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Framed- or Frameless Photovoltaic in Snow Experiencing Climates

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ABSTRACT

Correlated with the declining photovoltaic (PV) system's prices are the increase in areas they can be proven cost-efficient. PV systems are recognized as vital renewable energy sources for the contemporary societies, however, one considerable incentive for implementation is the PV systems' return of investment time. An elevation in PV systems' efficiency will decrease the break-even time, promoting justifications for implementation.

Evaluating PV systems installed in the northern hemisphere makes it eminent that the presence of snow is less than beneficial for PV energy production. As of now, there is a gap in the PV market where no purpose-designed PV system for snow exists. An optimized PV system for snow experiencing climates should contain measures that hinder accumulation of/remove accumulated snow. These measures cannot decrease the PV system's efficiency, meaning they should not consume grid-fed energy or energy from the PV system itself.

This article investigates one implementable measure capable of reducing the accumulation of snow on the PV system's exterior glass window. Two test-systems were created and exposed to the Norwegian winter. These test-systems represents the framed- and the frameless PV system, and have all but one component similar, being the geometry of the exterior frame. By processing the empirical data, a statistical significance was found between the two test-systems' power output, where a positive output difference favors the frameless PV module on snow experiencing days.

Keywords: Photovoltaic system; Snow; Framed PV; Frameless PV; statistical analysis, Norway.

1. INTRODUCTION

In evaluating today's society, it is evident that the global focus on sustainable solutions is increasing. Commemorating the exponential industrial- and technological progress from a 21st century perspective makes it eminent the important role fossil fuels have played for mankind. However, fossil fuels are now commonly associated with problems and pollutions. Furthermore, the world's supplies of fossil fuels are limited, and scarcity will follow business-as-usual consumption rates. Here, the incentive for developing and transitioning into renewable energy sources has materialized.

Renewable energy sources are replenishable, and solar energy is the main source of several renewable energy such as wind and bioenergy. The earth is exposed with an abundance of solar radiation, where a tiny percentage of this energy could meet the global demand for energy. The dominating commercial photovoltaic (PV) system technologies consists of monocrystalline silicon cells, polycrystalline silicon cells, amorphous silicon cells, or thin film semiconductors. Among the commercially available PV technologies are monocrystalline silicon cells the most demanding to produce, but provide the highest PV system efficiency [1]. Top-performing commercially available PV systems achieve a 23 percent efficiency, however, multi-junction PV cells can have efficiencies up to 46 percent [2]. The multi-junction PV cell consists of several silicon cells specialized in different portions of the solar spectrum. Due to the production expense, multi-junction PV systems are primarily utilized for space satellites and probes, and not for common energy production application.

According to Center for Climate and Energy Solution, about 2 percent of the world's electricity is produced from solar energy in 2018 [3]. As of 2019, Germany was the leading nation of solar energy production [4], being surpassed by China in 2020 . The assessment of the climate in Germany is that snow is widespread over the eastern belt of the country [5]. The transition from coal power to renewable energy sources is happening in Canada [6], a nation associated with harsh snowy winters. Estimations by National Resources Canada (NRC) indicate that about half of Canada's residential electricity consumption should be met by implementing PV technologies [7]. The use of solar energy is steadily increasing globally and studies for instance in Albania show high solar energy potential if favorable market condition are in place [8]. Norway, located in region with snow experiencing climate and known for its highly hydropower dominated power system, about 40MW of solar power was installed during 2020 alone, increasing the nation's total solar power capacity with almost 40 % [9]. The presence of snow appears as a double-edged sword for PV system power production. On one side, accumulated snow will absorb the solar specter utilized by PV cells, crippling power production. On the other side, the snow experiencing climate will provide an increase in albedo effect, reduced temperatures increase PV system power production, and sliding snow takes dirt with it cleaning the PV system's exterior glass window. Especially, the potential in the white snow's albedo effect is significant, and has previously been underestimated [10].

