McGill University
Department of Mechanical Engineering

MECH 346 Off-Grid Solar Greenhouse

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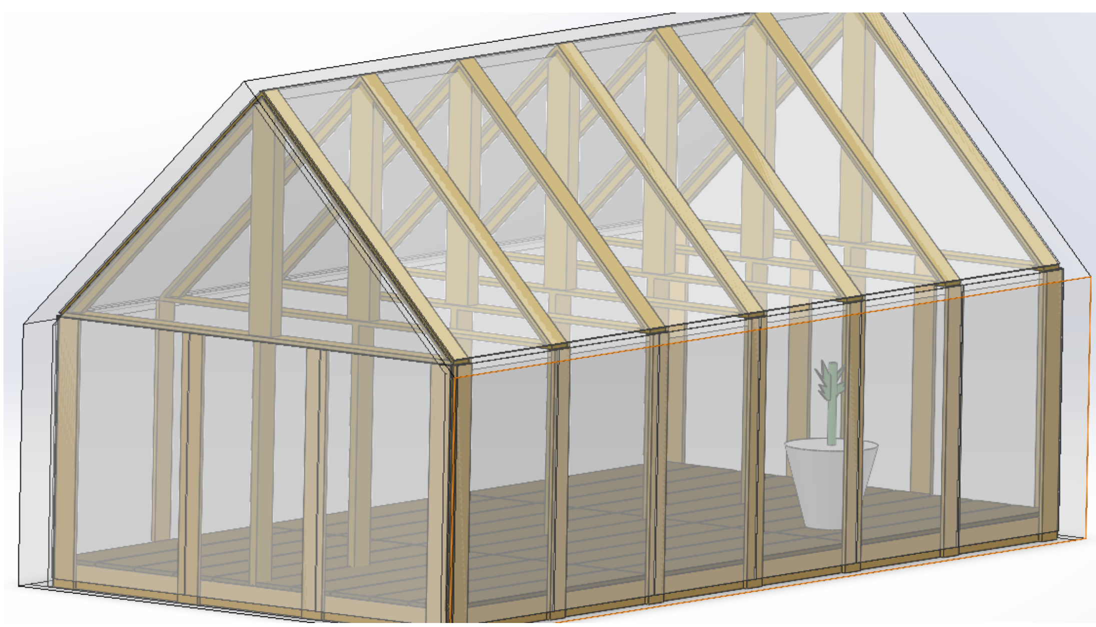

Table of Content

Problem Definition 1

Proposed Design 1

Critical Analysis 3

Discussions and Conclusions 7

Problem Definition

Some plants require specific temperature and humidity in order to grow. This would become difficult in areas where there is a large temperature difference between night and day, summer and winter. Therefore, a greenhouse is required to regulate these conditions, and ensure people living in high latitude can have difference food choices during winter. A greenhouse functions by having solar radiation pass through its transparent or opaque walls and ceiling then traps the infrared radiation inside (Çengel, 2014).

Generally, a greenhouse can be built from different materials such as glass, polycarbonates and acrylic, its temperature and humidity are regulated through ventilation and heating. Plants that are typically grown in the greenhouse includes tomatoes and peppers. The optimum temperature for tomato growth is around 60°F to 65°F or 15.6°C to 18.3°C. (Texas, n.d.), thus, our greenhouse will maintain the temperature around the above values. Canada grows its tomatoes predominately in southern Ontario (Nonnecke, 2013), thus our initial chosen location for the greenhouse will be in Windsor, Ontario. The Necessary data for our analysis such as solar irradiation, dry bulb temperature can be found on the Natural Resources Canada website.

Our team also decided to make the design to be more universal for promotion to the gardening market around the whole Canada, so the design of this greenhouse also features maintaining optimum plant growth temperature in more severe weathers, simpler structure, and easily accessible construction materials. The heat insulation needs to be adjustable to meet the customer's need from warm Vancouver to colder areas like Montreal and Halifax, where the weather conditions are significantly different. In our design, one of the biggest challenges would be providing appropriate insulation with low-cost materials for the most severe weather conditions.

The greenhouse with larger surface area but smaller height would have smaller heat loss rate and larger incident radiation. However, our greenhouse would need to fit in our customer's backyard, and it should have enough height such that it can fit in different types of plant shelves, pots, and boxes. So the size and shape of our design is constrained by the customer's need in this way.

