Greenhouse Snow Mitigation System

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LETTER OF TRANSMITTAL

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Andrea Scott
Technical Instructor
College of the North Atlantic
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Dear Mrs. Scott:

As required, a technical report was developed of our capstone project. The project has been developed over the course of our final year in the Mechanical Engineering Technology program from September 2020 to present day. The title of the report is Greenhouse Snow Mitigation System.

Developing a system that would mitigate snow buildup on greenhouses proved to be a very involved challenge. A copious amount of research has been done throughout all aspects of the process. This report outlines our process, approach, and findings along the way to our final proposed solution.

This project enabled us to demonstrate the application of skills and knowledge developed throughout the program. We hope this report helps those who may be in need of such a system. We are willing to answer any questions pertaining to the points discussed in the report. The best way to get in contact with us is through our college appointed emails.

Sincerely,

Stefan Abbott

Allyssa Byrne

Riley Yetman

Enclosure

SUMMARY

The project report is broken down into various sections to give the reader a better understanding of the development of the greenhouse snow mitigation system. To begin, an introduction is given to explain where the idea of a greenhouse snow mitigation system was derived from. Outlined in the introduction is the purpose, background on the greenhouse and garden center in Little Rapids, NL, scope of the problem and solution making process, and finally methodology. To follow is the preliminary findings which involves the development of proposed solutions and the final decision-making process where a heated mat was selected for further development. The third section of the report explains the design details of the snow mitigation system. This section delves into the design of a heated mat where an experiment was conducted, along with a heat transfer analysis to demonstrate the effectiveness, followed by the mounting hardware components. The last main section incorporates a cost analysis for the entire system. To finalize the report, concluding thoughts and recommendations are made based on our heated mat design. There are also appendices providing additional information available for readers.

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1.0 INTRODUCTION

Presented in the introduction is the purpose, background, scope, and methodology developed for the report.

1.1 Purpose

The purpose of this technical report is to develop a snow mitigation system designed to protect free standing greenhouses from damages caused by excessive snow loading. The system that was designed to complete this task is a heated auxiliary mat that runs along the sides of the structures. The mat is intended sto prevent excessive snow accumulation on and in between parallel running greenhouses. The loss of a greenhouse causes a great financial setback for these owners and operators, it can cost a facility from $45,000 to $70,000 in replacement costs (Dolter, 2020). Not only is the cost to replace a structure a concern, but also the loss of an operating space causing a slowdown in production. The snow mitigation system itself was designed particularly for an operation located in the West-Coast of Newfoundland and Labrador, where snow clearing is an issue. However, any greenhouse manufactures, owners and operators located in climates where excessive snowfall is present could also benefit from the contents of this report.

1.2 Background

Sean Dolter, the owner and main operator of the Greenhouse and Garden Center, approached the College of the North Atlantic with this problem in 2019. The Greenhouse and Garden Center is a four-greenhouse operation located in Little Rapids, Newfoundland and Labrador (NL). Mr. Dolter, along with other northern greenhouse operators face the possibility of structural damage and or loss as a result of excessive loading caused by copious amount of snowfall and drifting. Greenhouses are typically kept fully assembled throughout the winter months due to start-up times in mid-March (Dolter, 2020). In climates where snowfall amounts are moderate, the snow load often slides off the free-standing structures, gathers at the sides and can be removed to allow further sliding of snow. However, because of the close proximity of the structures at the Greenhouse and Garden Center, this issue becomes much more complex. The layout of their location has two 30 by 60 feet long greenhouses with 5.5 feet of space in between and two 30 by 100 feet greenhouses with 10 feet of space in between. An aerial view of the facility can be seen in (Figure 1). This problem starts in the early winter months; beginning in November, when the greenhouses are no longer being used to grow their produce (Dolter, 2020).

Figure 1: Greenhouse and Garden Center

The Greenhouse. (n.d.). Retrieved from https://www.thegreenhouse.ca/

1.3 Scope

There are some noteworthy challenges that had to be considered and worked around while coming up with a solution. The spacing between the structures are a limiting factor as to what can be implemented or used in the area. Because these are pre-existing structures, there are some design limitations concerning what can be modified or added. It is required that the system implemented could be used and assembled easily on site by greenhouse operators. The report concentrates on the design making process of a snow mitigation system. This includes, preliminary findings, a comprehensive review of the snow mitigation system, a cost analysis, and finally, a conclusion and recommendations. The section of preliminary findings consists of an initial review that breaks down the problem at hand. This is followed up by the decision analysis where a final solution was chosen from a group of options. This section uses forms of K.T analyses to support the findings. The design section discusses in depth, design factors such as heat transfer calculations, electrical specification, and the design assembly. The cost analysis details the capital and running costs associated with the system. The conclusion and recommendations discuss our views and opinions on how the systems should be operated and implemented at the Greenhouse and Garden Center. Topics such as automation of the snow mat has not been covered as this is a topic that has been covered briefly by a student in the Electrical Engineering Technology program.

1.4 Methodology

Research for this project was collected through a variety of primary and secondary sources. One primary source includes interviews via virtual meetings and email with the owner of the Greenhouse and Garden center, Sean Dolter. During these meetings, Mr. Dolter discussed elements such as his greenhouse operation specifications and layout, along with his experiences as a greenhouse owner and operator during the winter season. The meetings also allowed for the sharing of ideas and design possibilities while receiving his professional feedback. Research was also conducted by visiting local greenhouse operations such as Lester's Farm and Rise and Shine Nursery & Garden Care, to get their input on how they mitigate snow buildup. Another primary source includes an experiment conducted on a small-scale greenhouse. Secondary sources include various online platforms such as websites, discussion forums and articles.

2.0 PRELIMINARY FINDINGS

This section of the report delves into the initial review of the problem at hand, followed by the decision analysis conducted.

2.1 Initial Review

Upon consulting with Mr. Dolter, a Kepner-Tregoe (K-T) diagram was completed to break down the problem at hand. The issues related to the greenhouses were broken down into what the problem is, where it occurs, when it is happening, and the extent of the issue.

	IS	IS NOT	Distinction	Possible Cause
What	Greenhouses are Collapsing	Greenhouses are remaining intact	The Greenhouses are at times collapsing	An external force such as weather is the cause for the collapses
Where	Failing on the sides and top of the structures	Failing on the ends of the structure	The Greenhouses are collapsing do to a problem on the sides and top of them	Snowfall loads tend to accumulate between and on top of the greenhouses
When	During/after Snowfall	When no snow is present	Problem only exist during/after a snowfall	The weight accompanied with excessive snow buildup is causing greenhouse collapse
	During the winter months	During non winter months	Problem occurs over winter	The weather during the winter is the cause of the problem
Extent	Effects all northern greenhouse facilities	A one-off problem	Many other greenhouses in northerly areas are experiencing this problem	Harsh winter weather in northerly climates

Table 1 KT Diagram

Upon completion and review of this diagram, it was evident that the reason for collapse is due to excessive snow accumulation along the top and sides of the greenhouses. This problem only occurs in the winter months when snow is present. It was also noted during discussions with Mr. Dolter that snow accumulation between the structures was in fact the most problematic area for these greenhouses. Because all the snow that slides off the roof accumulates in this space, this amounts to heavy loads that could compromise the structure. It was important that a snow mitigation be implemented to reduce loads in these areas of concern.

2.1.1 Heat Required to Melt Snow

The idea of melting snow sounds very simple to many, however, snow melting is complex, and the ability to melt snow varies depending on the design of the system. Additionally, snow comes in a variety of forms, from wet heavy snow to light fluffy snow, therefore the packing density has a dramatic effect on the heat requirements for melting it. For example, 7.5 cm of wet snow is equivalent to 30 cm of dry snow which both equate to 2.5 cm of water (Tesmar, 1995) . Hence, measuring snow by its depth is somewhat meaningless as it does not consider the pack density or weight. Similar to the amount of human energy required to shovel wet snow as compared to dry snow. It is essentially the weight of snow and not the depth that will determine how much heat is required to cause the snow to melt.

