

**An Analysis of the Benefits of Vertical Solar Photovoltaic Systems and the
Effect of Artificial Ground Cover on Energy Output**

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By

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Executive Summary

Since climate change has been widely accepted as a global issue exacerbated by greenhouse gas emissions, the demand has increased for renewable energy technologies to replace carbon intensive energy sources. A clean and abundant energy source, solar energy ranks amongst the most sustainable of all energy sources. The growing demand for renewable energy has stimulated research and development in solar photovoltaic (PV) technologies. Increased research and development have reduced costs of PV systems while increasing their efficiencies. PV installations usually involve tilting PV systems to optimal angles for light capture and mounting them on building rooftops or ground-racks. Vertically mounted PV systems are less commonly developed.

Developed through a partnership between Rock Paper Sun Ltd. and the School of Environment and Sustainability at the University of Saskatchewan, this project examined the benefits of vertically mounted PV systems in southern Saskatchewan. The purpose of the project was to understand the performance of vertically mounted PV systems as they relate to the albedos of the adjacent ground surface. The specific objectives of this project were as follows: (1) to quantify the influence of artificial white ground cover on the electricity output from a vertically mounted PV system by statistically analyzing actual energy production data from a vertical PV installation, (2) to frame the efficiency of vertical PV systems in the context of conventionally tilted PV systems in a region prone to snowfall by comparing the actual performances of the vertical PV system with more optimally tilted PV systems that have operated in the Saskatoon area, and (3) to determine the beneficial applications of vertical PV systems by linking the findings from this study to local industries.

The experimental procedure involved collecting energy output data from a vertical PV system subjected to different treatments of ground cover, including natural ground and artificial white plastic cover. The use of white plastic from repurposed grain storage bags resulted in increased energy output from vertical PV modules, up to approximately 16%. When outfitted with artificial white ground cover, vertical PV systems were found to produce between 9% to 17% less energy than optimally tilted PV systems. The amount of energy produced depends on the tilt angle and snow clearing regimen of the optimally tilted PV systems. The potential benefits of vertically mounted PV systems are similar to the general benefits of solar energy technologies; however, specific beneficial applications of vertical installations include on-farm renewable energy generation in the industrial agriculture industry, as well as the integration of vertical PV systems into building walls to create more sustainable buildings.

Recommendations from this project include the following: (1) to enhance energy production by deploying vertically mounted PV systems adjacent to high albedo ground surfaces or outfitting vertically mounted PV installations with a high albedo ground surface cover, such as white polyethylene plastic; and (2) to consider vertically mounted PV systems as an option for renewable energy generation, particularly in northern regions that experience snowfall and when conditions do not favour optimum PV installations.

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Abbreviations

AC	Alternating current
BAPV	Building-applied photovoltaics <i>refers to photovoltaic materials that are installed over existing building parts</i>
BIPV	Building-integrated photovoltaics <i>refers to photovoltaic materials that are used in the building envelope</i>
GHG	Greenhouse gasses
HC	High control <i>refers to the module in the vertical PV system furthest from the natural ground surface</i>
HT	High treatment <i>refers to the module in the vertical PV system furthest from the white ground cover</i>
KW	Kruskal-Wallis <i>refers to a nonparametric analysis of variance test</i>
LC	Low control <i>refers to the module in the vertical PV system closest to the natural ground surface</i>
LT	Low treatment <i>refers to the module in the vertical PV system closest to the white ground cover</i>
P₀	Nominal power <i>refers to the rated power of PV modules under Standard Test Conditions</i>
PV	Photovoltaic <i>refers to the technology that generates electricity from photons from the sun through semiconductor material</i>
RPS	Rock Paper Sun Ltd. <i>refers to a solar electric and thermal design and installation company in Saskatoon, SK that is a stakeholder in this study</i>
SW	Sharipov-Wilk <i>refers to a numeric normality test</i>
vPV	Vertical photovoltaic <i>refers to a vertically mounted photovoltaic system tilted at 90°</i>
W	Watt
Wh	Watt hour
W_p	Watt-peak <i>refers to the peak power of PV modules under Standard Test Conditions</i>

1. Introduction

With expanding climate change impacts, increasing political pressure, and declining natural resources, the renewable energy transition has become a global effort. Governments, researchers and practitioners are seeking ways to reduce consumption of fossil fuels and greenhouse gas (GHG) emissions, and, with their costs decreasing and inefficiency increasing, PV installations are an attractive alternative. Their use has thus increased worldwide, including in regions with suboptimal latitudes and climate, such as Northern Europe and Canada, some of which experience snowfall (Andrews, Pollard, & Pearce, 2013). Snowfall may act as a limitation or an advantage depending on the geometry and tilt angle of PV systems (Heidari, Gwamuri, Townsend, & Pearce, 2015; Yoshioka, Hasegawa, Saitoh, & Yatabe, 2002).

In 2016, Canada issued the Pan-Canadian Framework on Clean Growth and Climate Change in which a collective plan was laid out to reduce greenhouse gas emissions by a target of 30% below the 2005 emission levels by the year 2030 (PCFCC, 2016). Canada's energy mix is progressively transitioning to a decarbonized system to achieve this target; individual provinces and territories are enacting separate energy policies concurrently to transition to sustainable renewable energy. In Saskatchewan, the provincial government has committed to doubling the percentage of energy generation from renewables by 2030 (SaskPower, 2018). This commitment includes plans for solar power generation from PV systems.

The increasing prevalence of PV systems in cold high-latitude regions (Heidari et al., 2015) and the diverse settings in which they could be applied suggests that specific PV system designs should be studied and optimized for northern conditions. This field study examined the performance of a vertically mounted solar PV system in Saskatchewan, Canada. The study quantified the influence of groundcover on energy output from vertical PV (vPV) systems by increasing the reflected solar radiation received at the PV panel surface.

1.1 Photovoltaic system overview

PV systems are devices that harness solar radiation from the sun and convert it into electricity. As solar energy is abundant, PV systems are one of the most sustainable renewable energy sources available. Recent years have seen numerous advances in solar photovoltaic technologies to meet society's increasing demand for alternative energy sources. This demand has stimulated research and development in the design of photovoltaic systems thereby increasing their efficiencies and applications. PV applications include off-grid systems or grid-connected systems depending on their connectivity with the electrical utility grid.

PV Modules, often referred to as solar panels, are the smallest unit of a PV system. Modules are typically rated at a specific watt peak of 135 to 300+ watts. As of 2014, most PV modules ranged in size from 0.6×1.5 meters to 1.4×1.8 meters and were usually made up of 36 to 80 solar cells that convert observed light directly into electricity through the photo-effect (Meristem Information Resources, 2013). Solar cells are manufactured from semi-conductor materials, most commonly silicon. Crystalline silicon modules are preferred in the PV industry due to their high

conversion efficiency and maturity (Mousa, 2014). When wired in series and/or parallel, connected modules compose a PV array (Figure 1). PV systems vary in their shape, appearance and size; however, grid connected systems generally consist of PV modules, inverters, a racking system, and wiring components.

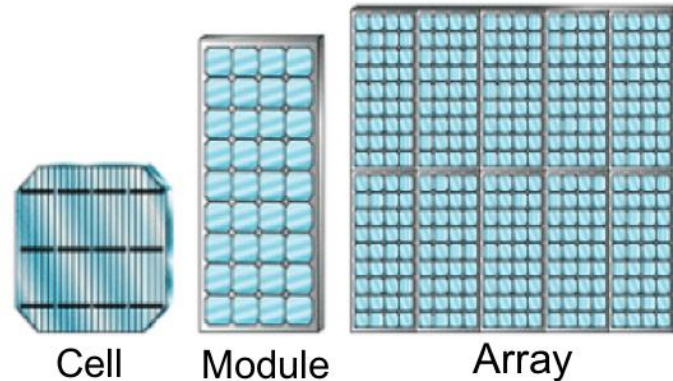


Figure 1. Components of a PV array. Cells form modules and modules connected in series and/or parallel form an array. (Kayal, 2009)

Grid connected PV systems must be outfitted with an inverter that converts the direct current energy produced by PV modules to alternating current (AC) energy to match grid electricity. AC electricity can be used directly in buildings or exported to utility providers through the electricity grid connection (Kayal, 2009). As solar radiation intensity varies throughout the day, most grid-connected inverters include a maximum power point tracker that ensures modules operate at their optimum power at all times (Green Rhino Energy Ltd, 2016).

An installation refers to the deployment method of PV arrays. PV systems can be mounted to the ground with purpose-designed racks, often using concrete piles, or mounted on existing structures by applying or integrating PV modules within building envelopes, most commonly on rooftops. Less commonly, PV arrays are installed vertically, where they are mounted on a building façade or on the ground with a supporting foundation. The orientation of PV systems refers to the azimuth angle, or the deviation from true south (Kayal, 2009). This project focused on small-scale grid-connected systems, including both ground-mounted PV systems and building-applied photovoltaic (BAPV) systems.

In terms of capital costs, the price of PV modules has declined dramatically in recent years. The price of PV modules in Canada has declined by approximately 80% in recent years, from \$10.7 CAD per watt in 2000 to \$2.27 CAD per watt in 2010 (Mousa, 2014). Other than snow removal, there are minuscule maintenance costs associated with PV systems.

1.2 Background review

Saskatchewan remains the biggest contributor of GHG emissions per capita in Canada (Harper et al., 2016; PCFCC, 2016). However, geophysical conditions in Saskatchewan favour solar energy production as southern Saskatchewan has the best solar profile in the country (Prebble, 2011). The Canadian solar energy market has continued to grow, from 557 Mega-Wp solar power

installed in 2005 to 3310 Mega-Wp in 2016 (National Energy Board, 2017), and it is anticipated that the solar PV industry in Saskatchewan will follow the same trajectory. Knowledge of region-specific conditions that influence PV performance is paramount for the successful and effective growth of the industry.

In the design of PV systems, maximizing the amount of incident solar radiation is usually a desirable configuration. Incident solar radiation is the amount of radiation energy received on an object's surface. The amount of electricity produced by PV systems is directly related to the solar radiation captured by the PV modules. Incident radiation occurs in three forms: direct radiation, diffuse radiation, and reflected radiation from other surfaces (Figure 2). Direct radiation reaches the Earth's surface without being reflected or absorbed by the atmosphere; diffuse radiation is scattered by particles in the atmosphere; and reflected radiation, also referred to as albedo, is partially dependent on the reflectivity of surrounding surfaces. Some surfaces are characterized by low albedos such as oceans, lakes, and forests, whereas snow, sea ice, and deserts have high albedos and therefore reflect relatively large fractions of the incident solar radiation (Coakley, 2003). In the context of PV energy production, direct and diffuse radiation are the two most important parameters to be assessed (Mehrtash, Rouse, & Quesada, 2013).