To meet the goal of environmental protection and cutting carbon footprint, our design relies 100% on clean energy for heat compensation during the nights. The design should use solar panels to collect the energy needed during the night and use batteries to store the energies. The energy available for heating, which is the energy remained after considering the efficiency for energy collection and energy storage process should be enough to cover the total need of energy during the night.

In this project, we do not need to consider vaporization loss, and the focus is on the worst-case scenario, so ventilation is not included, and external electricity source is unavailable, any extra energy required would be from solar panels and batteries.

Proposed Design

For our design we will use clear 2-walled polycarbonate of 10.3 mm thickness as our building material. This is because polycarbonate has a smaller thermal conductivity than class and is more resistive to damage. Polycarbonate panels also cost significantly lower than glass. The size adjustment and assembly process with polycarbonate can be easily done with electrical drills and saws. Of course, just using a polycarbonate may not be enough to protect the crops from the harsh winter of Canada, thus in the worst-case scenario we will spread polyethylene sheets of thickness 0.1524 on top to add more insulations. A clear 2-walled polycarbonate has an equivalent thermal conductivity of 0.0668 W/m*K (Čekon, 2020), refractive index of 1.59 (Refractive index, 2020) and emissivity of 0.9 (Goddijn-Murphy). Polyethylene has a thermal conductivity of 0.5 W/m*K (Engineering Toolbox, n.d.), refractive index of 1.54 and emissivity of 0.1.

According to table one, polycarbonate have excellent thermal conductivity, but higher emissivity, and polyethylene have lower emissivity but much higher thermal conductivity. Combination of the two material allows us to take advantage of their strength to optimize the design.

Table1, Properties of Building materials

Material	Thermal Conductivity (W/m*K)	Refractive Index (-)	Emissivity (-)
Polycarbonate	0.0668	1.59	0.9
Polyethylene	0.5	1.54	0.1
Oak	0.17		

The greenhouse will have a width of 3m, length of 6m, wall height of 1.5 m and roof of 3m. the roof tilt angle would be 45 degrees to reduce snow accumulation and make the convection heat transfer analysis easier. Oak is a kind of hard wood and features excellent strength and heat conduction properties. Its compressive strength is 4900 kPa (Green,2002), and its thermal conductivity is 0.17 W/m*K (Çengel, 2014)., which is very low. Oak panels were used as the structural and flooring material.