To utilize PV cells for power production, a protective exterior housing must be present. The common denominator for the commercially available protective exterior housing solutions is the utilization of transparent glass window(s). Two main types of protective exterior housings are commercially available, being the framed PV system and the frameless PV system. The framed PV system commonly consists of an aluminum frame encapsulating either a single transparent exterior glass window and a non-transparent back-sheet, or two exterior glass windows sandwiching the PV cells. The frameless PV system commonly sandwiches the PV cells with two exterior glass windows held together with adhesive glue. The utilization of two glass windows are referred to as glass on glass-, or glass-glass-, PV modules, and is a sub-category of either framed- or frameless PV systems. Most available studies on the thematic of snow and PV systems utilizes the framed PV systems in their experiments, where most of the studies investigates how PV system inclination affect snow accumulation and power production [11-16]. Here, it is shown that higher inclination angles are favorable for reducing the amounts of snow accumulating on the PV systems exterior window. Further, a high inclination angle will benefit the low solar zenith angle during the northern hemisphere's winter months as well as the increased albedo exposure.

Northern Alberta Institute of Technology (NAIT) in Canada did a performance comparison experiment with several inclination angles assessing the effects of snow if not removed, and found that the 90- and 53 degrees inclination angle was the two most efficient angles during the winter months [13]. However, the available solar radiation during these months are significantly less than the summer months [17]. The NAIT's performance comparison shows that static PV systems installed at the inclination angle of 90 degrees will produce the least of the angles they tested annually, being angles of 90, 53, 45, 27, 18, and 14 degrees [13]. Their results show the PV system with the lowest inclination angle in the experiment produces annually 8.9 percent more energy than the steepest, although 22 percent of its energy production is lost due to snow accumulating during the winter months.

The common strategies for addressing accumulating snow can be filtered within three approach. These are inspired by- and have their foundation in the snow philosophies firstly introduced by B. P. Jelle [18].

1. No measures taken to remove accumulating snow: Traditional PV systems are installed as they would be in non-snow experiencing areas. The snow accumulation and thawing are all driven by the weather.
2. Measures that consume energy are implemented to remove the snow: These measures depend on input energy, either fed from the electrical grid or produced by the PV system itself. This is interpreted as active snow removal.
3. Measures that do not consume energy are implemented to remove the snow: These measures do not depend on input energy to remove snow. This is interpreted as passive snow removal.

The recommendation from some photovoltaic companies is to not physically intervene with the accumulated snow, as misuse of equipment can damage the PV systems [19-21]. It is understood that PV companies seek the first approach, as many seem to underestimate the prohibiting effects accumulated snow imposes on the PV system's production [20-22]. The common argument is that gained production from cleared PV systems does not make up for the risks linked to manually removing snow. However, the prohibiting effects snow imposes on PV systems are recognized [11-13, 15, 16, 18, 23-26]. The second approach promotes snow removal by using energy. Here, effective and autonomous snow removal can be done by using heat and melting accumulated snow [27, 28]. One crucial aspect considering this approach is that utilizing energy to produce energy will affect the PV system's total performance. The third approach encourages removal activities that are not dependent on energy intake, which is the focus of this study. The particular component in focus is the framed PV system's aluminium frame, being how the frame's design affects snow accumulation. This aluminium frame slightly surpasses the flat exterior glass, creating a peripheral bulge being a couple of millimetres. It is hypothesized that the bulge's height increases the static friction between the accumulated snow and the exterior glass window compared to a completely flush surface. Naturally, if room is made for the snow to slide off and accumulate it is rational to expect the snow to slide off faster on an unobstructed surface. Further, how big this difference can be will be determined in this study. To determine this difference in power production were two test-systems created and deployed in the capital of Norway, to gather data from the Norwegian winter of 2019-2020.

The paper is divided into five sections. The first section gives background information and the state of the art within this field. Section 2 briefly explains the method used. Section 3 presents results obtained, while section 4 and 5 deal with discussion and conclusions respectively.

