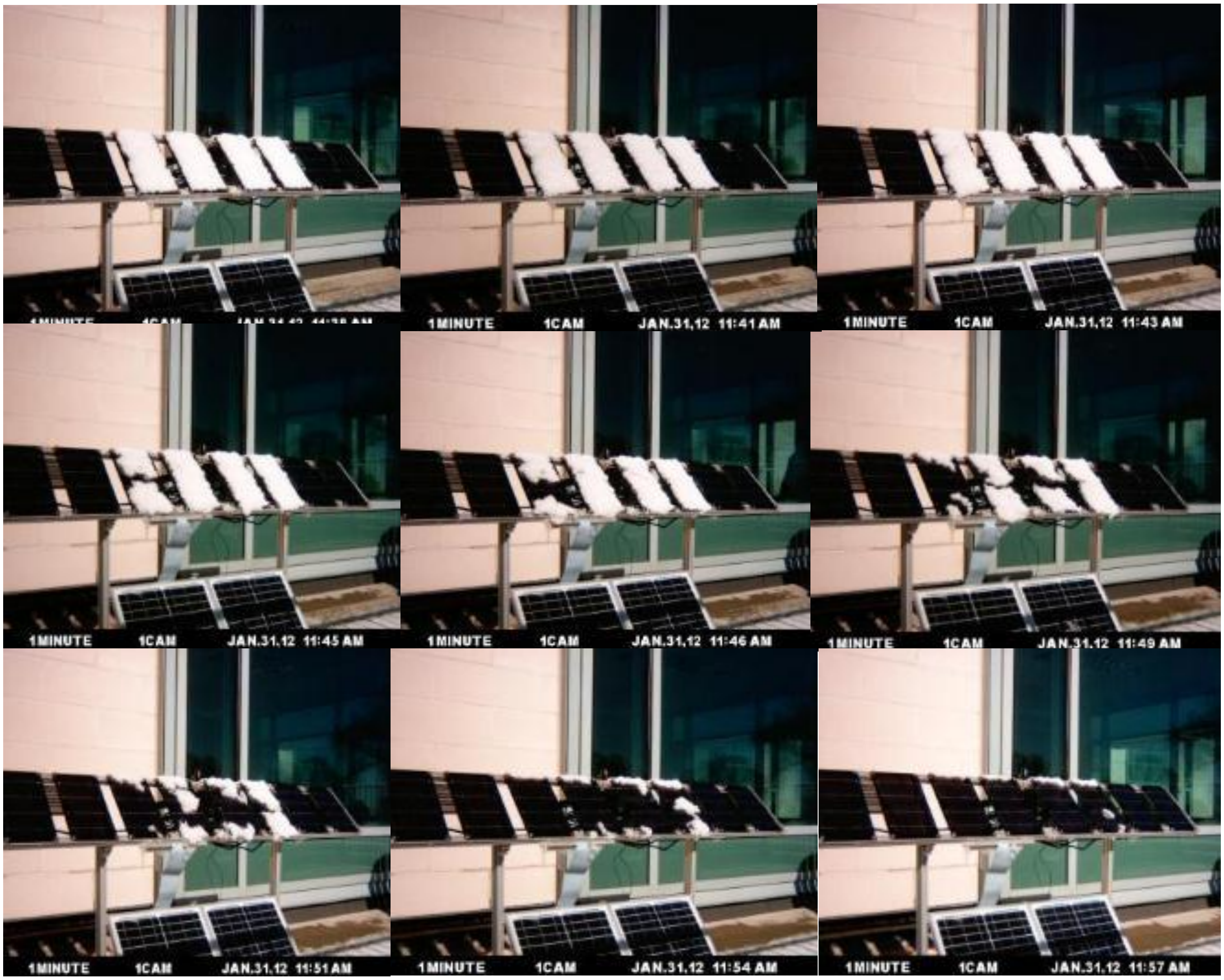
Daily Data Report for March 2012

Day	Max Temp °C	Min Temp °C	Mean Temp °C	Heat Deg Days	Cool Deg Days	Total Rain mm	Total Snow cm	Total Precip mm	Snow on Grnd cm	Dir of Max Gust 10's deg	Spd of Max Gust km/h
Sum				334.1*	0.0*	35.3*	24.9*	60.2*			
Avg	5.0*	-4.1*	0.4*								
Xtrm	15.3*	-12.4*								21*	95*
Summary, average and extreme values are based on the data above.											
01†	-5.7	-12.4	-9.1	27.1	0.0	0.0	0.4	0.4	5	4	39
02†	-1.7	-8.6	-5.2	23.2	0.0	0.0	2.8	2.8	8	6	39
03†	8.1	-4.8	1.7	16.3	0.0	22.9	T	22.9	8	16	67
04†	4.8	-0.7	2.1	15.9	0.0	0.0	4.2	4.2	T	24	33
05†	3.9	-4.0	-0.1	18.1	0.0	0.0	4.4	4.4	7	23	35