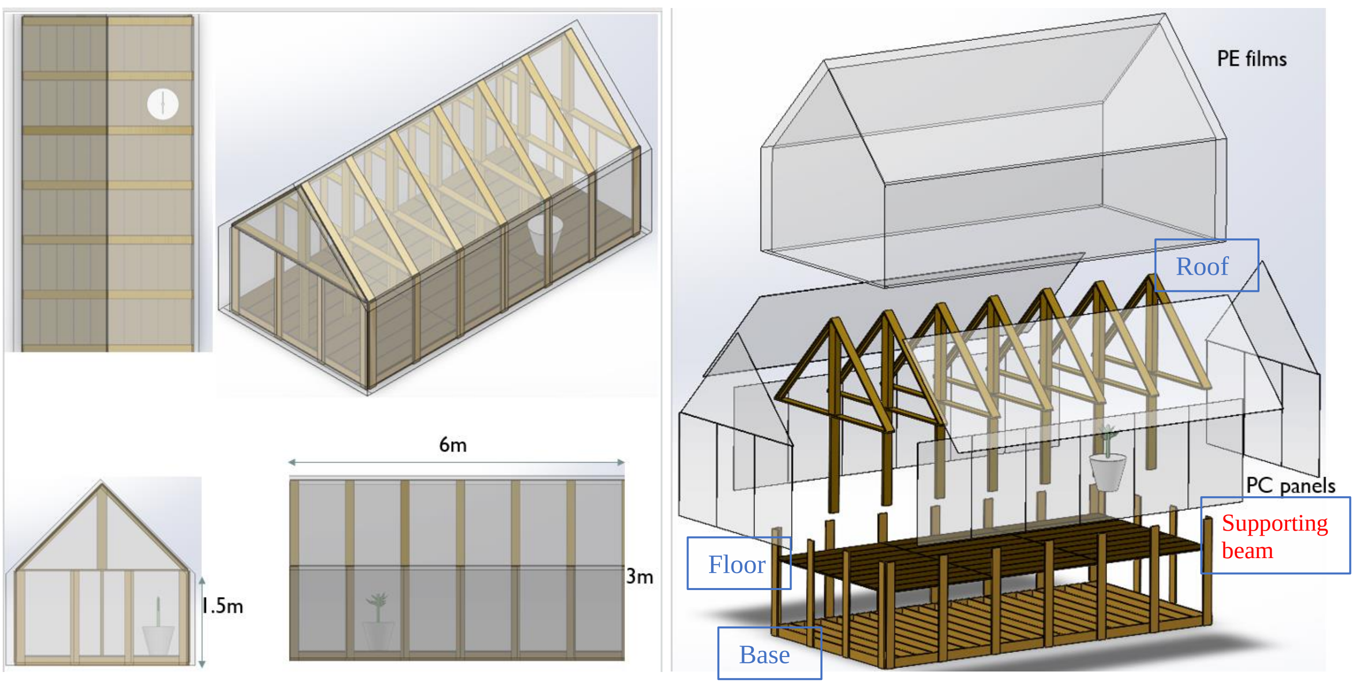

Figure 1, Greenhouse design.

As mentioned earlier, the chosen location for our greenhouse is Windsor, Ontario. And we chose the harshest months in the most recent years in which the data is available: December of 2016 and January and February of 2017. The operating temperature is 15 °C to 17 °C to achieve a mean temperature of 16°C.

Before verifying our design with its insulation properties. Its structural strength needs to be testified. The most critically loaded structural component of this greenhouse would be the central columns supporting the roof, which supports the largest areas. While the base is more heavily loaded, much more oak beams are used in the base for supporting and reduction of vibrations. Assuming a snow load of 3Kpa, and Wind load of 4 kPa on the roof. The total dead weight supported by 3 1”*6” cross sectional area oak beams is calculated by MATLAB code to be 31.3458kg in a 3m*1m area. The central column supports half of the area, including half of the dead weight and sum of snow load and wind load in its supporting area. The resultant compression load is calculated by MATLAB to be 14.549Kpa, which is much smaller than the compressive strength of the oak wood(4500Kpa). Thus, this design is not flawed structurally, and the greenhouse won’t collapse in most of weather conditions if it’s well maintained.

Critical Analysis

Due to the limitation of our knowledge, we must make some assumptions to simplify our model:

1. The system is in steady-state condition.
2. Since the greenhouse is within the sky, we can assume that A_{sky} is much greater than $A_{d.}$
3. Radiation across the dome can be neglected due to the property of its material.
4. Temperature of sky is assumed to be 10°C less than the temperature of air.
5. Sky is a black body in terms of radiation
6. There's 1mm of air between each sheet of polyethylene and polycarbonate.
7. Properties of air, polycarbonate and polyethylene are constant.

Next, we will tabulate the results from Environment Canada. The average dry bulb temperature and windspeed need to be timed 0.1 to get their values in degree and meter per second respectively. Since the design is aimed to measure the solar panels and batteries needed for winter, we would need to consider the worst-case scenario in the winter.

The day with the shortest sunlight time in northers hemisphere is on December 21st. The horizontal irradiance on this day is:

$$\frac{Q_{solar}}{A} = \int_1^{24} q(t)dt = 1869\,\frac{kJ}{m^2}$$

Assuming there's 6 hours of sunlight on this day, there will be 311.5 $kJ/m^2 \cdot h$ of irradiation during the day. Strongest wind in this 3-month period is 16.7m/s and the coldest temperature is -18.8°C or 254.2K, we will assume this is the case for the entirety of the day.

Table2, Values from Dec. 2016-Feb. 2017

	Average Horizontal Irradiation ($kJ/m^2 \cdot h$) during day timeth	Average Dry Bulb Temperature (°C)	Average Windspeed (m/s)
Dec. 2016	433.75	-1.72	5.60
Jan. 2017	525.5	-0.93	4.73
Feb. 2017	990.25	1.98	5.18
Overall	640	-0.30	5.17
Worst case scenario			
Day	311.5	-20	16

Overall equation:

The energy needed from solar batteries is calculated from

$$\dot{Q}_{loss} - \dot{Q}_{solar} = \dot{W}_{in}$$

$\dot{Q}_{solar}$ is irradiance from the sun. For solar panels, the value does not need to be adjusted. But for irradiance directly into the greenhouse, it will need to time the effective transmittance τ^* to account for the loss due to reflection. τ^* is calculated as $\tau^* = \frac{(1-\left(\frac{1-n}{1+n}\right)^2)^2}{1-(\frac{1-n}{1+n})^4}$. Multiple layers of the different material have been used to cover the green house in our design, the calculation of incident radiation thus need to take the effect of all these coverings into account. The adjust $\dot{Q}_{solar,adjusted}$ is:

$$\dot{Q}_{solar,adjusted} = \dot{Q}_{solar} \cdot \tau^*_{Pc} \cdot {\tau^*_{Pe}}^N$$

where N is the number of polyethylene sheet.