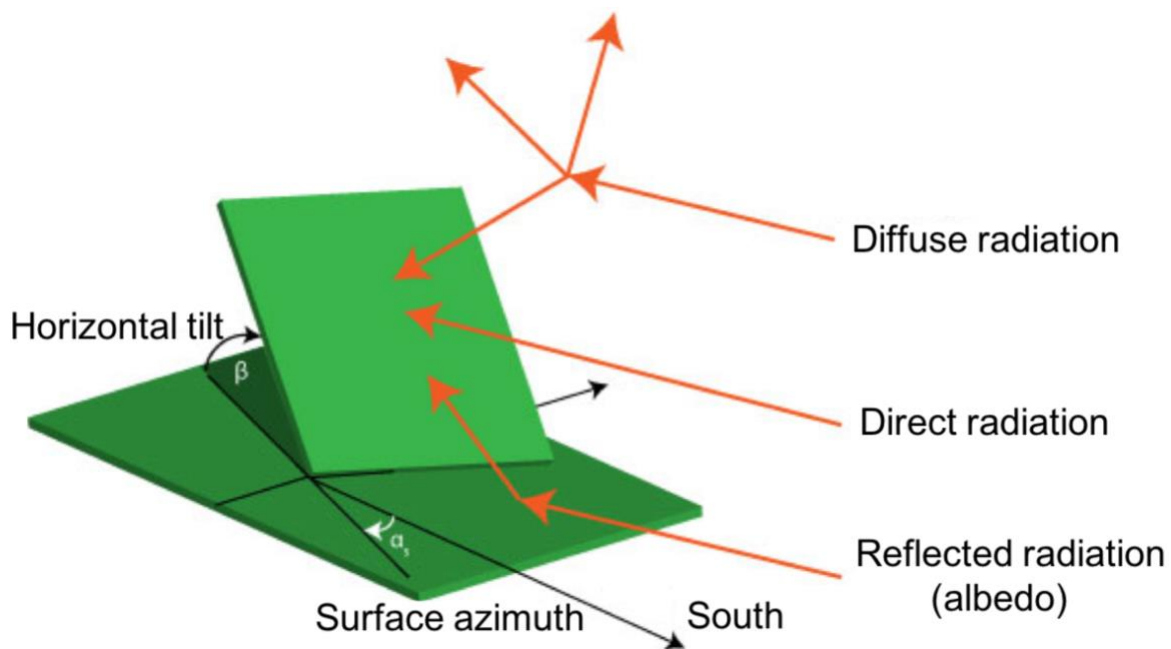


Figure 2. The forms of solar radiation received at a tilted surface. (Green Rhino Energy Ltd, 2016)

The highest amount of solar radiation is absorbed by PV modules when they are installed perpendicular to the sun's direct rays (Mehrtash et al., 2013). For maximum absorption, PV modules are commonly tilted at an angle approximately equal to the latitude of their location, referred to as an optimal tilt angle (Kayal, 2009). In a field study, Lin and Jiang (2015) demonstrated that optimally tilted PV systems capture considerably more direct radiation compared to vPV systems in Singapore, which is located at 1° latitude. Their study compared vertically tilted installations to more optimally tilted PV systems and found that the vertical system produced approximately 50% less energy than the optimum one. Similarly, Suri et al.

(2007) identified that the annual yield from vPV systems is lower than the energy yield from more optimally tilted PV systems. However, at higher latitudes, energy losses from vPV systems compared to optimal tilt systems were smaller owing to increasing optimal tilt angles with increasing latitude. Using a computer model, Suri et al. (2017) estimated that in Portugal and the Mediterranean region, at a latitude of 42°, vPV systems produced 33% less than optimally tilted systems, 28% less in Central to Northern Europe and below 20% less in Northern Sweden and Finland, which are located at 61° latitude. The results from both studies indicate that the performances of vPV systems improve as latitude increases, making them more efficient in high latitude regions.

Difficulties arise with optimally tilted PV systems in high latitude regions where snowfall accumulates (Figure 3). In a review of several relevant studies, Heidari et al. (2015) concluded that snow accumulation on PV module surfaces impacts their performance and decreases electricity output. In their own study, located in Michigan, US, Heidari et al. (2015) reported that annual energy losses related to snow cover range from 5% to 34% a year, depending on the orientation of PV systems. In southern Ontario, Canada, losses related to snow-cover were found to be 3.5% to 1% from the expected yearly yield (Andrews, Pollard, & Pearce, 2013). In Edmonton, Canada, at latitude 53°, a field study revealed that manually clearing PV modules from snow an average of 24 times in a winter season resulted in 0.85% to 5.31% more energy than modules where snow was not cleared manually. Energy gains depended on the module tilt angle (NAIT, 2016). In their studies of snow-related losses in analogous climate regions, NAIT (2016), Heidari et al. (2015) and Andrews, Pollard and Pearce (2013) obtained largely different results, the latter reporting a relatively low snowfall during the study period.

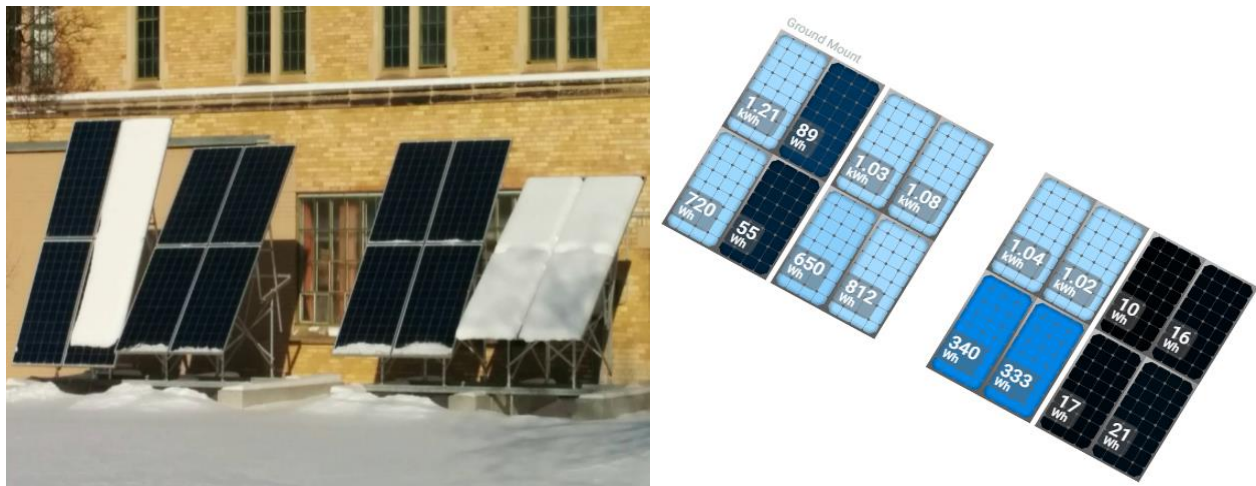


Figure 3. (Left) A ground-mounted PV system with snow-covered modules in January 2018 located at the University of Saskatchewan main campus. (Right) Energy output during the same day displayed per module.

Andrews, Pollard, and Pearce (2013) reported the effect of higher albedos of the surroundings of PV systems as they increased expected energy yields, particularly for high tilt angle systems. NAIT (2016), Heidari et al. (2015), and Andrews, Pollard and Pearce (2013) found that steeper PV module tilt angles generally result in less snow-related losses. This finding leads to the expectation that at the steep angle of 90°, vPV systems are likely to incur less energy loss related to snow accumulation than optimally tilted systems.

As discussed above, vPV systems may diminish the problem of snow-related PV energy losses as the steep tilt angle favours natural snow shedding. In addition, the high reflectivity of snow on the ground increases the amount of reflected radiation, which, in turn, significantly increases the amount of incident solar radiation received at the surface of vertically tilted PV modules (Yoshioka et al., 2002). The reflectivity of fresh snow is high compared to dirt; therefore, snow can be a natural concentrator of solar energy that can be used by PV modules (Meyta & Savrasov, 2015).

In high-latitude regions, such as Northern Canada, vPV systems are expected to perform relatively similarly to optimally tilted systems. In high-latitude regions the optimal PV panel tilt angle approaches 90°, thus the natural shedding of snow off PV module surfaces is similar between vPV and optimal PV systems, and energy losses due to vertically mounting PV modules are small. In mid-latitude regions, such as Southern Canada, optimally tilted PV modules are less steep, and the natural shedding of snow occurs to a lesser extent; therefore, snow shedding benefits from vPV installations are expected to be more visible. However, in mid-latitude regions, energy losses due to vertically mounting PV modules are higher compared to optimal PV installations. As a result, in determining the sustainability of vPV systems as an alternative to optimally tilted systems, the influence of high ground surface albedo on vPV energy production may be more important in mid-latitude regions than in high-latitude regions.

A number of methods and technologies are available to reduce negative snow impacts on PV systems. The most common are snow repulsion methods, which include the manual clearing of snow (Synergy Power, n.d.), and coatings and heating technologies integrated into the PV modules themselves to melt and shed the snow (US20150114450A1, 2015; US9605880B2, 2017). Available snow repulsion methods are often expensive, cumbersome, or may damage PV systems (Adochitei, Harabagiu, Astanei, & Burlica, 2014). Therefore, it is common for PV system owners to opt for conventional PV technologies without snow repulsion capabilities. Many PV system owners do not maintain manual snow clearing from module surfaces; instead, they rely on natural snow shedding processes.

Aside from the study by NAIT (2016), existing field studies examining vPV systems are located at lower latitudes than Canada. The study by NAIT (2016) examined PV installations with several feet of ground clearance, which is favourable to natural snow shedding. In PV installations on building rooftops, natural snow shedding may be impeded by obstructions such as gutters, equipment, and intersecting roof faces (Heidari et al., 2015). Studies examining the positive effect of snow albedo on vPV systems have not explored the potential of increasing PV performance from artificial high albedo ground surfaces. This project allowed for investigating whether energy production from vertically mounted PV systems can be augmented using artificial white ground cover to increase ground surface albedo when snow cover is not present. Additionally, this project examined the impact of snow on vertical modules, as well as inclined modules, using actual PV performance data from mid-latitude regions prone to snowfall such as southern Saskatchewan.

1.3 Objectives of the project

This project was brought forward through a partnership between the School of Environment and Sustainability at the University of Saskatchewan and Brent Veitch, director of Rock Paper Sun Ltd (RPS), a solar power solutions provider in Saskatoon, Canada. RPS provides solar PV and solar thermal design and installation services to both urban and rural communities in the region. RPS's interest in this project involved studying data from a vertically mounted PV system, which they designed and deployed for Anna and Doug Carman with financial support from Eco Friendly Sask. Their goal from this partnership was to inform stakeholders in the solar power industry about the beneficial applications of vPV systems in Saskatchewan.

The benefits of the project included the following: (1) increasing the knowledge surrounding vPV installations in high latitude regions prone to snowfall, and (2) shedding light on methods to enhance vPV system efficiency, which could ultimately benefit the development of renewable energy solutions catered specifically to Saskatchewan's climate and similar regions.