To change snow from its solid to liquid state it first begins by raising the temperature to 0°C, achieving a phase change. The specific heat of ice is about 2090 (J/kg C°) and since snow is made up of ice, one kilogram of snow will require around 2090 J/kg to raise its temperature one degree C°. If 20 cm of snow weighs 2.27 kg and is at -5.6 C°, it will take 295.27 kJ /m^2 to melt (Tesmar, 1995). In addition to this, the most significant factor affecting the amount of energy required to melt snow is the energy required to change the water in snow from a solid to a liquid. This phase change is accomplished by adding what is termed "Latent heat of Fusion" to the mass. The latent heat of fusion required for change over ice to water is 335 J/g. This means that on top of the 295.27 kJ /m^2 mentioned above there is an additional 8517.4 kJ /m^2 required meaning a total of 8812.6 kJ /m^2 is required to change 2.27 kg of snow into water.

2.1.2 Polyethylene

The polyethylene used on Mr. Dolter's greenhouses has an ultraviolet coating which holds many benefits, one of which is it reduces the number of living insects in the greenhouse such as whiteflies, thrips, and aphids. The UV coating contains an ultraviolet stabilizer that reduces degradation and can control the formation of fungal diseases that form in greenhouses due to the moist environment. Polyethylene has a warp temperature of 80 C° which is an important consideration throughout our project. (Hosch, 2009)

2.2 Decision Analysis

After some introductory research, there were four alternative solutions that had arose to protect these greenhouses against the snow loads. The first of which was to utilize the greenhouses pre-existing inflation system that is used to inflate the gap between the layers of polyethylene plastic. The idea was to add heated air in between the two plastic layers in order to melt falling snow on the structures entire surface. The second idea was to add extra supports to the frame of the greenhouses, enabling them to bare more load. The third option was to create a heated mat using electric heat trace in one of two configurations. The first configuration was along the sides of the greenhouse, and the second was to place the heated mat inground between the greenhouses. Each of these topics were placed into a decision analysis table (As seen in Table 2) where they were independently analyzed and compared.

Musts Assessment									
Alternative Solution		Mat on Greenhouse		Mat in Ground		Structural Support		Modified Inflation System	
Musts: 1. Provide greenhouse protection		Go		Go		Go		Go	
2. Able to be set up by greenhouse operators		Go		Go		Go		Go	
3. Incorporated to existing structure		Go		No Go		Go		Go	
4. Safe		Go		Go		Go		Go	
Wants	Weight	Rating	Score	Rating	Score	Rating	Score	Rating	Score
Reliability	10	8	80	No Go		9	90	5	50
Effective	10	9	90			6	60	6	60
Capital Cost	8	5	40			6	48	3	24
Operating Cost	7	5	35			7	49	3	21
Maintenance	7	7	49			7	49	4	28
Automated	6	4	24			6	36	4	24
Ergonomic	5	5	25			0	0	4	20
Aesthetically Pleasing	3	3	9			0	0	3	9
		Total =	352	Total=			332	Total =	236

Table 2 Musts Assessment

After evaluating the "Musts" section of this decision analysis, the idea of a heated mat inground along the greenhouses was ruled out. One of the musts was the ability to incorporate the design into the pre-existing structure, however this would not be plausible as the ground between the units would have to be excavated and reconfigured to incorporate heat trace. Three options were remaining. Next the "Wants" section was evaluated. For the modification of inflation system low scores in high weighing sections such as reliability, low operating cost, and low maintenance requirements were assigned due to the fact that heating the air between the plastic was a challenging task. High heat losses through plastic layers, and the fact that small tears are common in these structures proved to be large obstacles for this method. The second highest scoring option was the addition of structural supports. This idea proved hopeful in some categories however the drawbacks were that the addition of supports would impede greenhouse operations and its effectiveness was uncertain. The highest scoring method was the implementation of a heated mat along the sides of the greenhouses. This option proved to be promising as it could be hung from pre-existing rails along the greenhouses and would protect the main area of failure for these structures.

3.0 SNOW MITIGATION SYSTEM

In this section the heated mats were developed beginning with initial design and experiments, then leading into in depth heat transfer analysis and the design of mounting hardware onto the greenhouses.

3.1 Heated Auxiliary Mat

After analyzing the issue at hand, it was found that the main source of failure for these greenhouses was caused by snow accumulation between parallel running structures. Therefore, it was decided to develop a snow mitigation system that would protect this area from failure. The system developed was a multi-layer heated mat constructed of reflective foam insulation and electrical heat trace. The objective of this design is to melt falling snow, ultimately preventing buildup along the sides of the greenhouse. The reflective foam insulation was chosen as it would serve two main purposes. First of all, it would protect the polyethylene that covers the greenhouse from the heat created from the electric heat trace. Secondly, the insulation is enveloped in thin aluminum that will help direct heat away from the greenhouses. Electric heat trace was chosen over alternative heating methods as it provided an even heat source along the surface of the mat. Other systems such as a liquid based system were considered however, due to their complexity was deemed unfit for this application. The use of electric heat also gives opportunity for further development for renewable energy such as solar panels.

3.1.1 Heat Mat Design

These heated mats are to be divided into units that are 20 feet long and 7 feet tall. The reason for this is that these mats are to only be fixed to the greenhouses during the winter months. Keeping them this size allows for easy assembly and disassembly while providing protection the primary failure point of the greenhouses. The Sizing of the mats can be seen in Table 2.

Mat Specifications		
	Imperial	Metric
Mat Lenth	20 ft	6.10 m
Mat Height	7 ft	2.13 m
Surface Area	140 ft^2	13.01 m^2

Figure 2 Mat Specifications

Images of the heat trace, insulation along with a SolidWorks generated model can be seen in figures 3, 4, and 5.

Figure 3: Reflective Foam Insulation

Reflective Foam Insulation. (n.d)
Retrieved from Ebay:
https://www.ebay.ca/

Figure 4: Snow Melt Cables

Snow Melt Cable. (n.d.). Retrieved from
Warmly Yours:
https://www.warmlyyours.com/en-CA

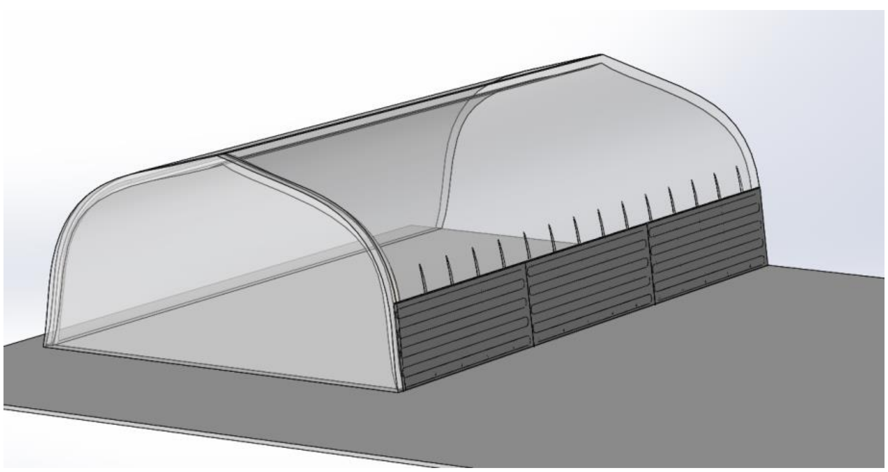

Figure 5 Heated Mat CAD Model (Own)

3.1.2 Small Scale Experiment

In order to verify the feasibility of this design, a small-scale experiment was conducted. To begin, a model of the greenhouses was constructed. Its shape was nearly identical to that of full-scale models as seen in figure 7. Next, a small-scale heated mat was made using reflective insulation and a small heating element. This mat was then mounted to the greenhouse and powered on during a snowfall. The experiment lasted for 3 hours and the total snowfall was 6 cm. However, snow accumulation along the side of the greenhouse was approximately 8 cm due to slight drifting. It is also important to note that the ambient temperature this day was 0°C making the snow very moist and heavy. This type of snow would be considered the most dangerous for greenhouse operators as the increased weight would result in a heavier load on the structures.

Figure 7 Pre-Experiment

Figure 6 Post-Experiment

As seen in figure 6, the experiment was a success, and the heated mat was capable of melting oncoming snow without causing any damage to the model greenhouse. This experiment proved that the design was in fact a plausible solution and was worthy of implementation on a full-scale system. The full report of this experiment can be seen in Appendix B.