Heat loss:

$\dot{Q}_{loss}$ from inside the greenhouse house to the surface of the outermost polyethylene sheet is done through the form of conduction and radiation, since natural convection between each sheet of polyethylene is negligible. $\dot{Q}_{loss}$ from the outermost sheet of polyethylene to surroundings (air and sky) is through convection and radiant. For radiation from the greenhouse to the sky, since our design is not a dome (Reynold's number is too big for Churchill and Bernstein), we cannot use linearized expression for radiation nor circuit analogy in our project. For convection outside the greenhouse, we considered 2 cases, case 1 is when the wind is blowing against the roof top, and case 2 is when the wind is blowing along the roof top. In the analysis below, T_2 refers to the temperature of polycarbonate board, and T_3 refers to the temperature of the outermost sheet of polyethylene.

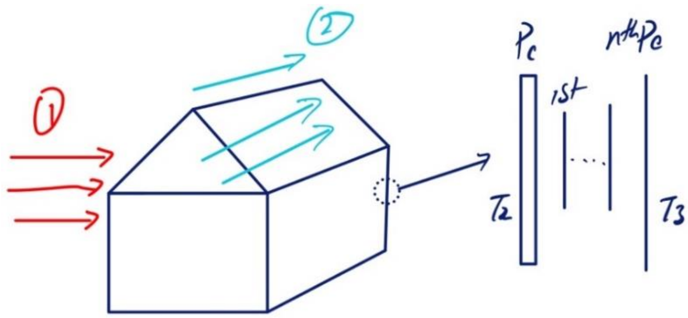

Figure 2, illustration for case 1 and case 2.

Conduction through the walls

For conduction, Q_{cond} is calculated by

$$\dot{Q}_{cond} = \frac{T_2 - T_3}{R_{total}} \qquad R_{total} = \frac{t_{pc}}{k_{pc} * A} + N * \frac{t_{pe}}{k_{pe} * A} + N * \frac{t_{air}}{k_{air} * A}$$

Where t is the thickness of each material, A is the area and k is the thermal conductivity of each material. Since the air between the PC panel and PE films, and air between PE films are very thin, the natural convection in between is negligible, and thus, the heat transfer in air between those materials are approximated to be conduction.

Radiation through the walls

For radiation from polycarbonate to the outermost polyethylene, we assume all the polyethylene sheets between them act as radiation shields,

$$\dot{Q}_{rad} = \frac{A\sigma({T_2}^4 - {T_3}^4)}{\left(\frac{1}{\varepsilon_{pc}} + \frac{1}{\varepsilon_{pe}} - 1\right) + N * \left(\frac{2}{\varepsilon_{pe}} - 1\right) + 1}$$

A again is the area, σ is the Stefan-Boltzmann constant which is $5.67 \cdot 10^{-8}$ W/m^{2}K^4, and ε is material's emissivity. Area of each layer is hold constant to simplify the computation and analysis, since the increase in area is very small.

According to our calculation, the internal radiation between the plasticfilms and panels were merely no more than 1 in if 20 layers of polyethylene were used to cover the

Outside Convection:

For case 1 where the wind is blowing against the rooftop, we will separate the structures into 3 parts, a non-tilted square, a square tilted 45°, and two sides. For the two sides, we will set the characteristic length as the width of the house, this may overestimate the heat transfer from the convection, but it is better to overestimate than to underestimate.

First, we calculate the Reynold's number

$$Re = \frac{VL_c}{\upsilon}$$

V is the windspeed, and υ is kinetic viscosity of air which is $1.338\cdot10^{-5}$ at 0°C, and only gets lower as temperature gets lowered. If the Re is over $5\cdot10^5$, the flow is turbulent,

$$Nu = 0.037Re^{0.8}Pr^{\frac{1}{3}}$$

If the Re is over $5\cdot10^5$, the flow is turbulent,

$$Nu = 0.064Re^{0.8}Pr^{\frac{1}{3}}$$

Where Pr is the Prandtl number of air at outside temperature. Pr and υ can be found through linear interpolation. The above expressions are from Çengel eqn. 7.21 and 7.22. Pr of air is above 0.7 at above -150°C so the expression is valid.