The goal of the project was to understand the performances of vPV systems as they relate to ground surface cover and its associated albedos. The specific objectives of this project follows: (1) to quantify the influence of artificial white ground cover on the electricity output from a vPV system by statistically analyzing actual energy production data from a vPV installation; (2) to frame the efficiency of vPV systems in the context of conventionally tilted PV systems in a region prone to snow fall by comparing the actual performances of the tested vPV system with more optimally tilted PV systems that have operated in the Saskatoon area; and (3) to determine the beneficial applications of vPV systems by linking the findings from this study to local industries.

2. Methods

Quantitative analyses were performed to accomplish the project objectives of (1) assessing the influence of white ground cover on energy output from vPV systems and (2) investigating the performance of vPV installations as compared to conventionally tilted PV installations. Actual performance data were extracted from a vPV installation designed purposely for this project, as well as pre-existing conventionally tilted PV installations. A statistical hypothesis test was applied to the data from the vPV system to achieve the first objective, and descriptive statistics were used to complete cross-comparisons between select PV installations to achieve the second objective.

2.1 Test site and experimental design

A south facing vertically mounted grid-connected PV system was commissioned in southern Saskatchewan, Canada, 52° N 106° W. This site falls within the prairie climate region characterized by flat land, a continental climate with cold and dry winters, and dry and humid summers. Precipitation is relatively low (347 mm per year), and the average daily temperature varies from -15 to 18 °C (Cragg, 2017). Historically, snow has covered the ground for about six months a year, but interannual variability in snow cover is considerable.

The tested vPV system was developed by Rock Paper Sun Ltd (RPS) and owned by Anna and Doug Carman. The PV array consisted of 84 JA Solar modules, each with a rated capacity of 260 W_p and containing 60 polycrystalline-Si cells. The study focused on six modules within the array. Funding was provided by Eco-friendly Sask to outfit the vPV system with six Enphase M215 microinverters. The microinverters were strategically installed on six modules located in the eastern half of the array. The modules near the centre of the array, where a white ground cover treatment was applied, are referred to as high treatment (HT), mid-high treatment (MHT), mid-low treatment (MLT), and low treatment (LT) modules, whereas the modules near the eastern edge of the array are referred to as high control (HC) and low control (LC) modules (Figure 4). The lower and upper edges of the system were 0.3 and 4.26 meters from the ground, respectively, on the eastern edge of the array and 0.8 and 4.76 meters on the western edge of the array.

The tested vPV system was outfitted with a segment of secondary-use white plastic as ground cover measured at 6.1 × 30.5 meters (Figure 4). The eastern edge of the array was excluded from the ground cover treatment for experimental purposes. The ground adjacent to the eastern edge of the system remained intact and was naturally covered with snow in the winter and dirt and grass in the summer; this section was used as the control treatment. The plastic used as ground cover was sourced from repurposed grain storage bags, which are commonly used in North American industrial agriculture operations (Figure 5).

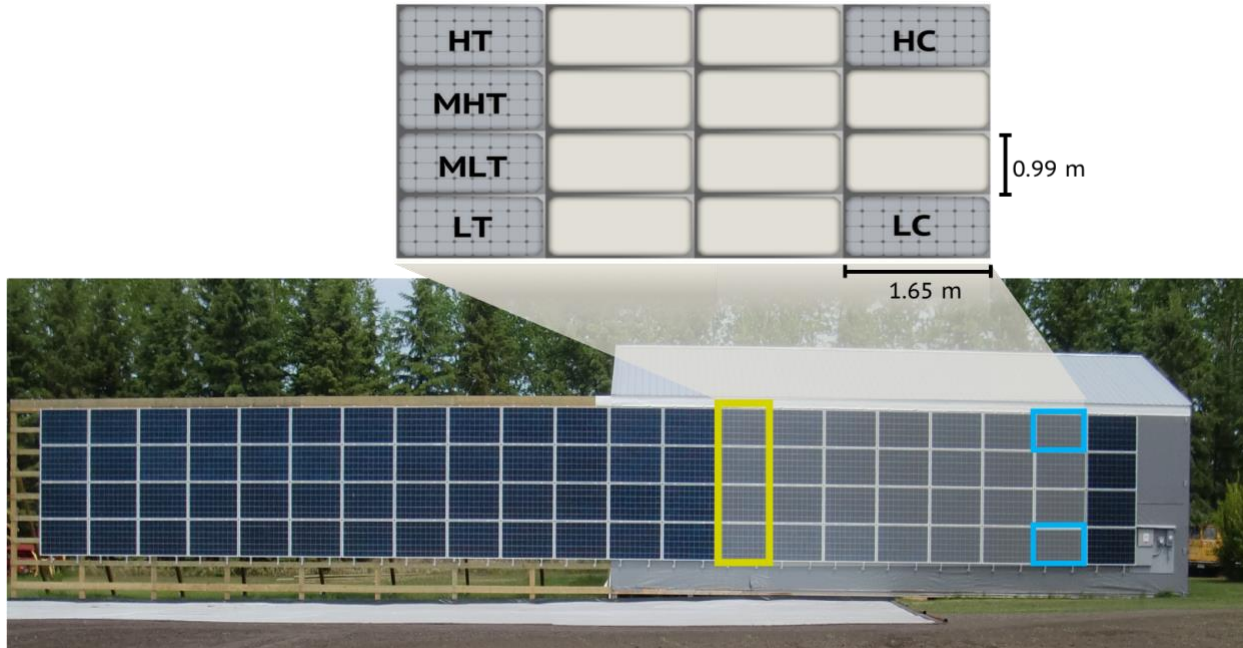


Figure 4. The study site displaying the tested vPV system with the artificial white ground cover treatment. The treatment modules are outlined in yellow and the test modules are outlined in blue. The six monitored modules in the tested vPV system are labeled by their height level (H-high, M-medium, L-low) and experimental level (T-treatment, C-control).



Figure 5. A white plastic polyethylene grain bag storage system commonly used by farmers to store crops

2.2 Vertical PV system data collection and statistical analysis

The six test modules were integrated with the solar monitoring tool Enlighten and used to collect data for electricity production. Enlighten is a web service product offered by the microinverter’s manufacturer, Enphase Energy. This monitoring tool allows users to track and download performance data for PV installations and individual modules.

Performance data was filtered for total daily AC electricity output per module in Wh. The raw dataset includes daily energy output per module starting on April 15, 2015 and ending on October 17, 2017. This dataset was further reduced to include only the days on which the ground cover treatment was applied, which spanned from May 15, 2015 to April 4, 2017. Table 1 shows data for the first 10 days of PV operation with the ground cover treatment.

Table 1. A sample set of the data for daily energy output per module obtained from Enlighten for the tested vPV system from May 15 to 25, 2015.

Date	Output (Wh)					
	HC	HT	MHT	MLT	LC	LT
2015-05-15	977	1080	1134	1195	982	1199
2015-05-16	775	855	911	964	777	962
2015-05-17	1115	1198	1272	1347	1132	1366
2015-05-18	1049	1162	1224	1287	1069	1299
2015-05-19	1021	1129	1191	1252	1041	1262
2015-05-20	1000	1105	1162	1221	1017	1235
2015-05-21	995	1104	1165	1224	1006	1231
2015-05-22	985	1091	1152	1206	993	1215
2015-05-23	865	950	1002	1054	875	1061
2015-05-24	967	1065	1120	1176	983	1192
2015-05-25	807	882	931	978	811	983

to determine whether the application of artificial white ground cover augmented energy production from the vPV system, the daily electricity output for each of the six modules was compared for different months. Data from January 1st, 2016 to December 31st 2016 was used in a time series plot to display seasonal variations in the tested PV system’s performance. The plot established that the influence from the white ground cover treatment on the vPV system’s energy output was only present in the absence of snow.

The dataset was divided into two sets based on time periods depicting the absence of snow and the presence of snow. Historical climate data from the Saskatoon RCS station was used to establish such periods for 2015 and 2016. Snow free months in 2015 included May through October, and, in 2016, May through September (ECCC, 2018). For the purpose of this report snow-free months in 2015 and 2016 are referred to as ‘summer months’.

Statistical analyses were applied on data from the combined summer months of 2015 and 2016 to quantitatively evaluate the effect of artificial ground cover on energy output. The objective of the statistical analyses was to determine if the energy output was statistically different between any of the six modules due to their differing ground cover treatments. To avoid incorrectly skewing the distribution of the data, only modules at the same height from the ground (HT, HC, LT, LC) were included in the statistical analyses. Using both histogram plots and a numerical method, the data was initially tested for normality, as many statistical methods assume normality and the violation of this assumption results in misleading inferences and invalid interpretations (Park, 2006). The Shapiro-Wilk (SW) normality test was chosen because it evaluates the null hypothesis that the sample is from a normal distribution and is a proper test for sample sizes smaller than 2000 data points (Park, 2006). To verify if the data can be transformed into a normal distribution, the Box-Cox transformation method was applied to the non-normal energy output datasets, and a SW test was applied to the transformed data (Mangiafico, 2016; Venables & Ripley, 2002).

A non-parametric test was chosen to conduct further analysis. The effect of ground cover on vPV productivity was analyzed using the non-parametric Kruskal-Wallis one-way analysis of variance (Kruskal & Wallis, 1952). To identify which pairs of modules are significantly different, a post-hoc pairwise comparison was conducted using Dunn's non-parametric multiple comparison test with the Bonferroni correction (Dinno, 2017). The hypotheses to evaluate if the energy output datasets for each of the HT, LT, HC, and LC modules in the tested vPV system are significantly different are as follows:

H_{null} : The medians of all groups are equal; therefore, there is no statistically significant difference between the four sets of data (HT, LT, HC, and LC modules) for energy output.

$H_{\text{alternative}}$: The median of at least one group is statistically different from the median of at least one other group; therefore, there is a statistically significant difference among the four sets of data (HT, LT, HC, and LC modules) for energy output.

For all statistical tests, an alpha value of 0.05 was used as the threshold for significance. The statistical analyses were done using RStudio (version 1.1.383) with the statistical language R (version 3.5.1). See Appendix A for the complete R Transcript (R Core Team, 2018).

2.3 Cross-comparison analysis with inclined PV systems

The cross-comparison analysis conducted in this study aimed at framing the productivity of the tested vPV alongside other conventionally configured PV systems in the region based on actual performance. This analysis was completed by examining energy output data from a list of PV systems operating in southern Saskatchewan along with the data from the tested vPV system. Similar to the tested vPV system, the PV systems considered in this analysis were designed and deployed by RPS. However, aside from the tested vPV system, RPS did not factor in any experimental objectives in the design of the PV systems examined in this analysis, rather the systems were designed for the best performance with respect to desirable installation costs for actual clients. Select PV systems were chosen for this analysis based on the following set of criteria:

- The systems operated for all of 2016
- The systems were located within a 50 km radius of the tested vPV system
- The systems were equipped with Enphase M215 microinverters similar to the tested vPV system

The above criteria were established to ensure that all PV systems considered in the analysis operate under analogous weather conditions, with the same level of solar insolation, and use identical microinverters to exclude the effect of different maximum power point tracking methods on the energy yield (ZinBer et al., 2007). As a result, the difference in energy output between the PV systems was primarily attributed to factors related to their differing orientation and installation parameters and not to differing ambient influences. The selection process identified five PV systems that were used in this analysis in addition to the tested vPV system (Table 2).