Appendix D- Photographs

Snow & ice cover on the PV setup on the Rowe Building. Note the variability in percent cover and snow characteristics

Control panels covered with snow; the snow on the treatment panels has been removed



A period of snow melting for the PV setup at the Rowe Building on January 31st, 2012

Appendix E- Time vs. Power Output Graphs

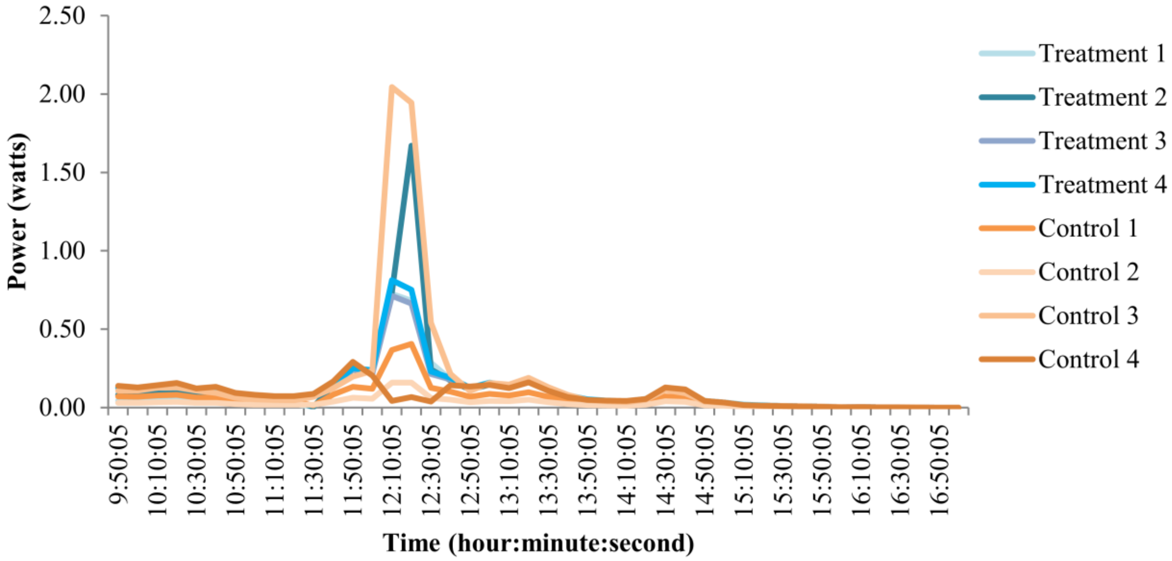


Fig 1: Power data for the photovoltaic set-up on the Rowe Building, Dalhousie University for the daylight hours on January 21st, 2012. Note: Treatment panels are those covered by snow, the snow on the control panels was removed.