Nusselt number formula is carefully chosen from the scenario where the flow pattern is similar to the flow pattern in our case. For the non tilted die walls, the flow pattern around it would be similar to the flow around thecylinder with square cross section. Its characteristic length would be length of the greenhouse. For the 45 degree tilted roof, the flow around it would be similar to the flow around the square cylinder tilted for 45 degrees. Its characteristic length would be width of the green house.

For the 45° tilted square and non-tilted square, we again find our correlation from Çengel, this time from table 7-1. The Lc is the same as the two sides, thus for windspeed over 1m/s, temperature below 0°C,

$Re = \frac{1\cdot3}{1.338\cdot10^{-5}} = 2.24\cdot10^5$, which is above 32000 and 46000, thus we can use

$$Nu_{non-tilted} = 0.0249Re^{0.811}Pr^{\frac{1}{3}}$$

$$Nu_{45^\circ\ tilted} = 0.0260Re^{0.839}Pr^{\frac{1}{3}}$$

```
%Roof
if Reb<46000
    Nub=0.258*(Reb)^0.588*Prsf^(1/3);
Else
    Nub=0.026*(Reb)^0.839*Prsf^(1/3);
End
```

```
%Nontilted Wall
if Rec<32000
      Nuc=0.094*(Rec)^0.675*Prsf^(1/3);
else
      Nuc=0.026*(Rec)^0.839*Prsf^(1/3);
end
```

The MATLAB code also implement Nusselt number calculations for lower Reynolds numbers, where the wind speed is lower. The convection heat transfer coefficient is calculated by

$$h = \frac{Nu\cdot k}{L_c}$$

where k is the thermal conductivity of air at outside temperature.

$$\dot{Q}_{conv} = hA\,(T_{air} - T_3)$$

Where A is the area of that face of the greenhouse. To add the convective heat loss together, each term need to be doubled, because, the roof, sides, and nontilted wall areas all have a faces of same size.

$$\dot{Q}_{conv,total} = 2 * (\dot{Q}_{conv,sides} + \dot{Q}_{conv,tilted} + \dot{Q}_{conv,nontilted})$$

For case 2, the side areas will be hit directly by the wind, so it should be approximated with the square cylinder non tilted formula. The wind flow over all other panels parallelly, so the roof and non tilted wall's Nusselt number can be calculated with the flat plate formula.

The total convective heat loss in case 2 is shown below, where A is the combined total area of the roof and non-tilted walls.

$$\dot{Q}_{total} = \dot{Q}_{conv} = hA\,(T_{air} - T_3) + 2 * \dot{Q}_{conv,sides}$$

To estimate the convective heat transfer of the sides, we need to take approximations. Since the roof section of the side is a triangle, for better approximation of the Nusselt number, the MATLAB code mesh this area into 10 pieces of equivalent height and treated each section as a rectangular plate to calculate Reynolds number and Nusselt Number. This approach should more precise than treat it simply as half area of a rectangular plate with characteristic length of the greenhouse width. All functions estimating convective heat transfer outputs h*A at a given surface temperature.

```
for i=1: NumMesh
    Reatop(i)=Rea*((10-i)/10+0.05);
end
for i=1: NumMesh
    if Reatop(i)<32000
        Nutop(i)=0.094*(Reatop(i))^0.675*Prsf^(1/3);
    else
        Nutop(i)=0.026*(Reatop(i))^0.839*Prsf^(1/3);
    end
    ha2=ha2+Nutop(i)*Ksf/(W*(10-i)/10+0.05)*(W*(10-i)/10+0.05)*H2/10;
end
Nua=0.094*(Rea)^0.675*Prsf^(1/3);
ha2=ha2+Nua*Ksf/(W)*W*H1;
end
```

Figure.3 Sample MATLAB Code Meshing the roof area of the side estimating convective heat loss.