2. METHOD

Two test-systems have been constructed to investigate the impact of snow on the performance of the framed- and frameless PV modules. These systems were deployed at the roof of Norsk Teknisk Museum, located in the capital of Norway, Oslo (latitude: 59.967, longitude: 10.783). In this study, two Axitec AXIpremium AC-310M/60S 310W monocrystalline modules [29], where one of the module's aluminum frame has been altered, were used. The un-altered system represents the traditional framed PV system in the experiment. To represent the frameless PV module, the lowermost part of the second module's aluminum was removed by grinding to make the module's exterior glass window flush with the aluminum frame. This flush surface represents the frameless module and was utilized in System 2 (S2). The module's alterations were necessary to create two identical modules with only one difference, in this case the aluminum frame's geometry. Both modules were encapsulated and mounted on wooden frameworks, as seen in Figure 1. In order to reduce the absorption of infrared radiation, the test systems were painted white. The unobstructed clearance between the bottom of the PV modules and the underlying ground were necessary to enable accumulated snow to slide off, functioning as a snow buffer [12]. The PV modules were installed with their longest side being tilted along the zenith axis, elongating the snow's sliding distance.

The system's inclination angle is determined based on two factors; firstly, since the study's goal is to investigate PV modules' ability to shed snow, it was necessary to create an opportunity for snow to accumulate. Secondly, the recommended all-year tilt for a fixed PV system situated in Norway is 40 degrees [30]. Thus, the test-systems were constructed with a slightly less inclination angle of 35 degrees. The plateau that forms the Norsk Teknisk Museums' roof is covered with gravel, creating some uneven ground. To ensure sufficient horizontal leveling for the test-systems, the inclination angle ended on exactly 34 degrees. The final inclination angle was determined with the assistance of a digital angle instrument. Once the systems were deployed at Norsk Teknisk Museum, the exterior glass surfaces both PV modules were cleaned equally to remove any grease, dust, or other impurities obstructing the modules' glass surface.

(a) **(b)**

Figure 1. (a) CAD drawing of the test-system. (b) Actual test-systems; S1 at right and S2 at left. (Photo by Jørgen P. Aubell).

Both systems were connected to an Arduino Nano computer, which measures and log each system's power output at one-second intervals. Measurement data were collected from the 13th of January to the 11th of March 2020. Some days have been excluded from this date range, due to potential interventions from the immediate environment. These potential interventions are potential shadow castings on either of the test-systems during data-extraction from the data-logger. An inspection of the excluded data shows no apparent significant data for the study were omitted, however, to safekeep the validity and quality of the data, six days were removed (being: 21. January, 3.+11.+25. February, 2.+12. March). The determination of which days experiences snow are done by analysing the location's weather data, obtained from Norsk Klima Service Senter's weather station at Blindern (station: SN18700), located about 4km from Norsk

Teknisk Museum [31]. The study will only consider data points between 07:00 and 18:00 each day, due to the significantly decreased solar irradiance before and after these timestamps. Furthermore, a 120-second interval were utilized for the data processing. The 120-second interval is perceived reasonable due to the rapid nature of weather fluctuations, that can cause information and trends can be lost within a too large time-interval.

The study's objective is to gather data on- and assess how the presence of snow affects the power production of either test-system, and determine how big of a difference can be observed. Thus, three null hypotheses have been created for testing and these are presented in Table 1**.** The null hypotheses will be rejected if the test's p-value is above 0.05, resulting in statistically significance between the datasets. The first scenario aims to determine whether the effects of the frameless PV-system provide a significant difference in power production considering the whole test-period. The second scenario will determine whether the systems are calibrated for the study's thematic, and the third scenario isolates the days with snow and assesses the observed effects.

Table 1. The systems' null hypotheses regarding power output.

Scenario	Weather condition	Null hypothesis
1	Days with and without Snow	H_0: S1=S2
2	Days not experiencing snow	H_0: S1=S2
3	Days experiencing Snow	H_0: S1=S2

3. RESULTS

The total snowfall for the winter period is 33.1 cm, and the test systems experienced 34% of it. Considering the months tested, the test location experienced an unusually dry winter. In general, there was 97% less snow than the previous five-year average and 98% less snow than the fifty-year average for this location throughout the 2019-2020 winter period. As can be seen in Figure 2, the 2019-2020 winter period was particularly poor in snow compared to previous years. Figure 3 shows that the winter experienced was unusually poor in snow. The data used to create the diagrams are annual average amounts of snow determined from the weather history of the test site [32].