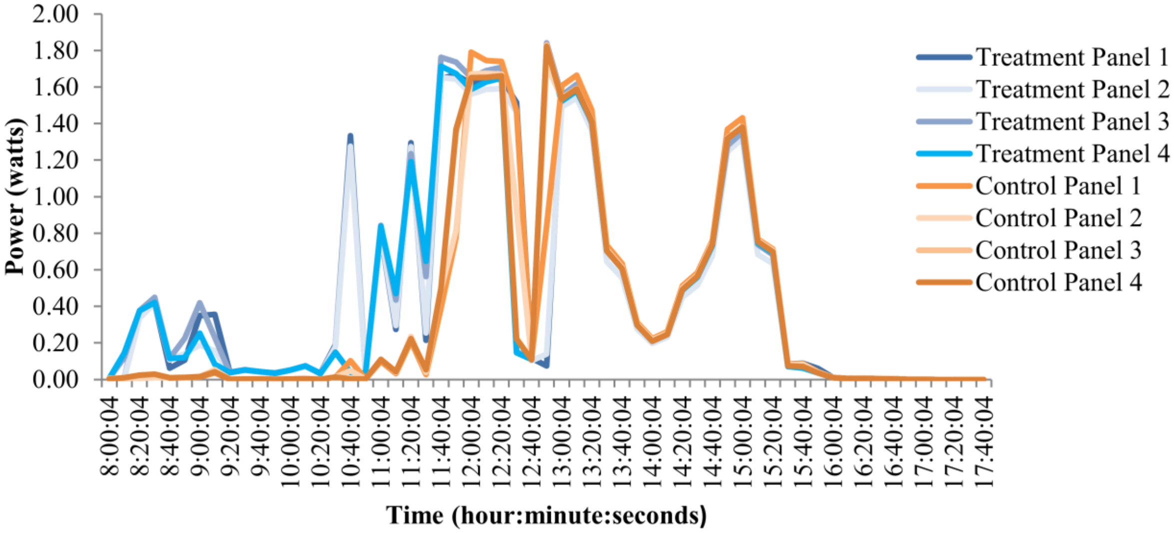


Fig 2: Power data for the photovoltaic set-up on the Rowe Building, Dalhousie University for the daylight hours on January 31st, 2012. Note: Treatment panels are those covered by snow, the snow on the control panels was removed.

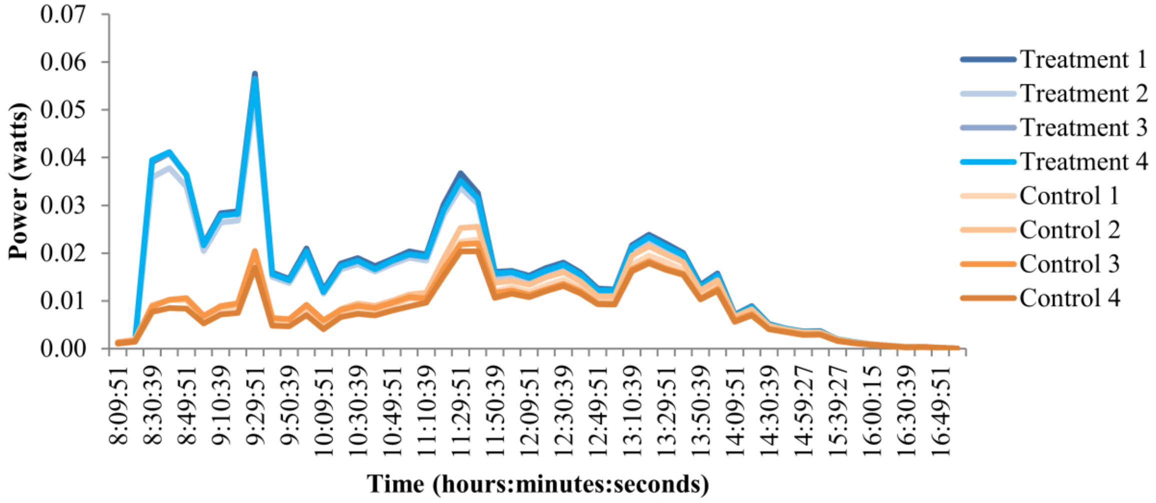


Fig 3: Power data (watts) for the PV setup on the Rowe Building at Dalhousie University in Halifax, Nova Scotia on February 2nd 2012. Note control means that the panels were left covered in snow and treatment means that the panels were cleared of snow