3.2 Heat Transfer Analysis

In order to specify the output and spacing required for the heat trace, a heat transfer analysis needed to be performed. The first step of this process was creating a heat transfer circuit for the system. As seen in figure 9 there are six points of thermal resistivity. Three of these include convection from inside the greenhouse (R_6), the air gap in between the layers of polyethylene (R_4), and the outside air (R_1). The other three points include convection through both layers of polyethylene (R_5, R_3) and the layer of insulation (R_2). Radiation was not considered during this study as it is believed that its effects will be minimal when compared to those of convection. It is also important to note that the output of the heat trace is represented by Q_H.

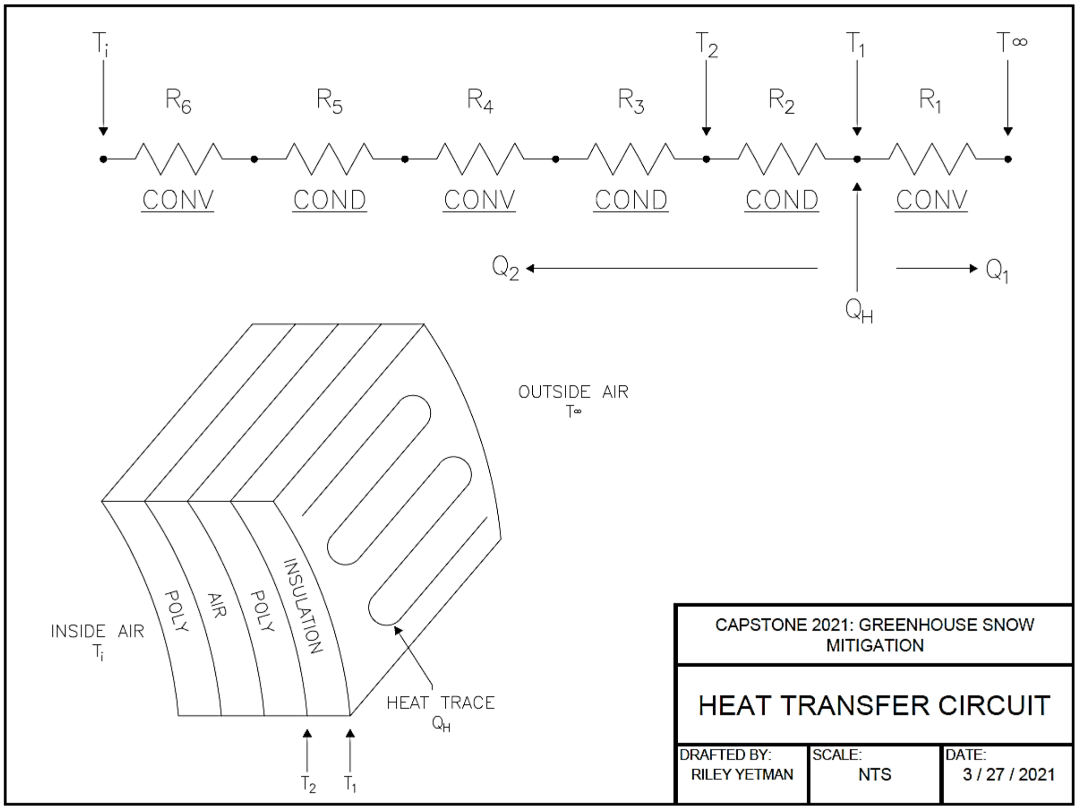

Figure 9 Heat Transfer Circuit

3.2.1 Heat Transfer Calculations

To order to find the thermal resistivity for the layers that undergo conduction, the thermal properties of the foam insulation (R_2) and polyethylene ($R_{3,5}$) (Thermal Properties of Plastic Materials, n.d.) were retrieved from the manufacturer's specifications. These values can be seen in table 4.

Materials		
Polyethylene		
L	0.008	m
k	0.33	W/m*K
Foam Insulation		
R	2.795	m^2*K/W
L	0.006	m
U	0.358	W/m^2*K
ε	0.050	N/A

Table 3 Material Specifications

Using these properties, the thermal resistivity (R) of these materials were found with the following equations.

$$R_2 = \frac{1}{UA}$$

$$R_{3,5} = \frac{L}{kA}$$

Where;

A= Area of heated mat (m^2)

U= Overall Heat Transfer Coefficient (W/(m^2*k)

K= Thermal Conductivity Constant (W/m*k)

L= Thickness of Material (m)

Next, the thermal resistivity needed to be found for the air located in the greenhouse, the gap between layers of polyethylene, and outside. To do this, the convection heat transfer coefficient for each space was found using the following formula (Convective Heat Transfer, 2003).

$$h_{air} = 12.12 - 1.16v + 11.6v^{1/2}$$

Where;

h_{air} = convection heat transfer coefficient (W/m^2*k)

V = air velocity (m/s)

For this calculation, the air velocity's differed in each area. For outside air a velocity of V_{ao}=33.33m/s was used as this represented worst case scenario 120km/hr wind gusts during a storm (Banfield, 1998). For the air between layers of poly V_{ab}=3.3m/s was used as this represents the small air flow introduced by the inflation system (Harnois Industries , n.d.). Finally, inside the greenhouse V_{ai}=1m/s was assumed as there is little to no air circulation inside the greenhouse over winter months. The results are displayed below in table 5.

Air Properties		
Air Between Poly		
k	0.024	W/m*K (0 deg)
h_{air} =	30.68	W/m^2*K
Air Inside Greenhouse		
k	0.024	W/m*K (0 deg)
h_{air} =	22.56	W/m^2*K
Air Outside		
k	0.024	W/m*K (0 deg)
h_{air} =	40.43	W/m^2*K

Table 4 Air Properties

These calculated values were then entered into the following formula to calculate their thermal resistivity.

$$R_{1,4,6} = \frac{1}{ha}$$

The following table displays the results for the thermal resistivity of each layer and their accumulated total for the whole system.

Thermal Resistivity		
R_1 =	0.3217	W/k
R_2 =	0.2149	W/k
R_3 =	0.0019	W/k
R_4 =	0.4239	W/k
R_5 =	0.0019	W/k
R_6 =	0.5765	W/k
R_{total} =	1.5408	W/k

Table 5 Thermal Resistivity Values

The next step to the analysis was to calculate the heat transferred (Q_H) from the electric heat trace. The output of the heat trace is 12 W/ft. However, the watts over the surface are (W/ft^2) dependent on the spacing between each run of cable. The heat trace manufacturers provide the W/ft^2 for three, four, and five-inch spacings. These values were then plotted and an exponential trendline was produced. An exponential function was chosen as it is known that the relation of heat trace spacing to W/ft^2 is not linear. As spacing becomes larger, the output of the heat trace decreases with a non-liner rate. The graph of this data can be seen in figure 10.

W/ft to W/ft²	
Spacing (Inches)	W/ft²
3	47.1
4	35.3
5	28.2

Table 6 Manufacturer Specifications

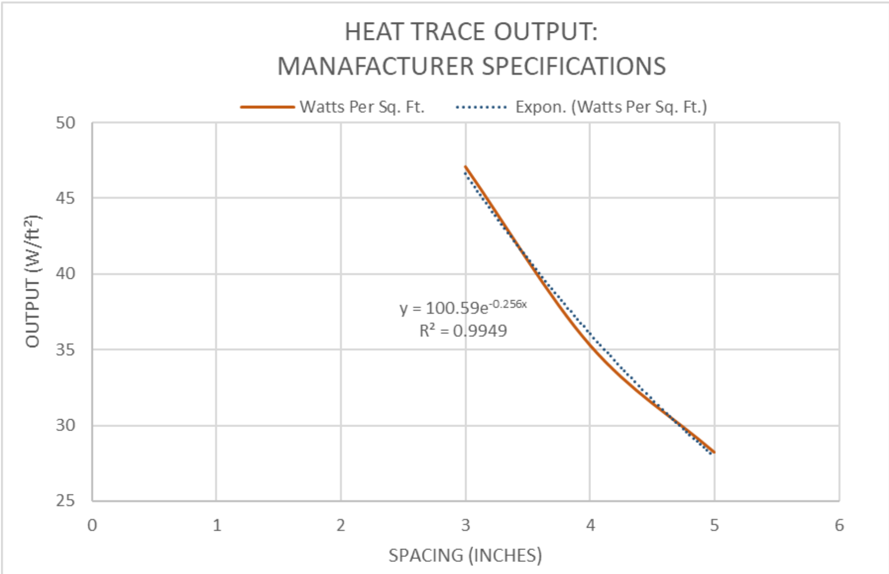

Figure 10 Manufacturer Specification Graph

Once the exponential function was found ($y = 100.59e^{-0.256x}$) the output for three to twelve inch spacing was calculated and plotted accordingly in figure 11.