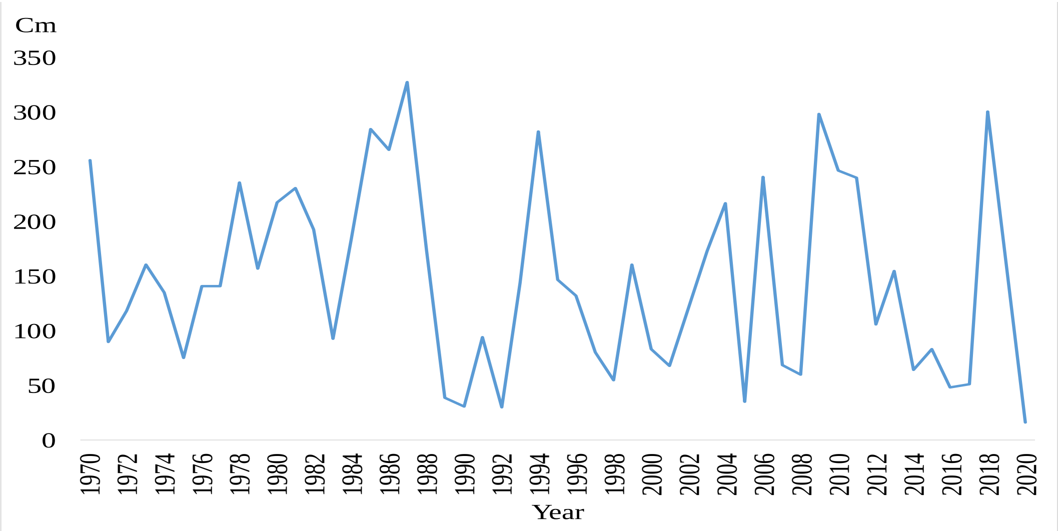

Figure 2. Average annual snow amounts for the test location in centimeter, 1970-2020

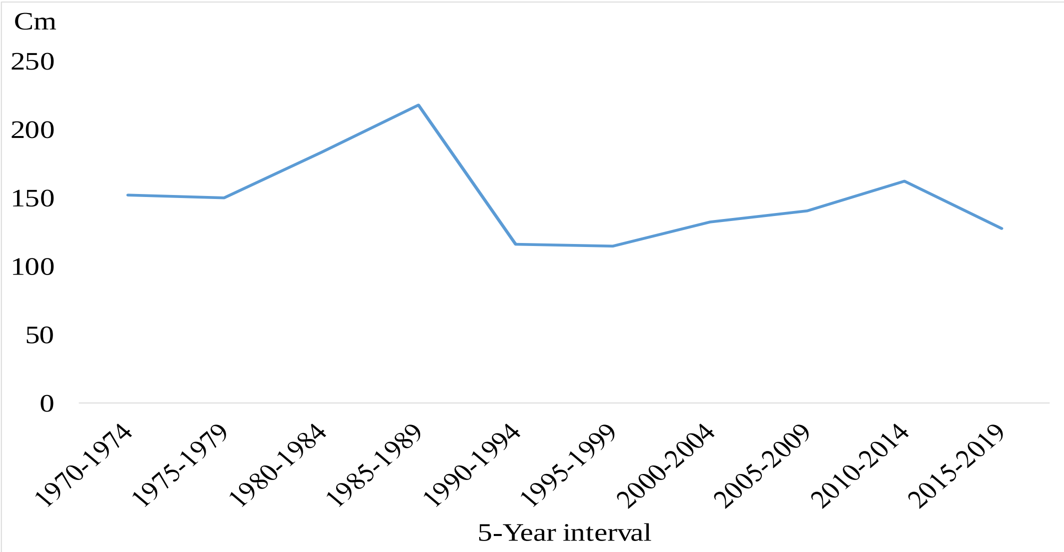

Figure 3. Five-year average snow amounts for the test location in centimeter, 1970-2019.

Table 2 shows the study's null hypotheses and Table 3 lists the days considered in each scenario. The null hypotheses state that the power output is the same for both test systems, regardless of whether they experience snow or not. The hypothesis testing methods are defined by the normality of the data [33, 34]. The collected data is non-normally distributed, motivating the utilization of a Two-sample Mann-Whitney U Test. These tests will be performed by using the statistical data analysis tool known as STATA, and the result of the scenarios are presented in Table 4**,** while Table 5-7 shows their descriptive statistics.

Table 2. The systems' null hypotheses regarding power output.