Table 2. Specifications of the PV systems deployed by RPS in the Saskatoon area that were used in the cross-comparison analysis. P_0 refers to the rated power of PV modules used in each installation.

Specifications					
ID	Installation	Tilt	Orientation	Modules	P_0 (W _p)
1	vPV + treatment	90°	South	4	260
2	vPV	90°	South	2	260
3	Inclined rooftop + snow clearing	14°	East & West	16	260
4	Inclined rooftop + snow clearing	14°	South	15	185
5	Rack-mount on flat roof + snow clearing	35°	South	116	230
6	Inclined rooftop	40°	70° East of South	41	255
7	Ground-mount	66°	South	21	250

For the purpose of this analysis, the PV systems are referred to with their ID numbers listed in Table 2. PV systems 1 and 2 reference the tested vPV system, where 1 denotes a vPV system with artificial white ground cover and 2 denotes a vPV system with natural ground cover. PV systems 3 and 6 experienced some level of shading that may have impacted their productivity. The owners of PV systems 3, 4, and 5 reported that they have maintained manual clearing of snow from the module surfaces during winter months. Half the modules in PV system 3 were installed on a west facing roof and the other half were installed on an east facing roof. See Appendix B for raw data from the PV systems.

Data for the comparison was accessed similarly to that for the tested vPV system, using the monitoring tool Enlighten produced by Enphase Energy but, however, filtered for yearly energy production reports, including the electricity production per month. The energy output data was converted to a normalized performance indicator to complete this analysis, which allowed for the valid comparison of the energy yields of PV systems of various sizes. According to Jahn et al. (2000), one of the most appropriate performance indicators for PV systems is the final yield, Y_F , normalized to the nominal power of the PV array, P_0 .

Final yield, Y_F , is equal to the time which a PV system has to operate with nominal power, P_0 , to generate the useful output energy E_{use} and can be calculated as:

$$\text{Final yield } Y_F = E_{use} / P_0 \quad (1)$$

Where $E_{use} = E_{AC}$ for grid connected PV systems, which is the PV installation's AC power output during the reference period (Häberlin, 2012).

The electricity production per month was divided by the number of days in each month to calculate the average daily E_{AC} . Daily E_{AC} was divided by the number of modules in each installation to calculate daily E_{AC} per module. This value was used to calculate Y_F per day for each PV installation. Additionally, the annual energy output of each PV installation was used to calculate Y_F per year.

Monthly PV potential in Saskatoon, obtained from Natural Resources Canada, was divided by the number of days in each month to calculate the average daily PV potential for each month in 2016 (NRC, 2016). This data provides estimates of the electricity that can be generated by photovoltaic installations in Saskatoon. These values were used to compare the actual performances of the PV installations to the estimated performances.

3. Results

The results from the quantitative analyses outlined in the previous section are presented in two subsections, each presenting the findings which address the specific project objectives. First, the results from the experimental vPV system’s performance as it relates to the white ground cover treatment are presented. The second subsection presents the results from the cross-comparison analysis, which investigated the performance of the experimental vPV system compared to conventionally tilted PV installations.

3.1 Vertical PV system analysis

The nonparametric Kruskal-Wallis (KW) test yielded the following results: chi-squared = 61.241, df = 3, p-value = 3.192e-13. The KW test returned a p-value $\sim 0.00 < 0.05$; therefore, the null hypothesis was rejected, indicating statistically significant differences between the four sets of data (HT, LT, HC, and LC modules) for energy output. The KW test verified that the medians of at least one pair of modules are not equal; however, it did not indicate which pairs are different or rank the productivity of each module based on their median energy output values.

Dunn’s post-hoc multiple comparisons test revealed which pairs of modules are significantly different. The post-hoc analysis results (Table 3) show that in snow-free periods, the energy output from the LT module is statistically higher than that from all other tested modules, whereas the HT module is statistically higher than the HC module and not statistically different from the LC module. Additionally, Table 3 confirms the trend observed in the time series analysis that both high and low control modules (HC, LC) are not statistically different in terms of energy output during summer months.

Table 3. Results of the nonparametric post-hoc Dunn multiple comparison analysis with p-values adjusted with the Bonferroni method to rank the energy output from treatment and control modules (HT, LT, HC, LC) from the tested vPV system with the artificial white ground cover treatment.

Comparison	Z	P-adjusted	Conclusion
HC - HT	-2.7499123	0.0358	HT > HC
HC - LC	-0.4841187	1	No statistically significant difference
HT - LC	2.2657936	0.141	No statistically significant difference
HC - LT	-7.0008985	1.53E-11	LT > HC
HT - LT	-4.2509861	0.000128	LT > HT
LC - LT	-6.5167798	4.31E-10	LT > LC

The largest difference in daily energy output per module was reported between the module closest to the white ground cover, LT, and the HC module, where LT produced on average 16.7% more energy per day (Table 4). The LT module produced an average of 15.7% more energy per day than the LC module. Although both LT and HT were subjected to the same white plastic treatment, the LT module produced 10.7% more energy per day than the HT module. The HT module was 2.88 meters further away from the ground cover treatment than the LT module.

Table 4. Average daily difference in energy output during snow-free months between pairs of modules found to be statistically different from the tested vPV system.

Comparison	Average daily output (Wh)	% Percent difference
LT > LC	959 > 808	15.7
LT > HC	959 > 799	16.7
LT > HT	959 > 856	10.7
HT > HC	856 > 799	6.7

Average daily energy output per month in 2016 was relatively consistent between all modules in winter months, whereas treatment modules produced more energy than control modules in summer months (Figure 6). The sharp decrease in energy output reported in October 2016 is likely due to weather conditions that occurred in Saskatoon during that month, including considerable snowfall and strong wind gusts (ECCC, 2018), both of which are unfavorable for PV energy production. The diverging trend lines of the treatment modules indicate a negative relationship between the impact of the ground cover treatment and the distance between the ground and vPV modules. Modules closest to the white ground cover, labelled LT and MLT (Figure 4), produced more energy than modules further away from the ground, labelled MHT and HT.

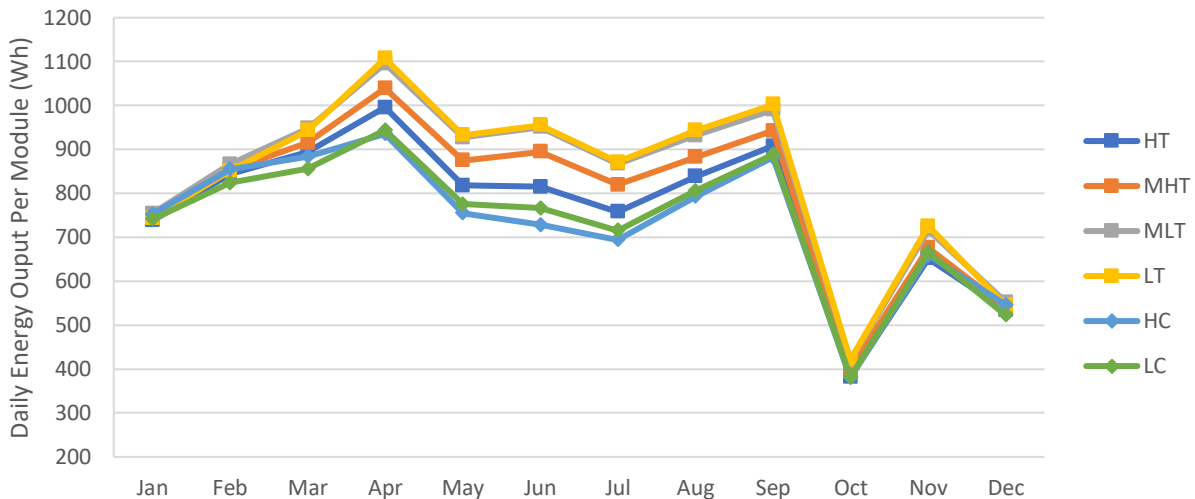


Figure 6. Average daily energy output per module shown for every month in 2016

The time series analysis and results from the statistical analysis indicate that at approximately 2.5 meters from the ground surface, the positive effect of ground cover on the tested vPV modules noticeably diminished. This can be observed as the trend line for LT and MLT basically overlap and a noticeable decrease is reported for MHT and, subsequently, HT. The reported significant difference between the LT and HT modules confirms this trend.

3.2 Cross-comparison analysis between PV installations

The cross-comparison analysis revealed varying performance outcomes from the different PV installations considered. Monthly PV energy output from systems 1 and 2 confirm the trend observed in the time series plot: that the control modules in the tested vPV system and the treatment modules performed similarly in the winter and relatively differently in the summer (Table 5). The cross comparison shows that the normalized final yield is almost identical between the two vPV configurations from October to February. While PV system 1, a vPV system outfitted with white polyethylene plastic as ground cover, outperformed PV system 2, a vPV system with no modifications, in June followed by July, May, April, August, September and March in decreasing order. Based on this analysis, vPV systems operating in a continental climate are expected to produce the most energy in the spring and fall and the least in the winter and summer. Summer production was augmented above winter levels by using a white ground cover treatment adjacent to the vPV modules.

Table 5. 2016 Energy output data from the PV systems listed in Table 2 normalized for final yield per month and annually

ID	Average Final Yield Y_F per Day (Wh/d. W_p)												Annual Y_F (Wh/y. W_p)
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
1	2.87	3.28	3.56	4.07	3.42	3.48	3.19	3.46	3.69	1.56	2.66	2.09	1137
2	2.87	3.23	3.35	3.61	2.94	2.87	2.71	3.07	3.40	1.46	2.55	2.05	1039
3	0.69	1.20	2.10	3.81	4.10	4.65	4.00	3.48	2.61	0.91	0.77	0.35	874
4	1.62	2.12	3.04	5.22	5.16	5.89	5.15	4.63	3.71	1.11	1.96	1.21	1245
5	1.66	2.39	3.28	5.08	4.79	5.50	4.88	4.54	4.09	1.34	2.05	1.39	1249
6	0.27	1.08	2.10	4.06	4.13	4.70	4.09	3.53	2.65	0.70	0.98	0.26	871
7	1.98	2.93	4.05	4.87	4.51	4.83	4.47	4.13	4.14	1.63	2.43	1.93	1277

Table 6 provides estimates of the electricity that can be generated by south-facing PV installations in Saskatoon (NRC, 2016). PV arrays tilted at 52°, the latitude of Saskatoon, and 37° have an approximately equal PV potential, which is nearly 5% higher than PV systems tilted at 67° and 21% higher than the potential for vPV installations. The final yield calculation for most systems show October as the lowest month for energy output in contrast with the PV potential for the region, which identifies December as the month with the lowest PV potential (Table 6).