Outside Radiation

As stated in assumption, the sky is assumed to be a blackbody, and its temperature is 10°C lower than outside air. The greenhouse has no concave surfaces, thus the view factor from the greenhouse to the sky is equal to one

$$\dot{Q}_{rad} = A\sigma\varepsilon_{pe}({T_3}^4 - {T_{sky}}^4)$$

Heat transfer equation

$$\dot{Q}_{loss} = \dot{Q}_{rad,wall} + \dot{Q}_{cond,wall} = \dot{Q}_{conv,outside} + \dot{Q}_{rad,outside}$$

$$\frac{T_2 - T_3}{R_{total}} + \frac{A\sigma({T_2}^4 - {T_3}^4)}{\left(\frac{1}{\varepsilon_{pc}} + \frac{1}{\varepsilon_{pe}} - 1\right) + N * \left(\frac{2}{\varepsilon_{pe}} - 1\right)} - hA\,(T_{air} - T_3) - A\sigma\varepsilon_{pe}\left({T_3}^4 - {T_{sky}}^4\right) = 0$$

In this case only T_3 is unknown, we can use bisection method to get the value of T_3.

Finding Surface temperature:

Figure .4 below is a screenshot of our MATLAB code to find external surface temperature of one plate. Since the surface temperature should be close to the dry bulb temperature, the initial guess were the dry bulb temperature and a temperature 10 degrees above it. For each iteration, convective heat transfer values, h*A were calculated for each guess. Followed by the energy balance function testing if the conductive heat loss equals sum of convective heat loss and radiative heat loss at this temperature.

Convective heat transfer needs to be estimated in each iteration because, it relies on mean temperature of surface temperature and the dry bulb temperature, which varies in each iteration.

The surface temperature of the sides, nontilted walls, and roofs were calculated separately in the MATLAB code.

```matlab
tla=tdb+10;tlb=tdb;tlc=(tla+tlb)/2;Error=0.0001;A=W*H1+W*H2/2;
hala=convcc2(tla,tdb,Kex,Kbt,tbt,vex,vbt,prex,prbt,Vwind,H1,L);
halb=convcc2(tlb,tdb,Kex,Kbt,tbt,vex,vbt,prex,prbt,Vwind,H1,L);
halc=convcc2(tlc,tdb,Kex,Kbt,tbt,vex,vbt,prex,prbt,Vwind,H1,L);
fa=f(tla,emasbl,tdb,hala,RAcond,tAVG,A);
fb=f(tlb,emasbl,tdb,halb,RAcond,tAVG,A);
fc=f(tlc,emasbl,tdb,halc,RAcond,tAVG,A);
while abs(fc)>Error
    if fc*fa<0
        tlb=tlc;
    else
        tla=tlc;
    end
    tlc=(tla+tlb)/2;
    hala=convcc2(tla,tdb,Kex,Kbt,tbt,vex,vbt,prex,prbt,Vwind,H1,L);
    halb=convcc2(tlb,tdb,Kex,Kbt,tbt,vex,vbt,prex,prbt,Vwind,H1,L);
    halc=convcc2(tlc,tdb,Kex,Kbt,tbt,vex,vbt,prex,prbt,Vwind,H1,L);
    fa=f(tla,emasbl,tdb,hala,RAcond,tAVG,A);
    fb=f(tlb,emasbl,tdb,halb,RAcond,tAVG,A);
    fc=f(tlc,emasbl,tdb,halc,RAcond,tAVG,A);
end
surftemp(6)=tlc;
```

Figure.4 Sample MATLAB Code Finding Surface Temperature

Solar panels and Solar Batteries

After calculation of outer surface temperature of each side the greenhouse, the heat loss rate can be easily calculated, by summing up all the conductive heat losses of the sides, non tilted walls, roofs, and the floor area to the ground. Ideally, the greenhouse is designed to use all the received radiation to maintain the internal temperature at 16 degrees, and without ventilation during the day in winter. During the night, extra PE films would be applied to further reduce the heat loss, the greenhouse would rely on the electricity collected by the solar panels during the day to power. The least amount of available power would be equal to the total amount of heat loss during this period of time.

Since our greenhouse is off grid, we have to use solar panels to collect extra energies for our greenhouse and use solar batteries to store that energy. The highest efficiency solar panels for commercial use is Solaria's PowerXT 430R-PL at 20.4% (High power, n.d.). Its dimension is 1.076m*1.957m*0.035m, so the area for one panel is 0.0737m^2. And the best solar battery is Tesla's Powerwall 2 with maximum capacity of 13.5 kWh and 90% efficiency for one battery (Tesla Powerwall, n.d.). One Solaria panel cost 484 USD or 703 CAD after tax and one tesla power wall is 5500 USD or 7992 CAD after tax.