Heat Trace Output (Exponential)	
Spacing (Inches)	W/ft²
3	46.67
4	36.13
5	27.97
6	21.65
7	16.76
8	12.98
9	10.04
10	7.78
11	6.02
12	4.66

Table 7 Heat Trace Output

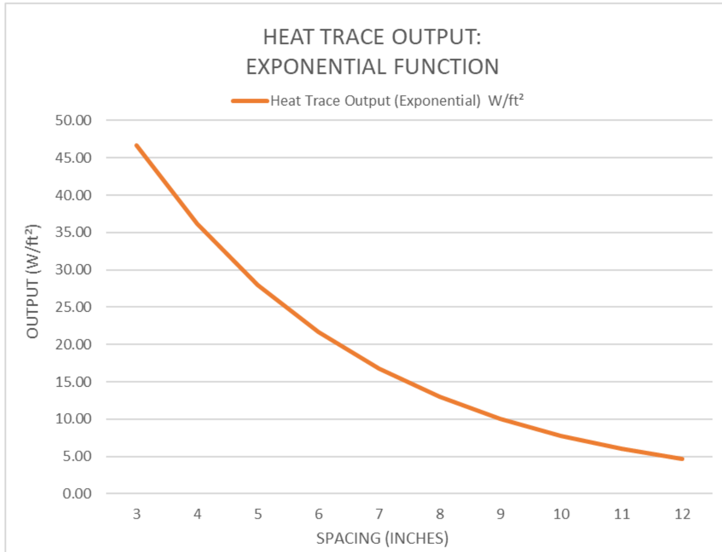

Figure 11 Exponential Graph

In order to utilize these values in the analysis, all units needed to be convert to metric. A series of different spacings were converted accordingly (Table 9).

Heat Trace Spacing	Linear Output (W/ft)	Linear Output (W/ft)	Surface Output (W/ft²)	Surface Output (W/m²)
12 Inches	12	39.37	4.66	50.16
11 Inches	12	39.37	6.02	64.80
10 Inches	12	39.37	7.78	83.70
9 Inches	12	39.37	10.04	108.12
8.5 Inches	12	39.37	11.42	122.89
8 Inches	12	39.37	12.98	139.67

Table 8 Heat Trace Spacing

From these results it was possible to find the desirable values. These included the heat transfer from the mat outwards to the snow (Q_1), the heat transferred into the greenhouse (Q_2), the surface temperature of the mat (T_1), and the temperature between the mat and outer layer of polyethylene that covers the greenhouse (T_2). Sample Calculations of this procedure can be found in Appendix C. The values for Q_1, Q_2, and T_1 were found with the following formulas.

$$Q_h = Q_1 + Q_2$$

$$Q_1 = \frac{T_1 - T_\infty}{R_1}$$

$$Q_1 = \frac{T_1 - T_i}{R_{2,3,4,5,6}}$$

The value for T_2 was then calculated using;

$$T_2 = T_1 - (R \cdot Q_2)$$

The first analysis was done with a twelve-inch spacing between each run of heat trace. The results of this study can be seen in table 10.

Heat Transfer Analysis #1				
12'' Spacing				
R_1 =	0.3217	W/k		
R_2 =	0.2149	W/k		
R_3 =	0.0019	W/k		
R_4 =	0.4239	W/k		
R_5 =	0.0019	W/k		
R_6 =	0.5765	W/k		
R_{total} =	1.5408	W/k		
T_1 =	7.99	°C	281.14	k
T_2 =	9.22	°C	282.37	k
T_∞ =	-10	°C	263.15	k
Ti =	15	°C	288.15	k
Q_h =	50.162	W/m^2		
Q_1 =	55.913	W/m^2		
Q_2 =	-5.751	W/m^2		
h_{air} =	40.426	W/m^2*K		

Table 9 Heat Transfer Analysis #1

After completing this, the surface temperature (T_1) in these conditions is found to be 8°C. This temperature output is capable of melting snow as it is above freezing, however, a higher temperature would be more desirable. Multiple different spacings were analyzed and the most suitable was eight and a half inches of spacing. The results of this analysis can be seen in table 11.

Heat Transfer Analysis #2				
(8.5'' Spacing)				
R_1 =	0.322	W/k		
R_2 =	0.215	W/k		
R_3 =	0.002	W/k		
R_4 =	0.424	W/k		
R_5 =	0.002	W/k		
R_6 =	0.577	W/k		
R_{total} =	1.541	W/k		
T_1 =	26.50	°C	299.65	k
T_2 =	24.47	°C	297.62	k
T_∞ =	-10	°C	263.15	k
Ti =	15	°C	288.15	k
Q_h =	122.89	W/m^2		
Q_1 =	113.45	W/m^2		
Q_2 =	9.43	W/m^2		
h_{air} =	40.426	W/m^2*K		

Table 10 Hat Transfer Analysis #2

At this spacing, the surface temperature (T_1) at these conditions is 26.5°C. This temperature was deemed acceptable and would provide sufficient snow melting. The temperature between the outer polyethylene layer and inside of the insulation (T_2) was calculated to be 24.5°C. This temperature is safe and will not damage the polyethylene. The final step to this analysis was to evaluate the temperatures at two extremes to find the range at which they would vary. First, a study was done as if the inside of the greenhouse temperature reached 30°C, with an outside temperature of 0°C and winds of 40km/h. These conditions are not very likely but would represent the highest temperature achievable by the mat at this spacing. Next, a study was done as if the inside of the greenhouse temperature was -10°C, with an outside temperature of -15°C and winds of 120km/h. These conditions are too, not likely, but replicate a worst-case scenario storm. The results are as seen in Table 11.

Heat Transfer Analysis (Low Range)				
(8.5'' Spacing)				
R_1 =	0.321	W/k		
R_2 =	0.215	W/k		
R_3 =	0.002	W/k		
R_4 =	0.424	W/k		
R_5 =	0.002	W/k		
R_6 =	0.577	W/k		
R_{total} =	1.540	W/k		
T_1 =	17.29	°C	290.4	k
T_2 =	12.48	°C	285.6	k
T_∞ =	-15	°C	258.2	k
Ti =	-10	°C	263.2	k
Q_h =	122.89	W/m^2		
Q_1 =	100.50	W/m^2		
Q_2 =	22.39	W/m^2		
h_{air} =	40.48	W/m^2*K		

Heat Transfer Analysis (High Range)				
(8.5'' Spacing)				
R_1 =	0.344	W/k		
R_2 =	0.215	W/k		
R_3 =	0.002	W/k		
R_4 =	0.424	W/k		
R_5 =	0.002	W/k		
R_6 =	0.577	W/k		
R_{total} =	1.563	W/k		
T_1 =	39.55	°C	312.7	k
T_2 =	37.87	°C	311.0	k
T_∞ =	0	°C	273.2	k
Ti =	30	°C	303.2	k
Q_h =	122.89	W/m^2		
Q_1 =	115.05	W/m^2		
Q_2 =	7.84	W/m^2		
h_{air} =	37.83	W/m^2*K		

Table 11 High and Low Range Analysis

The outside temperature (T_1) has an approximate range of 17.3-39.6°C, and the inside temperature (T_2) ranges from 12.5-37.9°C.