Table 6. PV potential for south-facing PV systems in Saskatoon.

Tilt	Average PV Potential per Day (Wh/d. W_p)												Annual (Wh/y. W_p)
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
90°	2.94	3.59	3.84	3.20	2.65	2.43	2.55	2.84	2.90	3.10	2.53	2.42	1066
67°	2.94	3.76	4.29	4.13	3.74	3.63	3.74	3.87	3.57	3.42	2.63	2.42	1283
52°	2.74	3.62	4.35	4.47	4.29	4.27	4.35	4.32	3.73	3.39	2.47	2.23	1349
37°	2.39	3.28	4.16	4.60	4.61	4.70	4.77	4.55	3.73	3.16	2.20	1.90	1344

The cross-comparison analysis reported PV system 7 as the highest performing PV system. PV system 7 was a ground-mounted south facing installation tilted at 66°. The observed annual performance was only 0.5% less than the estimated PV potential for a PV installation with a 67° tilt. PV system 7 compares closely with PV system 5, a south facing installation on a flat rooftop rack-mounted at a 35° tilt and regularly cleared of snow, and with system 4, a south facing rooftop installation tilted at 14° and regularly cleared of snow.

The lowest annual performance was reported for PV system 6, a rooftop installation tilted at 40°. This installation was facing 70° east of south and experienced shading from nearby trees. A PV system with a similar tilt, 37°, however, facing south, has a PV potential of 1344 Wh/y.W_p, which is approximately 35% higher than the observed performance of PV system 6. The difference between the performances of PV systems 3 and 6 is less than 1%. System 3 was an east-west rooftop installation tilted at 14° and regularly cleared of snow.

Data for systems 1 and 2 were based on the tested south facing vPV system, which outperformed systems 3 and 6, the only installations in the comparison that were not facing south. System 1, a vPV system outfitted with white plastic as ground cover, performed 6% more than the PV potential estimated for vertical installations. PV system 1 outputted only 9% less energy than the more optimal configuration of system 5, compared to 15% with no ground cover. Table 7 provides a summary of the results of the cross comparison.

Table 7. Summary of the cross comparison of PV installations in Saskatoon in 2016

ID	Specifications		Average Final Yield Y _F per Day (Wh/W _p)		Annual Y _F (Wh/y.W _p)
	Tilt	Orientation	Highest in	Lowest in*	
7	66°	South	Apr 4.87	Dec 1.93	1277
5	35°	South	Jun 5.50	Dec 1.39	1249
4	14°	South	Jun 5.89	Dec 1.21	1245
1	90°	South	Apr 4.07	Dec 2.09	1137
2	90°	South	Apr 3.61	Dec 2.05	1039
3	14°	East & West	Jun 4.65	Dec 0.35	874
6	40°	70° East of South	Jun 4.70	Dec 0.26	871

* This column excludes October (except for 3 and 6) due to the out-of-ordinary weather that was unfavourable for PV performance

4. Discussion

In this section, inferences are made from the results of the data analysis about the effect of artificial ground cover on vertically mounted PV systems. Moreover, the results are used to assess the expected performance of vertically mounted PV systems compared to tilted PV systems, thereby identifying their benefits and limitations. Additionally, this section will explore the possible implications of the findings about vPV systems with regards to sustainable industrial agriculture and building-integrated and building-applied photovoltaics to fulfil the third objective of this project. Finally, future opportunities for research and limitations of this study will be identified.

The performance of any PV system is not independent of ambient factors such as latitude, temperature, precipitation, and other environmental conditions. PV systems considered in this project operated within southern Saskatchewan; therefore, all inferences made from the results are in the context of southern Saskatchewan and analogous regions.

4.1 Using ground cover to enhance the performance of vertical PV systems

According to the results of this study, the type of ground cover was found to have an impact on energy production in vPV systems. This impact can be characterized by different levels of albedo associated with different ground surfaces. These results were reached because other factors impacting PV performance were controlled for, while ground cover surfaces associated with different albedos were reported to impact PV performance when applied selectively to specific modules and seasonally to the entire vPV system.

The results from the time series analysis in Figure 6 show the seasonal effect of albedo. The results of the post-hoc comparison in Table 4 show the extent of influence that artificial white ground cover has on vPV systems. The significance indicated in the results means that the difference between the modules is not attributed to chance and is, in fact, a statistical difference. The factors that influenced the performance of each module resulting in statistical differences were the type of ground cover adjacent to the module and the distance between the module surface and the ground.

The tested vPV system was subject to three types of ground cover, naturally occurring snow, grassland mixed with dirt, and artificial white polyethylene plastic treatment. Specific albedos were not measured for each of the surfaces; however, existing albedo measurements in the literature can be referenced to estimate the albedos of the above surfaces. Coakley (2003) reported the albedo of short grassland as 0.21, and Mehrtash et al. (2013) estimated that the average winter albedo in a snowy region in Canada is 0.8. While there are no records of albedo measurements from white polyethylene grain storage bags, the albedo of white single-ply membrane roofing material containing polyethylene plastic has been reported at values ranging from 0.7 to 0.8 (Bretz, Akbari, & Rosenfeld, 1988). Albedo is not an intrinsic property of a surface but depends on the atmospheric composition and the direction of sunlight, both of which impact spectral and angular distributions of incident solar radiation (Coakley, 2003). Therefore, the albedo measurements referenced from the literature are used only as rudimentary estimates.

Inferences about the influence of albedo from natural ground on vPV installations can be made by examining the results from the pairwise comparison of the high and low modules above the natural ground surface in the experimental vPV system. The lower module reported an average of 1% more energy per day than the higher module. However, this may not confidently be attributed to the surface albedo of grass 0.21 influencing the lower module, as the difference was not found to be statistically significant, meaning it could be due to chance.

The PV module 0.4 meters above the white polyethylene plastic treatment produced 15.7% more energy than the module at the same height above the natural ground. At a higher distance from the ground, the vPV module 3.5 meters above the white polyethylene plastic treatment produced 6.7% more energy than the module at the same height above the natural ground. The significant differences suggest that a 6-meter-wide ground surface with an albedo of 0.7 to 0.8 adjacent to vPV modules will increase energy production from modules up to 3.5 meters away, though at a diminishing rate as the distance increases. This finding is supported by Andrews and Pearce (2013), who reported that albedo has a large impact on the performance of vPV systems due to the large view factor of these systems to their surroundings and high levels of global irradiance. Yoshioka et al. (2002) reported similar results for vPV system performance in winter. The results of the current study indicate that the benefits of high surface albedo on vPV performance were observed in winter months when fresh snowfall occurred and weather conditions were clear. In the current study, all modules in the experimental vPV system performed relatively equally in the presence of snow, which has an estimated albedo of 0.8. This confirms the expectation that vPV systems are favoured in northern climates where snowfall occurs.

Ground surfaces with high albedo levels were found to significantly enhance the performance of vPV systems. The benefits of high surface albedo were observed closer to the ground surface, as opposed to for the higher modules further away from the ground surface. This information can be used to inform decisions on the placement of vPV modules. A landscape placement would maximize the benefits of reflective ground surfaces, as it would place a larger portion of the array surface closer to the ground than a portrait placement.

While the results of the analysis favour installing vPV systems closer to reflective ground surfaces, vPV installations in regions experiencing snowfall should account for the possibility of snow accumulation on the ground blocking the lower end of the PV array and resulting in energy production losses. Unwanted obstruction from snow may be avoided by installing vPV arrays with enough ground clearance for snow to accumulate without covering the modules, as was done for the experimental vPV system in this study.

4.2 Vertical PV systems compared to conventional PV systems in northern climates

Conventional PV systems refer to ground-mounted or rooftop-mounted PV systems that are tilted towards the horizontal plane to capture high amounts of direct sun radiation. The analysis completed in this study compared vPV systems with conventional PV systems of various sizes using a normalized performance indicator to assess the systems based on their final AC energy outputs. The goal of the analysis was to assess how different deployment factors, including horizontal tilt angle and orientation of PV arrays, affected PV performance. Since the results of this analysis were based on actual PV performance data, inferences are made while maintaining

that additional factors, aside from the tilt angle and orientation, may have influenced energy production.

The main reference point for an optimum tilt angle for PV systems is the latitude, where the latitude $- 15^\circ$ is the optimum tilt angle in the summer and the latitude $+ 15^\circ$ is optimum in the winter (Kayal, 2009). Additionally, optimum performance for PV systems in the northern hemisphere is achieved when the tilted PV array is properly aligned with true south (Kayal, 2009). The latitude of the study location is 52° ; therefore, 37° is the optimum tilt latitude in the summer and 67° in the winter.

The deviation from true south impacts PV energy production similarly to tilt angle (Gregg, Parker, & Swenson, 2005). Five of the considered PV installations were oriented towards the south, whereas two installations deviated from the south, one with an east-west orientation, and another with a southeast orientation. The five south-facing systems, including vPV installations, performed higher than the two PV installations that deviated from the south, despite the optimal tilt angle of 40° for the installation with the southeast orientation. In terms of monthly production, the southeast installation demonstrated high performance in the summer. This is likely due to its tilt angle, which is approximately equal to the latitude $- 15^\circ$. However, the same system performed particularly low in the winter, with its energy output 86% lower than it likely would have been had it been facing south. The poor winter performance may be attributed to the deviation from true south; however, it was also likely influenced by snow accumulation on module surfaces and shading from nearby trees.

The actual performance of a south-facing PV system tilted at 66° , approximately equal to the optimal tilt for the winter, was an average of 20% less than the PV potential for November through February. This finding matches previous research by Heidari et al. (2015), which found snow-related losses to range between 5% to 34% a year. However, it does not align with Andrews, Pollard, and Pearce (2013) who reported that snow-related losses were between 1% and 3.5%, although these authors reported more snowfall during their study period than what was reported in Saskatoon for the current study (Wittrock & Dunn, 2016). This disparity may be due to the nature of the current study in which the correlation of energy losses and snow accumulation cannot be confidently made. Additionally, the weather patterns in Saskatoon may have an impact on snow shedding from module surfaces. Andrews, Pollard, and Pearce (2013) reported a weak trend between temperature and snow shedding times where low temperatures correlate with longer shedding times; however, they reported that natural snow shedding from surface PV module surfaces is a complex phenomenon not easily predicted from individual atmospheric variables.