The supply of energy required for one day of working is

$$Q_{supply} = Q_{loss,total} - Q_{solar,total} \cdot A_g \cdot (\tau^*)_{total}$$

Thus, the amount of solar panels required is $No_{panel} = \frac{Q_{supply}}{0.2 \cdot 0.9 \cdot Q_{solar,total} \cdot A_{panel}}$, and the amount of solar batteries required is $No_{panel} = \frac{Q_{supply}}{Q_{battery}}$.

Equivalent monthly heating cost

For farm residence, HydroQuébec charge 41.168¢ for each consumption day then 6.159¢/kWh for the first 40kWh and 9.502 ¢/kWh for anything above in each day. Assuming on average 1750 W is required for normal day operation, that is 42 kWh for a 24-hour period, thus using solar energy would save us 41.168¢+42*6.159 = 299.8¢/day and 89.95CAD/month.

Discussion and Conclusion

The result of the analysis is tabulated below.

Table 3, tabulated results

	Areas of solar panels required (m^2)	Areas of solar panels required (m^2)
	51	113

Table 4, Estimated Performance

	Worst Case Scenario, Evening, 20sheets of 6mil PE films applied		Worst Case Scenario, day, 8sheets of 6mil PE films applied	
	Outer surface temperature	Radiation between the plastics	Outer surface temperature	Radiation between the plastics
Side Case 1	-19.3872	0.3819	-18.7019	2.0159
Roof Case 1	-19.4872	0.7212	-18.9185	3.8169
wall case 1	-19.4412	0.3797	-18.7266	2.0725
Side Case 2	-18.4904	0.3758	-18.1566	1.9948
Roof Case 2	-19.6103	0.7228	-19.1688	3.8349
wall case 2	-19.4526	0.3797	-18.8380	2.0768
Solar Rad Power	Heat Loss Case 1	Heat Loss Case 2	Heat Loss Case 1	Heat Loss Case 2
4510.4W	2063.5W	2055.1W	4126.6W	4129.0W
	Normal Day Scenario, Day, 8sheets of PE films applied		Normal Day Scenario, Day, no Extra PE films applied (Energy Surplus)	
	Outer surface temperature	Outer surface temperature	Outer surface temperature	Radiation between the plastics
Side Case 1	0.2683	1.1189	0.8116	2.0159
Roof Case 1	0.1890	2.1189	0.8426	3.8169
wall case 1	0.2442	1.1629	1.0726	2.0725
Side Case 2	0.5089	1.1042	1.1921	1.9948
Roof Case 2	0.0622	2.1334	0.4452	3.8349
wall case 2	0.2081	1.1652	0.7086	2.0768
Solar Rad Power	Heat Loss Case 1	Heat Loss Case 2	Heat Loss Case 1	Heat Loss Case 2
9446.0W	1929.0W	1930.4W	6105.2W	6194.6W

As can be seen from above, our design is very flexible, the thermal conservation of our greenhouse can be improved by adding more polyethylene sheets, from 0 sheets during summertime to 20 sheets during extreme winter. In the usual winter times, we can save 300¢ per day from using solar energy instead of using HydroQuébec, which to be frank is not a lot. If we considered the cost of solar batteries and solar panels, which is 23976 CAD for 3 solar batteries and 79439 CAD for 113 solar panels. the benefit of free electricity is nearly zero. Not to mention solar batteries may not perform well in extreme cold and during blizzard days the solar panels may be buried in deep snow, which is also the very days you do not want your solar powers to go out or your whole month of efforts will be wasted. However, this does prove the idea of powering a greenhouse that solely relies on solar energy is possible even in areas as cold and dull in winter like Canada.

If we wish to improve the design, flatter roofs could be applied, which might possibly reduce the heat loss. Wind turbines could be deployed along with the solar panel to extract extra energy from powerful winter winds. In this way, less solar panel would be needed for energy generation, and the system would occupy less space.

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Appendix

MATLAB Code:

Over 400 lines of matlab code have been developed to find the heat transfer rate caused by conduction convection and radiation of our design. It also automatically computes the total area of solar panels needed to collect enough energy for heating up the greenhouse during the night.

The executable MATLAB code and the solidworks CAD files have been uploaded to github repository in the following link:

.https://github.com/Zongxuan-Lin/MECH346Green-House-Design