3.2.2 Heat Transfer Summary

Upon completion of the heat transfer analysis several conclusions were made. The ideal spacing for the heat trace is eight and a half inches producing a surface output of 122.9 W/m^2. Additionally, this configuration is capable of producing a surface temperature of 17.3 – 39.6°C and an inside temperature ranging from 12.5 – 37.9 °C. This design proved to be superior as it provided adequate surface temperature for snow melting and did not risk damaging the greenhouses. With these findings, the physical design and factors such as the amount of heat trace required to produce each mat can be configured accordingly.

Heat Transfer Summary				
	Heat Trace Spacing (Inches)	Surface Output (W/m^2)	Surface Temperature (°C)	Inside Temperature (°C)
Symbol	N/A	Q_h	T_1	T_2
Value	8.5	122.9	17.3 - 39.6	12.5 - 37.9

Table 12 Heat Transfer Summary

3.3 Mounting Hardware and Implementation

During the project design phase, several installation concerns needed to be addressed. The greenhouses are not typically equipped with external mounting features. This proved to be a challenge for installing our new modification features. Additionally, weight of the mat equipped with all necessary hardware had to be considered. On the exterior of the greenhouses, a narrow aluminum 1.125” wide channel runs the length of the structure, as seen in Figure 13. It serves as the joint for securing the poly to the structure. A wiggle wire is fed into the channel to hold the poly in place (Figure 12). This design tensions the poly preventing it from slackening. The wiggle wire serves a vital purpose; however, it creates an obstructing in the channel which affects mounting capability. Since this channel is the only mounting surface available, it is necessary to be used for attaching the mat.

Figure 13 Channel on Exterior Walls of Greenhouse

Figure 12 Wiggle Wire in Channel

3.3.1 T-Slot Nut

Mounting the heated mats to the greenhouse channel required a mount which would compensate for the wiggle wires obstruction. After assessing available T-slot nut options, supplier options did not meet the dimensions and profile required for the channel. Therefore, custom designed T-Slot nuts were deemed necessary.

The objective for the custom design was to create a way to overcome the interference caused by the wiggle wire. A T-slot style nut was modified on one end to allow the nut to be rotated into position without contacting the wiggle wire. This design functioned well and is aesthetically pleasing. The nuts are spaced 2 feet apart requiring 10 clips per mat. The custom design nuts were developed using SolidWorks modeling and prototypes were created using Fused Deposition Modeling (FDM), a form of 3D printing. The printed parts functioned flawlessly when assembled on a 3D printed channel scaled to the actual greenhouse at a reduced length. Since these nuts are not subjected to extreme loads and the maximum weight of the mat is 10lbs, these parts could be manufactured using low grade aluminum. This part can be produced at a high rate and a very low cost while obtaining satisfactory mechanical properties.

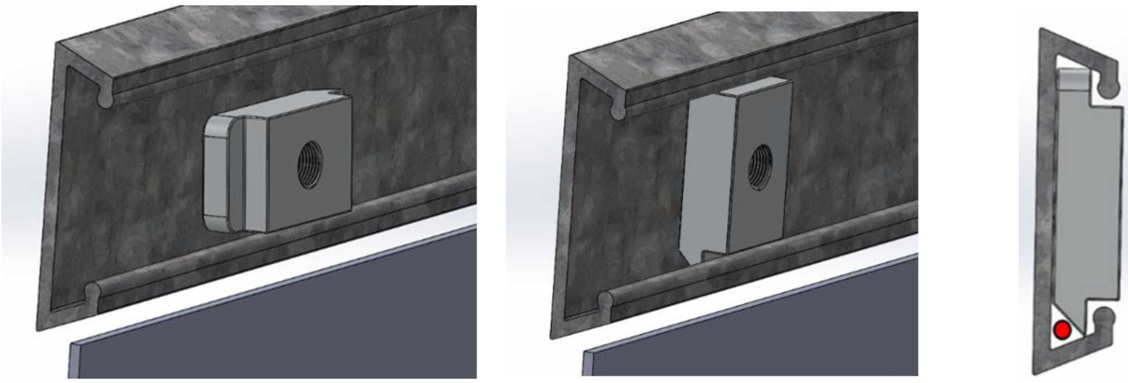

Figure 14 Installation of Custom T-Slot Nut (Own)

3.3.2 Mat Clip

A custom design mat clip was created for mounting the heat trace mat to the T slot nuts. The clips are attached to the mats prior to installation, then mounted to the T-slot nuts. These clips allow for easy installation, with a sleek appearance. The clip is fastened using a screw which threads into the T-slot nut, see Figure 15. When the screw is tightened it brings both parts together against the channel, preventing shifting. An aluminum rivet is also used as a fastener for mounting the mat to the clip, ensuring a long-lasting connection.

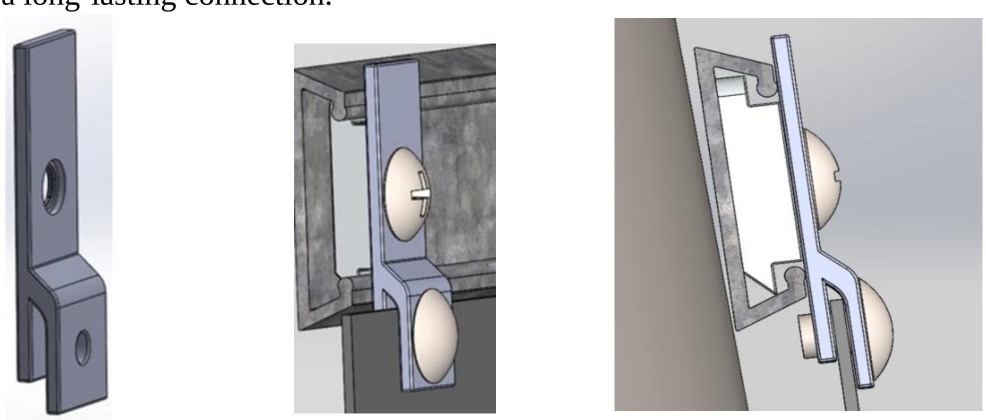

Figure 15 Mat Clip (Own)

3.3.3 Cable Clip

Cable clips are utilized to affix the heat trace cable to the insulating material. Design considerations for this application were the clip needed to be unaffected by temperature variations while providing a firm hold on the cable, and most importantly durability under harsh conditions. Through our research, we discovered a wide range of suitable cable clips for this application. However, simple steel brackets, shown in Figure 16, were deemed ideal for this application since they provide a strong hold on the cable while preventing it from buckling or deviating out of line. The aluminum design provided durability against harsh weather conditions and are affordably priced. Similar to the mat clip, the aluminum rivet fastener provides a stronger application than screws.

Figure 17 Manufactured Cable Clip (Grizzly Shelter Ltd., n.d.)

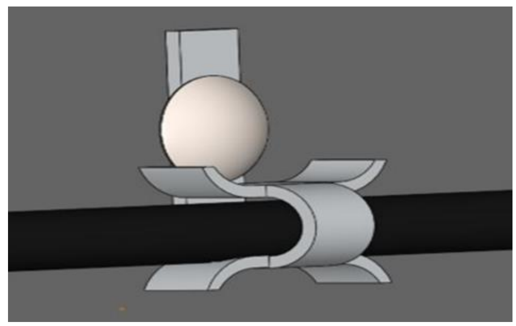

Figure 16 SolidWorks Cable Clip Model (Own)

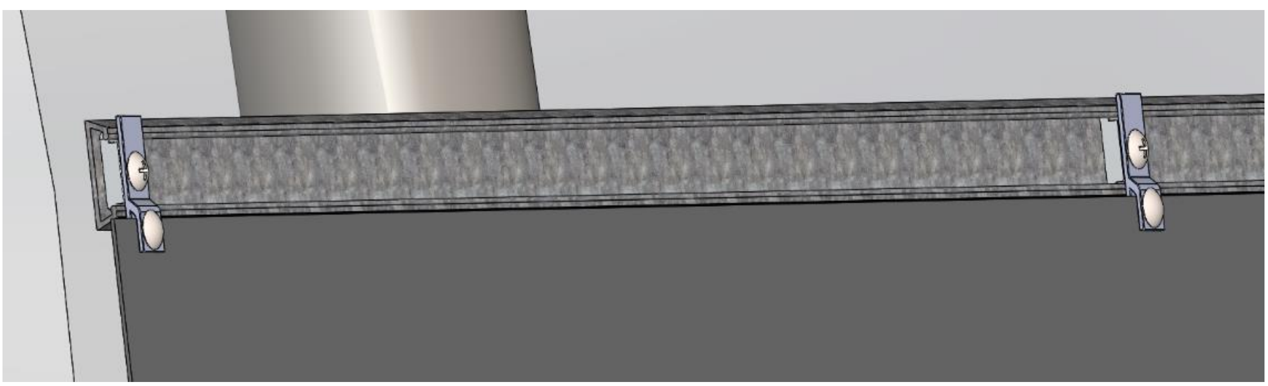

Figure 18 Cable Clip Attached to T-Slot Nut (Own)

Figure 19 shows 3D printed components for all the mounting hardware which was created to verify its functionality. The mats are easy to install and fully transferable to other greenhouse units. At the onset of the winter season the mats can be installed onto the greenhouse for snow control. At the end of winter, the mats can be removed, rolled up and packed away for next season. Future system development could incorporate a source of renewable energy such as solar or wind power to supply system power, as previously mentioned.