The experimental vPV system was outperformed by conventional PV systems that were facing true south. Previous studies support this finding; however, these studies reported greater energy losses from vPV systems compared to conventionally tilted PV systems. Lin and Jiang (2015) reported that at 1° latitude, vPV systems generated 37% to 51% of the amount of energy generated by conventional rooftop PV systems. Previous research has identified that vPV systems perform better in higher latitude regions. Therefore, at 52° latitude, it was expected that the performance of the vPV systems would surpass that in Lin and Jiang's (2015) study. Suri et al. (2007) reported that vPV systems produced 28% less than optimum angle systems in central

and northern Europe and reported a difference below 20% for northern Sweden and Finland, which are closer to 60° latitude. Results from the current study show smaller differences between vPV systems and conventionally tilted systems. The biggest losses were observed when comparing the tested vPV system with a south facing PV system tilted at the latitude + 14°; the vPV system generated about 17% less energy than the more efficient tilted PV system, and 11% less with the application of the white ground cover surface adjacent to the vPV array.

When comparing the two PV installations regularly cleared of snow and tilted at 35° and 14° with the vPV system, lower energy losses were reported. The vPV system generated approximately 17% less energy than the conventional installations, however, this number decreased to 9% when white polyethylene plastic was used to augment energy production from vPV modules by increasing the ground surface albedo. A difference of 9% between vPV and optimal PV installations is lower than energy losses found in the literature, including results from Suri et al. (2007) and Lin and Jiang's (2015).

An examination of the monthly data revealed exceptionally low PV performances in October 2016. Poor weather was reported for this period, including heavy snowfall and strong winds. Additionally, monthly data revealed that the vPV systems outperformed all conventionally tilted systems from December through February. This is likely due to the negative effects of snow accumulation on PV panel surfaces for horizontally tilted systems and the positive effects of snow albedo that enhance the performance of vertical systems. The winter performance of vPV systems in the current study supports Andrews et al.'s (2013) findings that as PV modules increase their view factor of the snow surface, the ambient albedo improves PV performance, therefore masking snowfall losses when long term averages are taken.

The review of various PV installations reveals that despite differences in orientation and tilt angle, all installations have produced substantial amounts of energy when operating in southern Saskatchewan. The PV installation, which demonstrated the lowest performance, was oriented towards the southeast and affected by shading, yet its yearly energy output surpassed the yearly PV potential reported for Berlin (Kerrwil, 2018), also located at 52°. Nonetheless, the comparison completed in this study demonstrates the potential for increasing PV productivity in southern Saskatchewan. To maximize energy production, specific environmental and structural surroundings should be considered when PVs are installed. As expected, in the current project, the orientation and tilt angle of PV systems influenced their performances. This is particularly true for crystalline PV technologies, which are highly sensitive to the direction of incident solar radiation (Gregg et al., 2005). As the tilt angle of PV systems increases the greater the impact of deviating from true south is on annual energy production (Gregg et al., 2005). Therefore, it is expected that vPV systems will experience higher energy losses if they deviate from the south.

Many conventional PV systems are rooftop installations, which are dictated by the slope of the roof and the orientation of the building. Vertical deployment should be considered if rooftops do not favour optimal PV production (e.g., are not south facing) and if snow accumulation is expected to result in energy losses. The application of high albedo covers on surfaces adjacent to vPV systems makes them more competitive with conventional tilt systems. As the latitude increases, vPV systems are expected to be more efficient; therefore, they may prove to be more viable in regions with higher latitudes such as northern Canada.

4.3 Practical applications of vertical PV systems

A great benefit of PV technologies is their versatility, allowing them to fit seamlessly into our existing infrastructure and economies. The final objective of this project was to identify how vPV systems may benefit local industries and communities, which is done by discussing the findings from this study in the context of local industries. This subsection is divided into two parts: the first part discusses the possible applications of vPV technologies in industrial agriculture; the second part addresses how vPV applications fit into the built environment.

4.3.1 Vertical PV systems for sustainable industrial agriculture

The direct link between this study and industrial agriculture lies in the design and location of the studied vPV installation. The system was located within an agricultural operation, where the vertical wall of an existing agricultural building was used to partially support the vPV system. In addition, the white polyethylene plastic used as high albedo ground cover to enhance PV performance was repurposed from grain storage bags, an industrial agriculture product. This section explores the benefits of PV systems for industrial agriculture in general and the specific benefits and potential applications of vPV systems for industrial agriculture in the context of southern Saskatchewan and analogous regions.

Industrial agriculture is an important part of the economy and culture of southern Saskatchewan and North America in general. Recent decades of progress in industrial agriculture have seen major electrification in all aspects of agriculture. Many agricultural operations rely on intensive electrical equipment and electrified structures such as feed milling equipment, electric egg collecting systems, livestock feeders, refrigeration, electric fencing, milking machines, compressors, and pumps for fish farms, to list a few. With high electrical demands, energy costs are often a burden on industrial agricultural producers, particularly as energy prices and volatility have increased in recent decades (Xiarchos & Vick, 2011). High electricity use also results in large amounts of GHG emissions. In Saskatchewan, the agricultural sector accounts for 24% of all GHG emissions, the second highest emitting sector after the oil and gas industry (Government of Saskatchewan, 2017). As a result of high costs and adverse environmental impacts, renewable energy alternatives are increasingly emerging in agriculture.

The low maintenance requirements for PV energy systems and the abundant supply of solar energy make PV systems a reliable option for on-farm renewable energy. Agriculture hosted some of the first terrestrial PV applications to power solar and remote locations around ranches and farms (Xiarchos & Vick, 2011). Moreover, an increasing number of renewable energy policies have incentivized farmers to deploy solar PV projects in recent years (Navigant Consulting Inc., 2012).

Economic efficiency is essential for the longevity of industrial agricultural operations; therefore, land is generally reserved primarily for revenue generation from crop and livestock production. However, industrial agricultural operations usually include farm buildings and enclosures such as barns, greenhouses, grain storage buildings, water storage structures, as well as a residential dwelling with roads and fencing. Allocating additional land for renewable energy production

from PV systems may not always be possible due to economic constraints and limited land availability. Rooftop PV applications are commonly used as alternatives to ground-mounted systems. However, challenges remain with available roof areas, the direction which the roof faces, and the angle of the rooftop. The vPV installation examined in this study may prove to be a unique renewable energy solution for sustainable on-farm energy generation. Unlike conventional ground-mounted PV systems, vPV systems do not require a large land area for their deployment.

The tested vPV system in this study occupied approximately five square meters adjacent to a preexisting building, whereas a ground-mounted system with the same power rating occupied approximately 98 square meters. A benefit of vPV systems is that, similar to rooftop installations, they can be built on existing infrastructure, using the walls of buildings and enclosures for energy generation and saving on the capital costs associated with PV installations, such as racking and cladding materials (Šúri et al., 2007). Capital costs are a major factor in determining the viability of PV systems. As a result, installing a sub-optimal PV system that produces 20% less energy for 60% of the cost of an optimal installation may be the most desirable option. Because capital costs of vPV systems are often lower than those of optimally tilted systems, a larger vPV system can be installed for the same price as that of a smaller optimal-tilt system, offsetting the 9 to 17% energy loss associated with vPV systems reported in this study and, ultimately, resulting in more energy production over the lifetime of the larger PV installation.

Compared with tilted fixed rooftops or ground-mounted systems, vPV systems do not require regular maintenance to clear snow accumulations from the modules. This feature is appealing to agricultural producers wishing to increase the sustainability of their operation without adding to their work load. As was revealed in this study, for seasonally adjusted PV installations, vertical deployment during the winter may be favourable. When snow was not cleared manually, snow accumulation was observed to reduce PV performance from optimally tilted ground-mount and rooftop installations, therefore, reducing annual energy losses from vPV installations to an average of only 10% when compared to optimally tilted systems. This finding was observed when repurposed agricultural grain storage bags were used as a reflective ground surface treatment adjacent to the vPV installation.



Figure 7. Plastic waste from single-use grain storage bags

Innovative plastic products such as grain bags provide benefits for farmers and ranchers; however, as the industrial agriculture industry continues to grow, plastic waste generated on farms is increasing. Grain bags are commonly used on farms for temporary storage of grain and silage and are designed for one time use only (Figure 7). Each bag weighs between 135 to 315 kg, making their disposal a challenge. Despite regulations which prohibit it, many farmers burn their grain bags (Government of Saskatchewan, n.d.). Burning polyethylene grain bags releases toxic chemicals detrimental to human health and the environment (Government of Saskatchewan, n.d.). As demonstrated in the design of the studied vPV system (Figure 4), grain bags can be repurposed as reflective ground surface cover near a vPV array to significantly enhance energy production. Reducing plastic waste is increasingly becoming a topic of interest for various levels of government and industry. The use of vPV systems in industrial agriculture would provide an opportunity for farmers to reuse some grain storage bags and is a low-cost solution to improving vPV performance. Although using recycled grain bags in vPV systems on farms will have minimal environmental impact as the grain storage bags supplied exceed the potential for using them with PV installations, this solution provides an example for prolonging the usability of single-use plastics. Ultimately, more sustainable innovation is required to adequately address the challenge of plastic waste on farms.

This study examined grid-connected PV systems. However, there are opportunities for off-grid PV systems for on-farm energy production, particularly in areas where outbuildings are not connected to the electrical grid and such connections would be expensive. When long-term outcomes are considered, the benefits of PV systems in industrial agriculture are evident: they do not require fuel and therefore reduce pollution and increase farmers' self-reliance. The cost of PV technologies has been declining over time and is expected to continue declining, making PV applications more economically viable for agricultural operations.

4.3.2 Vertical PV systems as building-applied and building-integrated photovoltaics

Although the focus of this study was not on the integration of PV technologies in existing buildings or on the design of new buildings, the findings about vPV installations can be used to inform the design and development of building-applied photovoltaics (BAPV) and building-integrated photovoltaics (BIPV). BAPV systems involve the installation of PV cells over existing building parts and provide no architectural function to buildings, whereas BIPV systems are the complete integration of PV technologies into the building envelope in which PV cells replace conventional building materials (Kayal, 2009). Much of the literature that has examined vPV systems considers them on building walls and, therefore, as BAPV systems (Kayal, 2009; Lin & Jiang, 2015; Mohammadi & Khorasanizadeh, 2015; Yoshioka et al., 2002).

Since buildings account for 50% of the total energy consumed in Canada, our built environment is a large contributor to GHG emissions (Mousa, 2014). As the world population continues to grow and communities around the world strive to improve their standards of living, the built environment is only expected to expand. With growing efforts to mitigate climate change, the building industry, including developers, engineers, architects, and planners, is seeing advancements towards more sustainable building designs that improve energy efficiency and involve on-site renewable energy production, commonly from PV technologies (Mousa, 2014). Many stakeholders in the building industry in Canada have adopted the Architecture 2030

initiative, which aims for the development of carbon-neutral buildings by 2030 (Architecture 2030, 2010; Mousa, 2014).

