BERG White Paper 1501

Engineering Study: Using Waste Heat from the Western Sugar Plant to Heat a Greenhouse in the Winter

A Report for the Big Horn Food Hub,
Lovell, Wyoming

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1. Introduction

The Big Horn Food Hub seeks to explore the feasibility of a producer-owned, cost-competitive, year-round multiple use greenhouse(s) in Lovell, Wyoming. There is a unique opportunity in the Big Horn Basin to heat a substantial (up to 3 acres) greenhouse in the winter using the waste hot water discharged from the local sugar plant.

Every day during the winter beet processing campaign (Nov-Feb) a large amount of waste heat from the Western Sugar Plant is discharged into three onsite holding ponds as hot condenser water at an average temperature of 115°F and an average flow rate of two million gallons per day. Currently, the water must be cooled to below 80°F before it is discharged into the river. The “waste” heat represents a tremendous opportunity to save energy and money.

The purpose of this study is to quantify the amount of waste heat available, and compare this quantity to the heating needs of a greenhouse in this climate.

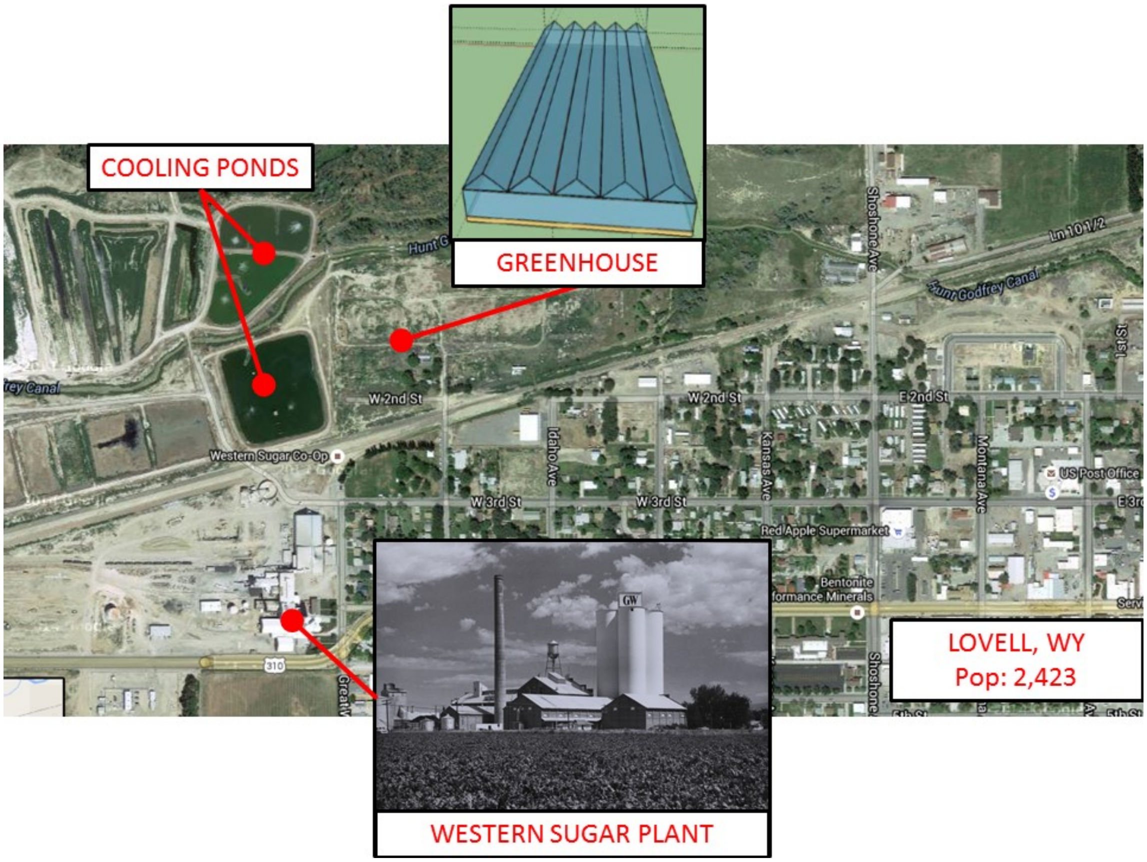


Figure 1. Illustration of Project Elements
Source: (authors)

2. Calculation of Available Heating Energy from the Sugar Plant

2.1. Annual Average Hourly Heating Energy Available

Calculate available heating energy from the sugar plant's discharged hot condenser water figured on a low temp (115F) high flow (2 million gallons per day) water heat source calculated based on a maximum extraction of 30F from the flow of water diverted to the greenhouse for heating.