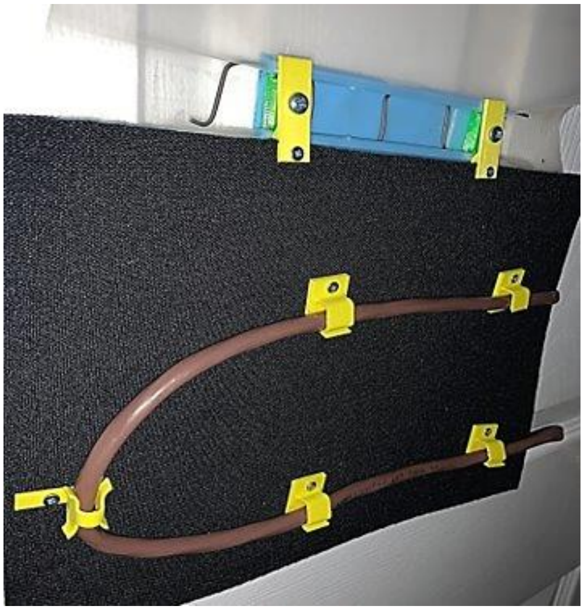

Figure 19 3D Printed Model of Mounting Hardware (own)

4.0 COST ANALYSIS

A comprehensive capital and running costs associated with the heated mats is provided. An evaluation was also completed to determine the investment value of the design.

4.1 Capital Costs

For capital cost determination for each heated mat, the cost of heat trace, insulation, and mounting equipment were considered. The first step to this was to determine how much of each material is necessary. Each mat is sized at 20’ long and 7’ tall, a breakdown of material for this size mat can be seen in Table 13. It is also important to note that if each exterior wall of the greenhouse has a mat installed, 32 mats will be needed. This section will be provided using imperial units as this is the unit system used by manufacturers.

Materials List					
	Insulation (LxH) (ft)	Heat Trace (ft)	Cable Clips (Qty)	Custom T-Slot Nut (Qty)	Mat Clip (Qty)
Per Mat (20'x7')	20x7	180	108	10	10
Total (32 Mats)	640x7	5760	3456	320	320

Table 13 Materials List

The cost for the mounting hardware considered all necessary components for mounting the cable to the mat, and the mat to the greenhouse. This consisted of the cable clips, Custom T-Slot Nuts, mat clips and all the additional hardware such as rivets and screws. Prices for cable clips were estimated based on those found in home improvement vendors. The custom designed T-Slot nuts and mat clips were priced off average 3D printing cost. The additional hardware was priced by the average cost of a singular rivet and screw. The prices and screenshot of mounting hardware configuration can be seen in Table 14 and Figure 21.

Mounting Hardware				60 ft Greenhouse		100 ft Greenhouse	
	Qty/mat	Cost Per Unit ($)	Cost Per mat ($)	Qty of Mats	Cost Per Greenhouse ($)	Qty of Mats	Cost Per Greenhouse
Cable Clips	108	0.4	43	6	259	10	432
Custom T-Slot nuts	10	1	10	6	60	10	100
Mat Clip	10	1	10	6	60	10	100
Hardware	128	0.1	13	6	77	10	128
Total			**$76**				**$2,432**

Table 14 Mounting Hardware

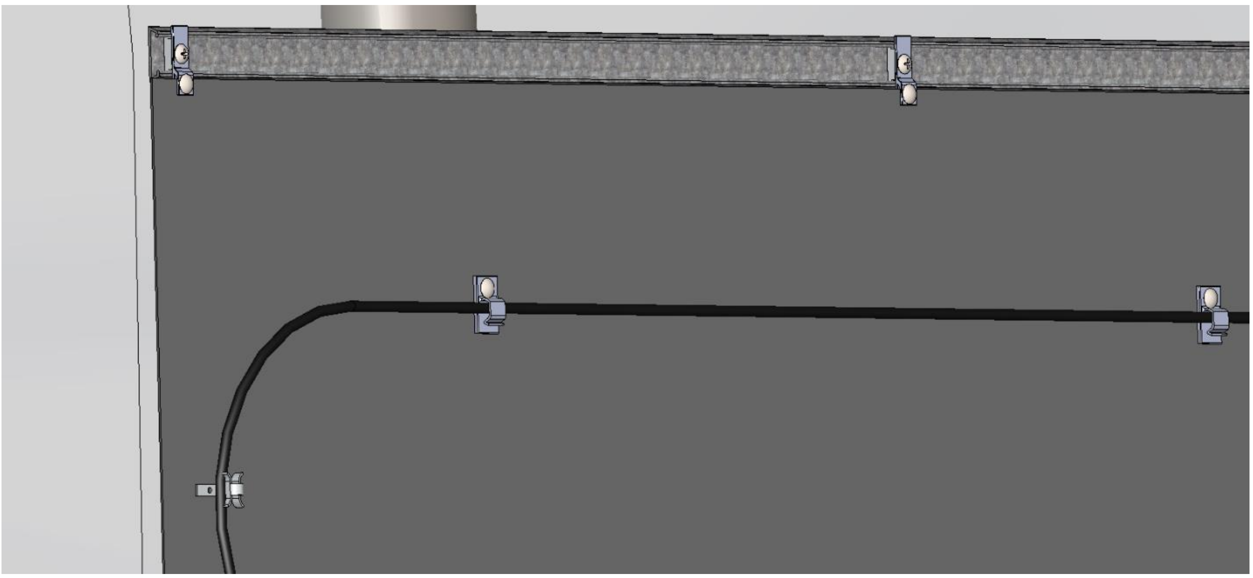

Figure 20 Mounting Configuration

Once the quantity of materials was known, the capital cost could be estimated. Pricing was gathered from various sources that will be noted within reference areas. A tax rate of 15% and an estimated labor cost was applied to the accumulated total. It was assumed that each mat would take approximately one hour to assemble at a rate of $75 per hour.

Cost Estimation							
	Price per foot ($/ft)	Heat Trace Cost ($)	Insulation Cost ($)	Handwear Cost ($)	Materials Total ($)	Assembly Cost ($)	Grand Total
Per Mat	2.38	428.4	130	76	729.56	75	$805
Total Cost (32 Mats)	2.38	13708.8	4160	2432	23345.92	2400	$25,746

Table 15 Total Cost Estimation

4.2 Operating Costs

Another factor that needed to be considered is the operating cost of the heated mats. It is assumed that these mats are to be connected to the pre-existing electricity supply. In order to determine this cost, an electrical analysis needed to be performed on the system. Considering that there is 180 feet of heat trace on each mat, at an output of 12 Watts per foot an analysis was performed accordingly (Table 16).

Electrical Analysis					
	Voltage (V)	Output (W/Ft)	Power (W)	Power (kW)	Current (A)
Per Mat	240	12	2160	2.16	9
Total (32 mats)	240	12	69120	69.12	288

Table 16 Electrical Analysis

The total power consumption for each mat is 2.16 kilowatts, and for the whole system is 69.12 kilowatts. To estimate energy costs, these findings needed to be converted to kilowatt hours. Since the heated mats are only operational during snowfalls, annual runtime needed to be estimated. To do this, data was gathered from Environment Canada regarding the number of days in a month which there are snowfalls equal to or greater than five centimeters (CCN, 2010). It was than estimated that this system would need to be operational for 10 hours per snowfall. This seemed fitting as some smaller weather systems may only need 6 hours of protection while others require upwards to 14 hours. This data was then summed over six months and resulted in an estimated run time of 255 hours per year (Figure 17).