Advancements in PV applications now allow for the seamless integration of PV modules into buildings as roofs, walls, skylights, and sunscreen devices. As a result, there is a growing demand for BIPV and BAPV products (Mousa, 2014). The vertical nature of vPV designs make them an ideal candidate for integration with preexisting building walls and future building designs. A section of the vPV system examined in this study is a BAPV, where the wall of a building was used to support PV modules, therefore, allowing the vPV system to overlay the façade of an existing building. This study revealed the impact of altering the surroundings of BAPV façade designs. To artificially increase the ground surface albedo, the surroundings of the studied BAPV (vPV) system were altered by using white polyethylene plastic on the ground adjacent to the building wall. The white ground cover had various levels of influence on energy production at different distances between PV modules and the ground surface. An artificial ground surface with an albedo of approximately 0.8 enhanced energy production by 15.7% when the distance between the vPV modules and the ground was between 0.4 to 2.5 meters, and 6.7% when the distance was between 3.5 to 4.5 meters. The reflective ground surface considered was six meters wide. Adjusting the width of the surface may have an implication on its impact on energy production.

Integrating vPV systems as BIPV components is likely to make them more viable as the initial cost of the PV system is offset by reductions in costs of conventional building materials replaced by BIPV components (Kayal, 2009). The current study sheds light on the influence of albedo on vPV modules, information that can be used by architects to assist in determining what materials and colours to consider when integrating vPV modules into BIPV and BAPV designs. As the building industry becomes more aware of BIPV and BAPV technologies in Saskatchewan and around the world, more information about maximizing the performance of vPV modules as building walls for renewable energy generation will be needed.

4.4 Limitations

Despite the full commitment of the project stakeholders to the robustness of the study design and analysis, there are a number of limitations associated with the methodology and the subsequent results from the analysis. The identified limitations are listed below:

- Data for the analysis were sourced from a number of PV installations deployed over the span of four years. Polycrystalline silicon PV modules degrade by an estimated 0.6% per year (Jordan & Kurtz, 2013). The variation in the performances of the considered PV systems may have been influenced by their respective degradation rates, however to a very small extent. Energy losses due to degradation rates was not captured in the analysis.
- The PV systems included in the cross-comparison analysis in this project were not monitored or observed by the project practitioners. As a result, technical and environmental issues influencing the performance of the PV systems and, subsequently, the results from the analysis may have not been captured.
- The performance of PV systems depends on weather conditions. PV systems considered in the analysis were dispersed across a geographic region with a 30-kilometer radius. As

there were no onsite weather stations used, site-to-site weather variations that may have influenced PV performance were not captured. Rather, historical climate data from a Saskatoon weather station were used to determine important weather trends.

- PV systems with varying sizes and using different PV module models were used in the cross-comparison analysis. Differences in the performances of the PV systems that may have been due to their different models were not captured. A normalized performance indicator was used to conduct valid comparisons.
- The discussion of the results simplified the performance of PV systems to their respective tilt angles and orientation; however, other factors certainly affect PV performance, including shading, inverter defects, cable connections, module defects, and insulation faults (Green Rhino Energy Ltd, 2016).

4.5 Future research opportunities

As is the case with most scientific research, this study provides a number of opportunities for future research and development. As well as enhancing PV performance by using artificial ground cover, future research into vPV systems would be beneficial for the solar electricity industry.

Further experimentation may be conducted in an attempt to replicate this study but with a higher degree of certainty. The actual performance of vPV systems compared to the actual performance of optimally tilted systems can be better understood by implementing an experimental design in which PV systems are deployed specifically for experimental objectives. This proposed experimental design could be done to address some of the limitations listed above.

Further studies could take advantage of the findings from this study to identify different ground cover materials and conduct experiments to assess their impact on vPV performance. In addition, future research may examine the effect of ground cover on various PV installation with different tilt angles.

This project did not consider the economic benefits or limitations of vPV systems. The viability of vPV systems in Saskatchewan and analogous regions can be further understood by conducting a cost benefit analysis that would rank vPV systems amongst other PV installations. Such an analysis may examine performance parameters reviewed in this study, including positive albedo impacts and snow-related energy losses, as well as capital costs associated with each installation.

5. Conclusion and Recommendations

This project centered on demonstrating the actual performance of vPV systems in southern Saskatchewan as it relates to the ground surface cover and its associated albedos. Specifically, the project aimed at quantifying the influence of artificial white ground cover on the electricity output from a vPV system. The use of white polyethylene plastic from repurposed grain storage bags resulted in enhancing the energy output from vPV modules up to nearly 16%. The project also aimed at framing the efficiency of vPV systems in the context of conventionally tilted PV systems in a region prone to snow fall. When outfitted with artificial white ground cover, vPV systems were found to produce between 9% to 17% less energy than optimally tilted PV systems, depending on the tilt angle and snow clearing regimen of the PV systems. Lastly, this project aimed at identifying the potential benefits of vPV systems to local industries. Both the industrial agriculture industry and the building sector were identified as potential industries for vPV applications. vPV systems could play a role in on-farm renewable energy generation and may be integrated in BAPV and BIPV designs.

The implications of this project lie in informing the local solar electricity industry about the possible benefits of vPV systems. In addition, the study addresses PV electricity generation issues in northern regions prone to snowfall and, therefore, addresses the broader PV industry and research community. More general implications of this project align with the United Nations Sustainable Development Goals, namely Goal 7, to ensure access to affordable, reliable, sustainable, and modern energy for all, and Goal 13, to take urgent action to combat climate change and its impacts (UNSDG, 2015). These goals are recognized as global goals that the nations of the world have adopted as a vision for a sustainable future.

The main recommendation from this project is for stakeholders in the solar electricity industry to consider vPV systems as an option for renewable energy generation, particularly in northern regions that experience snowfall and when conditions do not favour optimum PV installations. A summary of the recommendations specific to vPV system deployment based on the findings and the literature reviewed for this project is listed below:

- Where possible, vPV systems should be deployed near ground surfaces associated with high albedos (0.7 - 0.9) or when space is available adjacent to the PV array, outfitted with high albedo ground surface cover, such as white polyethylene plastic. To maximize the benefits of the ground surface albedo, vPV arrays should be installed in a landscape orientation as the positive effects of albedo are observed closer to the reflective surface.
- In regions where snowfall occurs, enough distance between the ground and PV modules should be left as ground clearance to avoid snow-related energy losses.
- Orienting vPV systems towards true south is recommended for their optimal performance. Large deviations from true south have a more significant effect on energy production for PV arrays with larger tilt angles, such as vPV installations.
- Lastly, future research exploring the economics of vPV technologies is needed to better understand the benefits of vPV systems in southern Saskatchewan and analogous regions.

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Appendices

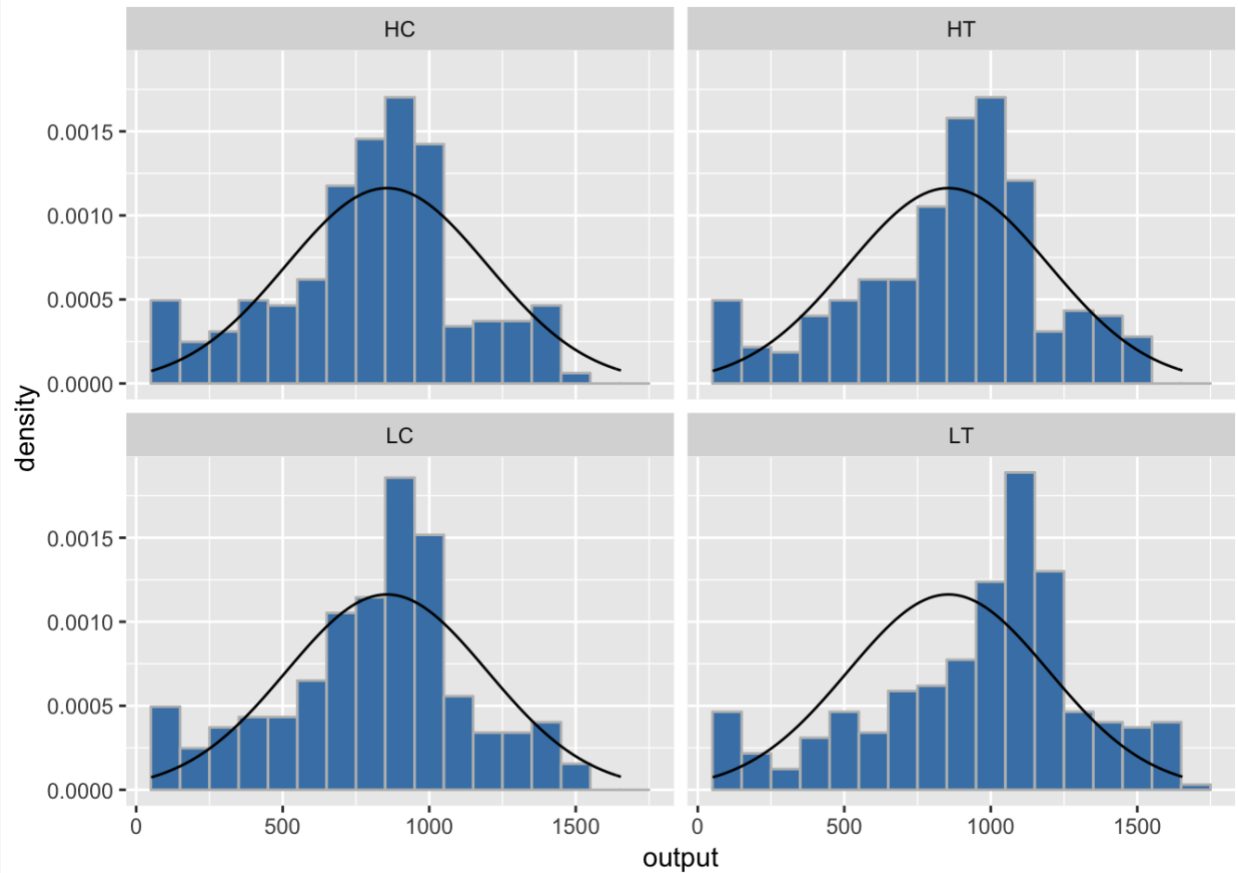
Appendix A: R script for statistical analysis

```
library(dplyr)
library(data.table)
library(reshape2)
library(ggplot2)
library(rcompanion)
library(dunn.test)
library(FSA)
library(MASS)

fullData = fread("raw/verticalpv.csv")

data = fullData %>%
  mutate(day = as.Date(day, "%Y-%m-%d")) %>%
  filter(((day >= "2015-05-15") & (day<= "2015-10-31")) |
         ((day >= "2016-05-01") & (day<= "2016-09-30")))

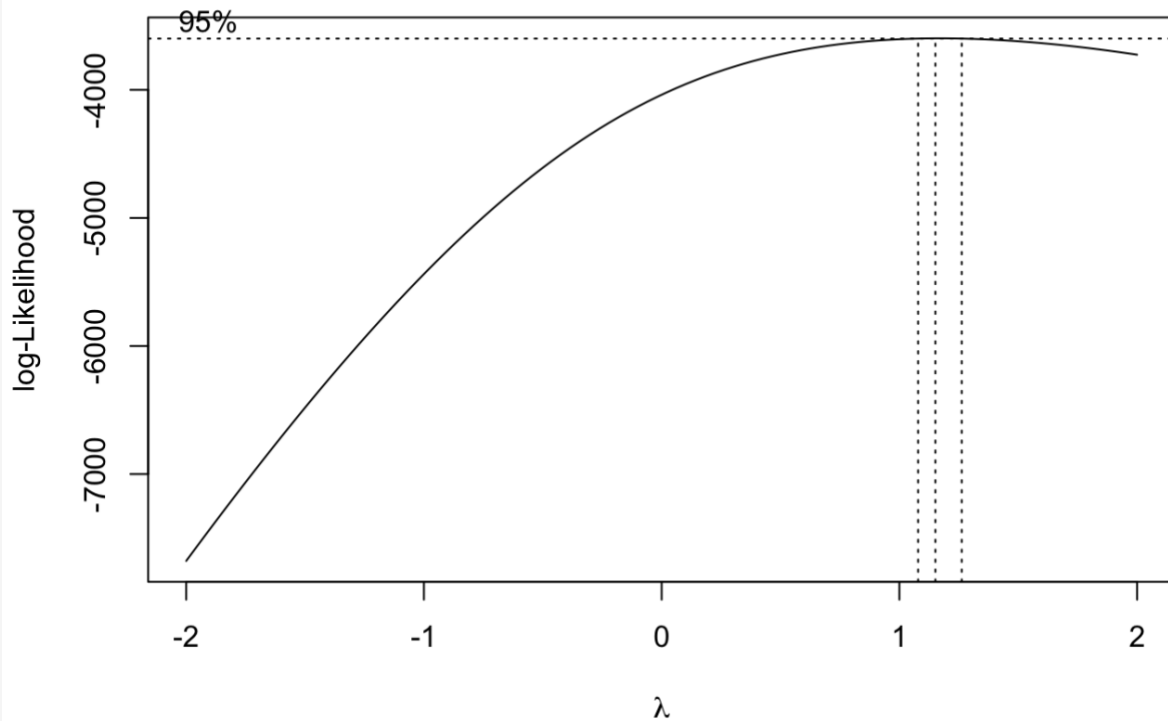
# individual histograms.
ggplot(data, aes(x = output)) +
  geom_histogram(aes(y = ..density..), fill = "steelblue", color = "grey", binwidth = 100) +
  stat_function(fun = dnorm, args = list(mean = mean(data$output), sd = sd(data$output))) +
  facet_wrap(~treatment)
```



```
# test for normality
shapiro.test(data$output)

##
##  Shapiro-Wilk normality test
##
## data:  data$output
## W = 0.97799, p-value = 3.881e-13

# Box Cox transformation
Box=boxcox(data$output ~ data$treatment, data = data)
```