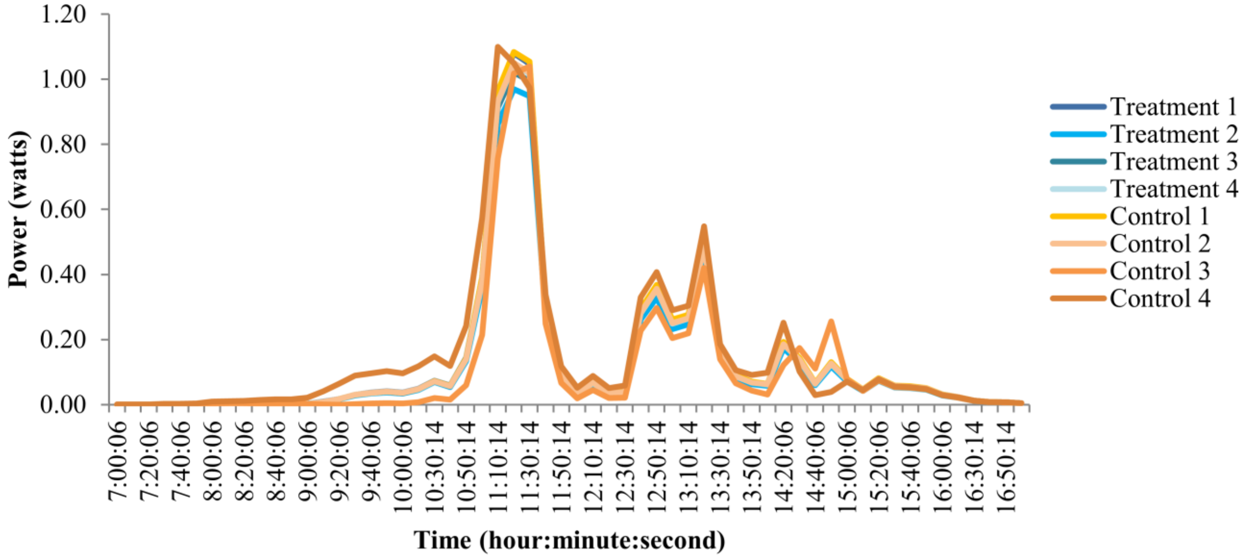


Fig 4: Power data (watts) for the PV setup on the Rowe Building at Dalhousie University in Halifax, Nova Scotia on February 28th 2012. Note control means that the panels were left covered in snow and treatment means that the panels were cleared of snow.

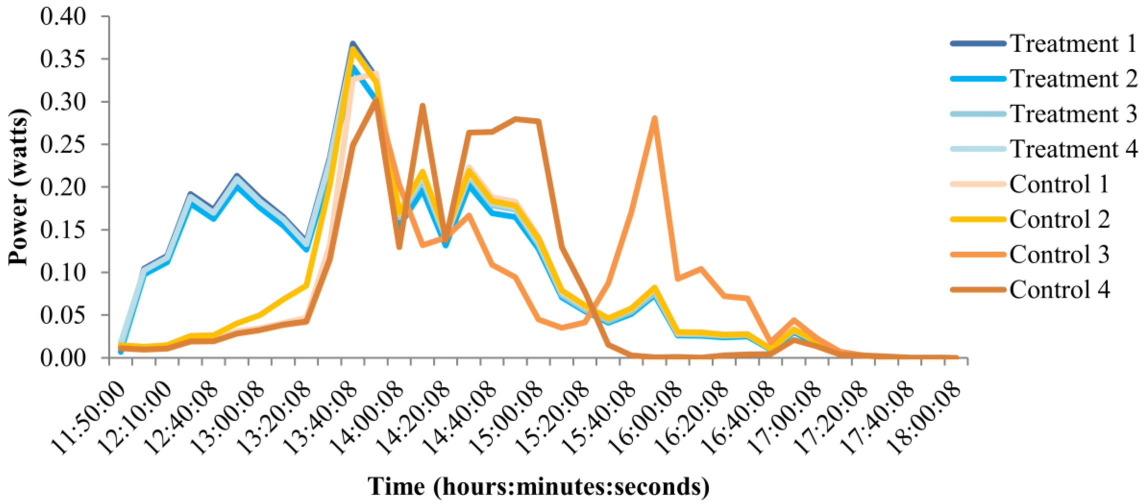


Fig 5: Power data (watts) for the PV setup on the Rowe Building at Dalhousie University in Halifax, Nova Scotia on March 2nd 2012. Note control means that the panels were left covered in snow and treatment means that the panels were cleared of snow.