Scenario	Null hypothesis	Weather condition	Number of days	Number of datapoints, per system
1	H_0: S1=S2	Days with and without Snow	51	16826
2	H_0: S1=S2	Days not experiencing snow	44	14516
3	H_0: S1=S2	Days experiencing Snow	7	2310

Table 3. Specific dates considering each scenario.

Month	Scenario 1, dates	Scenario 2, dates	Scenario 3, dates
January	16 – 20, 22 – 31	16 – 20, 22 - 28	29 - 31
February	1 – 2, 4 – 10, 12 – 24, 26 – 29	1 – 2, 5 – 10, 12 – 24, 26 – 29	4
March	1, 3 – 11	3, 6 – 11	1, 4, 5

Table 4. Results from the Two-Sample Mann-Whitney U test on all scenarios.

Scenario	Weather condition	p-value	Keep/Reject H_0
Scenario 1	With and without snow	0.09	Keep H_0
Scenario 2	Days without snow	0.58	Keep H_0
Scenario 3	Days with snow	0.0003	Reject H_0

Table 5. Summary of S1 and S2 descriptive statistics, scenario 1. Days with and without snow.

Statistic	System 1	System 2
Observations	16826	16826
Mean (W)	13.41	13.67
Variance (W)	267.53	269.16
Standard deviation (W)	16.36	16.41
Skewness	0.69	0.66
Kurtosis	1.65	1.61
Min/Max values (W)	0/43.49	0/43.49
50^{th} percentile (W)	2.41	2.70
Performance Ratio (%)	5,75	5,86

Table 6. Summary of S1 and S2 descriptive statistics, scenario 2. Days without snow.

Statistic	System 1	System 2
Observations	14516	14516
Mean (W)	14.17	14.27
Variance (W)	275.41	276.36
Standard deviation (W)	16.60	16.62
Skewness	0.60	0.59
Kurtosis	1.53	1.51
Min/Max values (W)	0/43.49	0/43.30
50^{th} percentile (W)	3.25	3.33
Performance Ratio (%)	5,99	6,03

Table 7. Summary of S1 and S2 descriptive statistics, scenario 3. Days with snow.

Statistic	System 1	System 2
Observations	2310	2310
Mean (W)	8.69	9.93
Variance (W)	192.31	207.67
Standard deviation (W)	13.87	14.41
Skewness	1.34	1.14
Kurtosis	3.12	2.59
Min/Max values (W)	0/41.61	0/42.04
50^{th} percentile (W)	0.35	0.80
Performance Ratio (%)	4,08	4,66

4. DISCUSSION

Table 4 shows the results of the two-sample Mann-Whitney U tests showing one of the tested scenarios with statistically significant results. Strictly speaking, the p-value from scenario 3 can be interpreted as 0.3 times a thousand can a meaningless difference of five percent or more be expected to be observed. The low p-value in this case indicates that the observed difference most likely did not occur by chance. Although the test suggests that the null hypothesis is rejected, which means that the power output of the system is not equal, it does not indicate which PV module is producing the positive output difference.

In order to separate and determine which PV module contains the perceived increased properties, the scenario-descriptive statistics shown in Table 7 must be assessed. The descriptive statistics show that the highest average output by the test systems is S2. With an average power output of 1.24 watts, S2 is 12.49 % better than the S1. The 50th percentile is twice as big for S2 compared to S1. The higher values within the 50th percentile can indicate that S2 might outperform S1 when reduced amounts of solar irradiation are available. Given the impact snow has on the power generation of PV systems, this difference can build up against the assertion that frameless PV systems have enhanced snow removal properties. It is worth noting, however, that the values within the 50th percentile of both systems are perceived as low, indicating that the datasets are dominated by smaller values, with some larger values considering the mean and maximum values.