Snow Patterns		
Month	Snow Days >= 5cm (Per Month)	Estimated Run Time (hrs)
November	2.7	27
December	6.8	68
January	7.9	79
February	5.4	54
March	3.8	38
April	1.6	16
Total	25.5	255

Table 17 Snow Patterns

This run time was then multiplied by the power outputs to find kilowatt hours, then multiplied by the average electricity rate in Newfound and Labrador this being 13.2¢/kWh (Newfoundland Power, 2021). The cost per mat is estimated at $72.71 annually, while the total for all 32 mats is $2326.58 per year. Mr. Dolter is already connected to local power supply therefore it was assumed that there would be no upfront costs. A breakdown can be seen in figure 18.

Operating Cost					
	Power (kW)	Runtime (hrs)	Energy Consumption (kWh)	Electricity Rate ($/kWh)	Annual Cost
Per Mat	2.16	255	551	0.132	$72.71
Total Cost (32 mats)	69.12	255	17626	0.132	$2,326.58

Table 18 Operating Cost

4.3 Costs Summary

After completing the cost analysis, the combined capital and annual cost for the first year of operation can be seen in table 19.

Costs Summary			
	Capital Costs	Annual Cost	Total
Per Mat	$805	$72.71	$877
Total (32 Mats)	$25,746	$2,327	$28,072

Table 19 Cost Summary

Once the costs had been calculated a Return on Investment (ROI) study was completed to evaluate financial feasibility. For this study, it was assumed that the heated mats had a life span of 15 years. Because the risk of losing a greenhouse is completely unpredictable the study was completed under 4 scenarios. The first ROI was calculated for one structure collapse in 15 years, for the second study two structure losses, for the third study three structures losses, and for the fourth study four lost greenhouses. The cost to replace greenhouses vary from $45,000 - $70,000 (Dolter, 2020) therefore an average of $57500 was used. The outcomes are located on table 20.

Return On investment						
Graanhouse Price ($)	Structures Lost (Qty)	Cost of structure failure ($)	Capital Cost ($)	Operaing Cost over 15 years ($)	Total Investment ($)	ROI (%)
57500	1	57500	25746	34899	60645	-5.2%
57500	2	115000	25746	34899	60645	89.6%
57500	3	172500	25746	34899	60645	184.4%
57500	4	230000	25746	34899	60645	279.3%

Table 20 Return on Investment

This ROI analysis concluded that if only one structure is lost over 15 years the system is not feasible. However, if two or more structures are lost over this time frame the system will result in large savings for Mr. Dolter.

5.0 CONCLUSION

Based on the snow accumulation problems experienced by Mr. Dolter along with other northerly greenhouse operators, a snow mitigation system was necessary. During the initial phases of this project, the problem itself was analyzed with the help of Mr. Dolter and other local greenhouse operators. The problem was then pinpointed to a main area of concern; this being the area between parallel running structures. Once this was complete, a number of alternative solutions were explored until the heated mat was deemed superior. Initial development of the heated mat began with a small-scale experiment that aided to determine the potential effectiveness of the system. Next, a heat transfer analysis helped to determine the amount of heated cable needed to meet the snow melting requirements. With this information, a mounting system was developed for the mats, and modeled accordingly. Finally, a cost evaluation was conducted along with a return-on-investment study for the system as a whole. All in all, it is strongly believed that the snow mitigation system developed in this report could indeed serve as an asset for Mr. Dolter and other northerly greenhouse operators.

6.0 RECOMMENDATIONS

Based on our conclusions our team recommends the following to Mr. Dolter. Firstly, develop and implement this snow mitigation system in the most problematic areas of his establishment. This would be between the two 60 feet greenhouses which are placed at five and a half feed apart (Figure 22). Six mats should be installed in this space and their effectiveness should be analyzed. If the heated mats perform properly and provide greenhouse protection, then expansion may be considered to all other sides. Because this type of product has never been used in this style of application, it is anticipated that design parameters may need to be altered upon installation.

Figure 21 60ft Greenhouse (Ryan, 2021)

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Appendix A

Draft Proposal

Memorandum

To: Andrea Scott & Trevor Moss, Instructors, College of the North Atlantic

From: Stefan Abbott, Allyssa Byrne & Riley Yetman

Date: October 26, 2020

Re: Draft Proposal 1: Snow Mitigation

Thesis

The project details the development of a snow loading mitigation system applicable to greenhouse structures. These structures being studied are located on the West Coast of Newfoundland where the average snowfall is four meters. Snow accumulation on greenhouses can lead to structure damage and potential collapse leading to negative effect on business operations. The planning, development, and execution details contained in this proposal are specific to equipment under ownership of Greenhouse and Gardens Greenhouses Ltd.

Rationale

The underlying rationale for this project is that greenhouses supply a source of food and a livelihood for the business owners. Greenhouse owners have been dealing with a snow load crisis for many years. Snow accumulation causes greenhouse destruction leaving people with a lack of food and an enormous expense to the business owners. A potential solution to this problem will be beneficial to West Coast greenhouse owners and will potentially be applicable to other similar operation in Canada. Additionally, a potential solution must be cost effective and require minimum maintenance to be successful. A practical approach through visits to greenhouse facilities and research of similar operation are required to fully understand the effect of snow accumulation and develop workable solutions.

Research Summary

Research methods used to support and complete this project are primary and secondary resources. This includes articles, journals, and infield observation. The information is provided by credible sources that are listed in the reference section. This project is also completed in collaboration with fellow electrical engineering technology students, industrial engagement advisors, and Sean Dolter, a prospecting facility owner. Site visits and discussion with greenhouse owners will and have been conducted to understand the problem and derive potential solutions.

Research Analysis

The owner of the greenhouse and garden store, Sean Dolter serves as a primary source for the project. Mr. Dolter introduced the topic with a document that he had prepared. This document describes the problem in which he and his company have been facing with snow buildup on and in between their greenhouses. This description also discusses the financial impact of losing greenhouses and identified project constraints such as cost and design criteria. Mr. Dolter also proposed a potential solution using the pre-existing infiltration systems that are equipped in each greenhouse. There will be more communication with Mr. Dolter as research progresses. Another primary source includes small scale testing that will be completed by our team. Tests on a small-scale model will help to provide more insight on design outcomes.

Secondary sources for this project include pre-existing research from Sheila Pike, a fellow electrical engineering technology student. Ms. Pike began research on this topic earlier this year and proposed several electrical systems that could use to detect snow levels on the greenhouses. Our team will be focusing on mechanical systems that will direct mitigate snow accumulation however an electromechanical system may be a potential solution for this problem. Other secondary sources include articles and journals surrounding greenhouse construction and pre-existing mitigation systems.

Methods

The methods section will include an analysis of each of the developed snow mitigation systems. The Analysis will include drawings, calculations, and an in-depth description of how the system functions. A scaled down model of the greenhouse will also be created to aid in small scale testing of the facility. The exact design of these systems has yet to be established, our group is awaiting a meeting the facility owner to collect information surrounding the exact sizing of the greenhouses as well as other restraints.

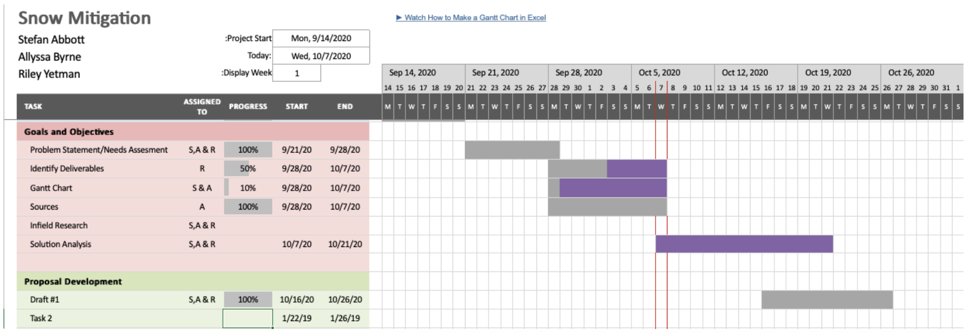
Cost

The cost of each system is to be discussed and explained. The systems will operate in different ways hence, the variations between components explicates the variations in the cost. These costs are to be compared to the given budgets which will determine whether they serve as feasible solutions.