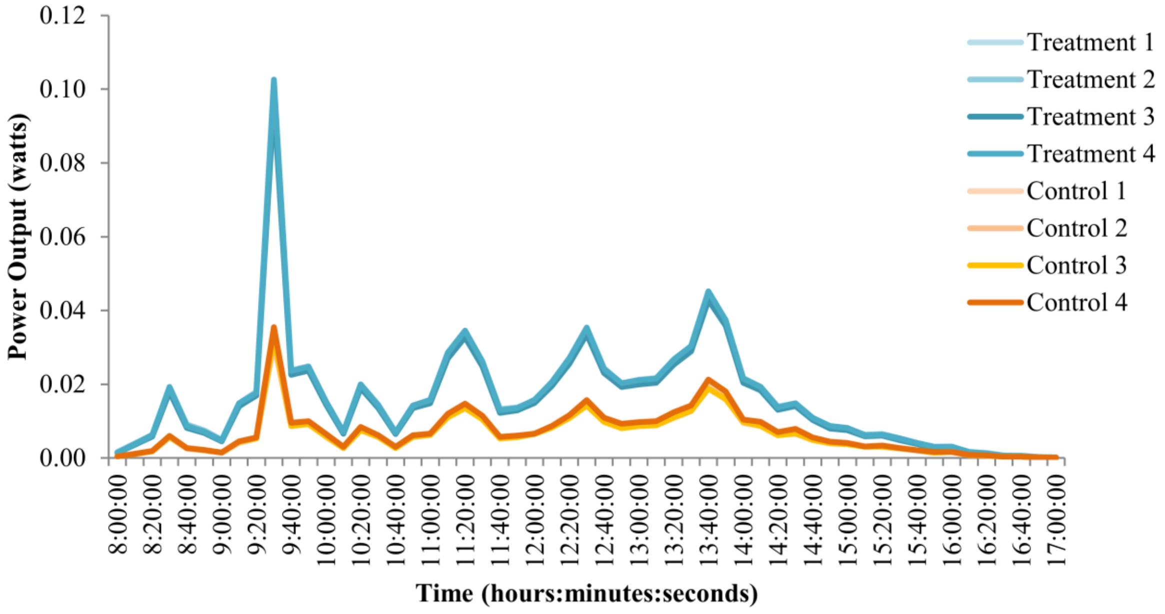


Fig 6: Power output data (watts) on Febraury 2nd, 2012 at the residential neighbourhood study location in HRM. Note: Control panels are those which remained covered with snow

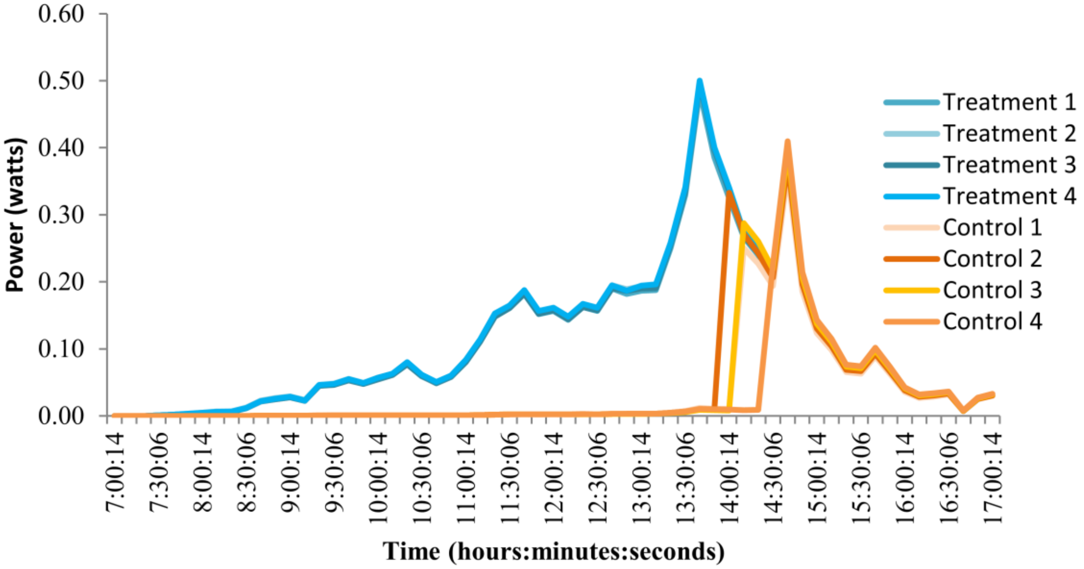


Fig 7: Power data (watts) on March 2nd, 2012 at the residential neighbourhood location, HRM Nova Scotia. Note: Control panels are those which remain covered with snow.