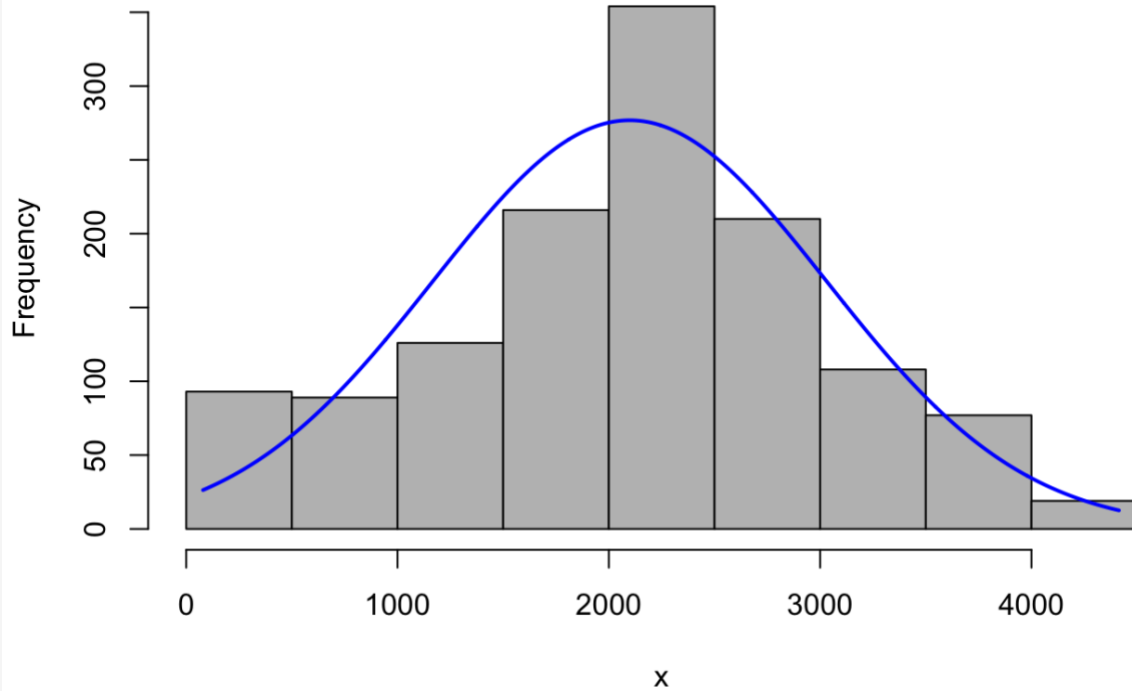
```

# Create a data frame with the results
Cox = data.frame(Box$x, Box$y)
# Order the new data frame by decreasing y
Cox2 = Cox[with(Cox, order(-Cox$Box.y)),]
# Display the lambda with the greatest
Cox2[1,]
##      Box.x    Box.y
## 79 1.151515 -3597.816

# log likelihood
# Extract that lambda
lambda = Cox2[1, "Box.x"]
# Transform the original data
T_box = (data$output ^ lambda - 1)/lambda

plotNormalHistogram(T_box)

```

```
# test for normality (Box Cox transformation)
```

```
shapiro.test(T_box)
```

```
##
```

```
## Shapiro-Wilk normality test
```

```
##
```

```
## data: T_box
```

```
## W = 0.98484, p-value = 2.298e-10
```

```
# Kruskal Test for entire population
```

```
kruskal.test(output ~ as.factor(treatment), data = data)
```

```
##
```

```
## Kruskal-Wallis rank sum test
```

```
##
```

```
## data: output by as.factor(treatment)
```

```
## Kruskal-Wallis chi-squared = 61.241, df = 3, p-value = 3.192e-13
```

```
# pairwise comparison with Dunn's test
```

```
dunnTest(data$output, data$treatment, method="bonferroni")
```

```
## Dunn (1964) Kruskal-Wallis multiple comparison
## p-values adjusted with the Bonferroni method.
## Comparison          Z          P.unadj          P.adj
## 1    HC - HT -2.7499123 5.961121e-03 3.576673e-02
## 2    HC - LC -0.4841187 6.283016e-01 1.000000e+00
## 3    HT - LC  2.2657936 2.346402e-02 1.407841e-01
## 4    HC - LT -7.0008985 2.543262e-12 1.525957e-11
## 5    HT - LT -4.2509861 2.128314e-05 1.276988e-04
## 6    LC - LT -6.5167798 7.183278e-11 4.309967e-10
```

Appendix B: Raw data summary

<p>PV System ID: 1</p> <p>Configuration: wall-mount</p> <p>Tilt: 90°</p> <p>Orientation: south</p> <p>Microinverters: 4</p> <p>Deployed: December, 2014</p> <p>Notes: white plastic ground cover adjacent to array</p>	Month	Total AC output (Wh)
	Jan-16	2980
	Feb-16	3414
	Mar-16	3700
	Apr-16	4237
	May-16	3553
	Jun-16	3616
	Jul-16	3315
	Aug-16	3596
	Sep-16	3842
	Oct-16	1621
	Nov-16	2770
	Dec-16	2173
Total	38817	

<p>PV System ID: 2</p> <p>Configuration: wall-mount</p> <p>Tilt: 90°</p> <p>Orientation: south</p> <p>Microinverters: 2</p> <p>Deployed: December, 2014</p>	Month	Total AC output (Wh)
	Jan-16	1494
	Feb-16	1679
	Mar-16	1740
	Apr-16	1879
	May-16	1530
	Jun-16	1495
	Jul-16	1409
	Aug-16	1598
	Sep-16	1770
	Oct-16	761
	Nov-16	1324
	Dec-16	1069
Total	17748	

PV System ID: 3

Configuration: rooftop

Tilt: 14°

Orientation: east-west

Microinverters: 16

Deployed: July, 2014

Notes: Regular snow clearing off PV array
Shading present from nearby trees

Month	Total AC output (Wh)
Jan-16	89090
Feb-16	144436
Mar-16	270805
Apr-16	475497
May-16	528812
Jun-16	579753
Jul-16	515527
Aug-16	449142
Sep-16	325211
Oct-16	117858
Nov-16	95825
Dec-16	45087
Total	3637043

PV System ID: 4

Configuration: rooftop

Tilt: 14°

Orientation: south

Microinverters: 20

Deployed: November, 2010

Notes: Regular snow clearing off PV array

Month	Total AC output (Wh)
Jan-16	139340
Feb-16	170643
Mar-16	261617
Apr-16	434463
May-16	444127
Jun-16	490246
Jul-16	443378
Aug-16	398203
Sep-16	309048
Oct-16	95558
Nov-16	163052
Dec-16	104120
Total	3453795

PV System ID: 5

Configuration: rack-mount on flat rooftop

Tilt: 35°

Orientation: south

Microinverters: 116

Deployed: August, 2012

Notes: Regular snow clearing off PV array

Month	Total AC output (Wh)
Jan-16	1369016
Feb-16	1850128
Mar-16	2709370
Apr-16	4069937
May-16	3961112
Jun-16	4400384
Jul-16	4034102
Aug-16	3754693
Sep-16	3271432
Oct-16	1111096
Nov-16	1643148
Dec-16	1145809
Total	33320227

PV System ID: 6

Configuration: rooftop

Tilt: 40°

Orientation: 70° east of south

Microinverters: 41

Deployed: August, 2012

Notes: Shading present from nearby trees

Month	Total AC output (Wh)
Jan-16	87780
Feb-16	326621
Mar-16	680947
Apr-16	1274919
May-16	1339115
Jun-16	1472889
Jul-16	1324535
Aug-16	1145172
Sep-16	831831
Oct-16	226874
Nov-16	308040
Dec-16	84958
Total	9103681

PV System ID: 7

Configuration: ground-mount

Tilt: 66°

Orientation: south

Microinverters: 21

Deployed: August, 2013

Month	Total AC output (Wh)
Jan-16	322608
Feb-16	446369
Mar-16	659718
Apr-16	767358
May-16	734000
Jun-16	760293
Jul-16	728156
Aug-16	672619
Sep-16	652100
Oct-16	264972
Nov-16	382668
Dec-16	314554
Total	6705415