The data distribution trends can also be observed by the high positive skewness, which confirms that smaller values dominate the datasets. The analysis of the systems' kurtosis tells that S1 has leptokurtic tendencies, while S2 has platykurtic tendencies [35]. This means that S1's data set has an expanded distribution consisting of a higher and sharper peak under its data, while S2's dataset has a shorter distribution consisting of a lower and broader peak under its data. The standard deviations of the data sets are not too different and indicate that the data in both data sets are relatively distributed. Assessing the variance of the system shows that the data from S2 deviates more from the mean than the data from S1, suggesting that the data from S1 do not vary as much as the data from S2. Given that the data are time series covering power output, the higher variance may be favorable for S2 and suggest a higher production peak, especially if the maximum and mean values are higher than that of S1. The calculated performance ratio for the test systems put S2 in the foreground, with an increased value of around 12 percent compared to S1. The performance ratio is a definition-based variable and plays a central role in the performance evaluation of PV systems [36]. The ratio is affected by environmental factors, the PV system's ability to utilize the available solar irradiation, and losses within electrical components within the system [36, 37]. Taking into account the identical electrical components of the test systems and the identical alignment of the PV modules in identical weather, the higher power ratio of the S2 is a clearer consequence of the frameless PV module, which has favorable properties considering the days on which snow occurs. Figure 4 clearly shows how S1's aluminum frame appears to slow down the sliding of the snow, also note the pile of snow in front of S2.

Dealing with the second scenario's two-Sample Mann-Whitney U-test's results clearly show that a statistical significance between S1 and S2 is missing. The high p-value can be interpreted as 580 times in a thousand, a meaningless difference of five percent or more can be expected to be observed. The high p-value indicates that the observed difference within the dataset most likely occurred by chance. By analyzing the scenario's descriptive statistics in Table 6, a small difference in the average energy generated can be observed, which benefits S2. However, the difference in the average value is exactly 0.7 percent, which can be perceived as minimal. Comparisons of variance, standard deviation, min / max values and performance ratio show that data differ by less than one percent. One reason for the small difference that slightly benefits S2 can be explained by the inaccuracy of the snow depth sensor used at Blindern weather station. Raw data is sorted based on values of snow depth from Blindern and the author's own weather log. A deviation that has been observed occurred on 28 January 2020, where figure 4 clearly shows that snow is getting stuck on the solar modules and the immediate environment. Weather data from Blindern, however, shows that there was no snow that day [31]. Considering the inaccuracy of the snow depth sensor, the data from the test systems on days without snow can certainly be stated as similar. The calibration of the test systems is ensured by perceiving similar data on days without snow. Any significant differences between the test systems on these days would lead to biased results and affect the validity of the test systems.

Figure 4. Snow accumulating on the test-systems, 28th of January 2020. Framed PV module situated at the right (S1), and ‘frameless’ PV module situated at the left (S2). (Photo by Jørgen P. Aubell).

Logically, the magnitude of scenario 3's effects on the test period will be visible in scenario 1's results. Seen from the two-sample Mann-Whitney U test, the perceived beneficial properties of the frameless PV module revealed in scenario 3 are not sufficient to create statistical significance, given the entire test period. Table 5 shows the descriptive statistics of scenario 1, where most of the statistical values appear the same at first glance. The descriptive statistics show that the variance, standard deviation and maximum values of the test systems are below one percent, while the skewness and kurtosis of the data are below 4.5 percent. However, addressing the 50th percentile of test systems shows the largest difference between the two data sets. S2 has about a 10 percent higher value than S1, which can be explained by the 50th percentile presented for scenario 3. Scenario 3 indicates that S2 produces more energy when reduced solar radiation is available, which creates a significant amount of lower values. The difference in scenario 1's 50th percentile may be where scenario 3's results show their most significant impact.

5. CONCLUSION

The data collected by the test-systems gave legitimate results, even though the experiment was performed during an unexpectedly abnormal snow-poor winter. However, the seven days with reasonable amounts of snow provided data containing a statistically significant difference in power production between the test-systems. The frameless PV-system produced on average 12.49% more watts on these snow experiencing days, which can indicate it containing a favourable exterior characteristic for PV-systems aimed to be installed in snow-experiencing climates. However, the increase in the frameless PV-system's power output was not enough to provide statistical significance considering the whole test period. Given this condition and the experiments circumstances, it cannot be concluded that that the frameless PV-system will severely outperform a framed PV-system on days with snow. More tests should be done in circumstances with more snow, and a revisit on how PV-system inclination angle affects snow shedding should be done assessing the frameless-PV-systems.

CONFLICT OF INTEREST

The authors confirm that there is no conflict of interests associated with this publication and there is no financial fund for this work that can affect the research outcomes.

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