Constraints

The circumstances in which our project is based on was proposed by a facility owner. Because of this, we have been challenged to follow certain criteria. The physical space we must work with is limited by the position of the greenhouses relative to one another as well as the design because they are pre-existing structures. A budget has also been requested which is intended to be followed.

Project Schedule



Updates to the Gantt chart are being made as the project progresses.

Conclusion

To summarize, the proposal detailed the development of a snow loading mitigation system applicable to greenhouse structures. The project is comprised of different methods of snow mitigation, which are developed through research using primary and secondary resources. The project constraints are limiting factors which have a substantial impact on the way solutions are developed. It is important that all design criteria and constraints are considered to achieve success in developing an effective and sustainable snow mitigations system.

Recommendations

Methods in which a snow mitigation system can be produced, will be provided. Their operation and benefits present in different manners. The recommendation would be to choose the system in which would best suit the situation of a facility owner.

Appendix B
Small Scale Experiment

College of the North Atlantic

Capstone

Andrea Scott

Greenhouse Experiment

Riley Yetman, Allyssa Byrne, Stefan Abbott

20102778, 20155696, 20154814

February 1, 2021

1. Table of Contents

Table of Figures

Experiment Objectives

1. To examine the effectiveness of the small scale heated mat's ability to mitigate snow loads

Materials and equipment

- Power Source- Small Lithium Ion batteries, 12V Car Battery
- Temperature Gun- Raytek Minitemp
- Model Greenhouse
- Heated Mat- Reflective insulation + Heated coil
- Camera and Tripod
- Snow Measuring Stick

Procedure

As snowfall began, the heated snow mat was powered on until the snowfall subsided. During this time the snow accumulation and temperature of the mat was recorded every 15 minutes. Pictures and videos were also taken in order to capture visual evidence concerning the effectiveness of this device.

Results and Analysis

Greenhouse Experiment			
Time (PM)	Snowfall (CM)	Mat Temp (°C)	Comments
2:30	0	40	Element was connected to two lithium ion batteries
2:45	0.5	40	Snow fall was wet and heavy
3:00	1	35	N/A
3:15	1.5	35	Snow began to drift against the greenhouse
3:30	2	36	Heating mat was able to prevent snow buildup along greenhouse
3:45	2.5	36	Lithium Ion batteries died (@3:50)
4:00	3	45	Element was connected to 12V Car battery
4:15	3.5	45	N/A
4:30	4	45	N/A
4:45	4.5	45	N/A
5:00	5	45	N/A
5:15	5.5	45	N/A
5:30	6	45	Snow Fall ended

The experiment lasted for 3 hours and the total snowfall was 6cm, however snow accumulation along the side of the greenhouse was approximately 8cm due to slight drifting. About 1 hour and 20 minutes into the experiment the lithium batteries ran out of power and the heating element was then connected to a 12V car battery. This lead to a downtime of about 10-15 minutes. The average temperature with the lithium batteries was 37 °C, with the car battery it was 45°C.

It was also important to note that the ambient temperature outside was 0°C, because of this the snow that was falling was quite wet and heavy. This type of snow would be considered the most dangerous for greenhouse operators as the increased weight would result in a heavier load on the structures.

Overall, the heated mat was able to mitigate snowfall effectively without damaging the greenhouse. The heated element was able to melt snow approximately 3 inches above and in front of the mat.

Conclusion

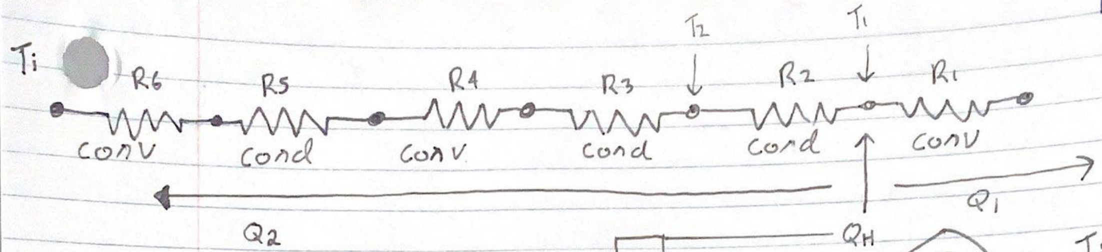
After completing and analysing the results of this experiment, the heated mat mounted alongside the greenhouse proved to be a plausible solution for a greenhouse snow mitigation system.

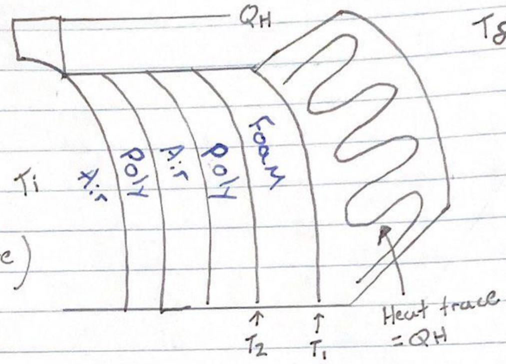
Appendix C

Heat Transfer Calculations

(Greenhouse Heat-transfer Calculations)

R-Yetman





Known

$T_i = 15°C = 288.15K$

$T_\infty = -10°C = 263.15K$

$Q_H = 50.16\ W/m^2$ (For 12" wire spacing)

$R_1 = 0.321\ W/K$

$R_2 = 0.215\ W/K$

$R_3 = 0.00186\ W/K$

$R_4 = 0.443\ W/K$

$R_5 = 0.00186\ W/K$

$R_6 = 0.496\ W/K$

$$Q_H = Q_1 + Q_2 \quad - (1)$$

$$Q_1 = \frac{T_1 - T_\infty}{R_1} \quad - (2)$$

$$Q_2 = \frac{T_1 - T_i}{R_{2,3,4,5,6}} \quad - (3)$$

FIVE STAR

$$Q_1 = \frac{T_1 - 263.15}{0.321} \qquad Q_2 = \frac{T_1 - 288.15}{1.158}$$

$$Q_H = Q_1 + Q_2$$

$$50.16\ W/M^2 = \left(\frac{T_1 - 263.15}{0.321}\right) + \left(\frac{T_1 - 288.15}{1.158}\right)$$

$$50.16 = 3.115T_1 - 819.782 + 0.863T_1 - 248.83$$

$$T_1 = 281.24K$$

$$T_1 = 8.09°C$$

$\therefore$

$$Q_1 = \frac{281.24 - 263.15}{0.321}$$

$$Q_1 = 56.36\ W/M^2$$

$$Q_2 = Q_H - Q_1$$

$$Q_2 = 50.16 - 56.36$$

$$Q_2 = -6.2\ W/M^2$$

$$V = IR$$

$$(T_1 - T_2) = R \cdot Q$$

$$T_1 - (R \cdot Q_2) = T_2$$

$$T_2 = 281.24K - (0.215 \cdot (-6.2))$$

$$T_2 = 282.573$$

$$T_2 = 9.42°C$$

FIVE STAR

Appendix D

Declaration of Group Authorship

Declaration of Group Authorship

This report has been prepared as a group project for the Mechanical Engineering Technology, program at the College of the North Atlantic on April 19, 2021. The group members are Stefan Abbott, Allyssa Byrne and Riley Yetman.

We, Stefan Abbott, Allyssa Byrne and Riley Yetman, confirm that this work submitted for assessment is our own and is expressed in our own words. All uses made within the Technology Report of the works of any other author, separate to the work group, in any form (ideas, equations, figures, texts, tables, programs), are properly acknowledged at the point of use. A list of the references used is included.

Stefan Abbott

Stefan Abbott

Allyssa Byrne

Riley Yetman

Riley Yetman