General Heat Equation

Available heating energy was calculated using the general heat energy equation, Equation 1 (Formula 1: Heat Energy n.d.).

$$Q \ = m \times c_p \times \Delta T \qquad \text{Equation 1}$$

Where

Q = Available Heating Energy [J]

m = Mass [kg]

c_p = Specific Heat [J/kg˚C]

ΔT = Change in Temperature [˚C]

Calculation of Mass Flow Rate

In order to calculate the mass flow rate of water from the heat source, a conversion calculation was performed. A volumetric flow rate of 2 million gallons of water per day was given which is equivalent to approximately 313,280 kilograms of water per hour. Conversion factors can be found in *Fundamentals of Heat and Mass Transfer* (Bergman, et al. 2011). The conversion calculation is shown below.

$$\dot{V} = \frac{2{,}000{,}000\ gal}{1\ day} \times \frac{1\ day}{24\ hours} = 83{,}333.33\ gal/hr$$

$$\frac{83{,}333{,}33\ gal}{hr} \times \frac{35.315\ ft^3}{264.17\ gal} \times \frac{1\ lb_m}{0.01613\ ft^3} \times \frac{1\ kg}{2.2046\ lb_m} = \dot{m} = 313{,}278.3\ kg/hr$$

Where

$\dot{V}$ = Volumetric Flow Rate [gal/hr]

$\dot{m}$ = Mass Flow Rate [kg/hr]

Temperature Conversions

In order to use the general heat equation (Equation 1), temperatures must be converted from degrees Fahrenheit to degrees Celsius. Equation 2 shows the conversion from degrees Fahrenheit to degrees Celsius (The Old Farmer's Almanac n.d.).

$$℃ = (°\mathrm{F} - 32) \times .5556 \qquad \text{Equation 2}$$

With the above temperature conversion equations, the following temperatures were found.

$$T_i = (115°\mathrm{F} - 32°\mathrm{F}) \times .5556 = 46.1148℃$$

$$T_o = (85°\mathrm{F} - 32°\mathrm{F}) \times .5556 = 29.4468℃$$

Where

T_i = Incoming Temperature [˚C]

T_o = Incoming Temperature [˚C]

Calculation of Change in Temperature

The general heat equation calls for a change in temperature, which can be expressed by the following calculation.

$$\Delta T = T_i - T_o = 46.1148℃ - 29.4468℃ = 16.668℃$$

Calculation of Specific Heat of Water at T_{ave}

In order to calculate the available heating energy from the hot condenser water, the specific heat of water at a certain temperature must be found. The specific heat of water was evaluated at an average temperature of about 40˚C, found by Equation 3.

$$T_{ave} = \frac{T_i + T_o}{2} = \frac{46.1148℃ + 29.4468℃}{2} = 37.78℃ \cong 40℃ \qquad \text{Equation 3}$$

At 40˚C, it was found that c_p, or the specific heat of water, is equal to $4179\ J/kg \cdot K$, which is also equivalent to $4179\ J/kg \cdot ℃$ (Bergman, et al. 2011).

Calculation of Available Heat Energy

Finally, with all conversions and calculations determined above, Equation 1 can be used to find the total available heating energy from the discharged hot condenser water from the sugar plant.

$$Q = m \times c_p \times \Delta T = 313{,}278.3 \frac{kg}{hr} \times 4179 \frac{J}{kg} \cdot ℃ \times 16.668℃$$

$$= 2.182 \times 10^{10} \frac{J}{hr} = \boxed{21.82\ GJ/hr}$$

$$= 21.82 \frac{GJ}{hr} = 21.82 \times 10^9 \frac{J}{hr} \times \frac{1\ Btu}{1055.05585\ J} = 20{,}681{,}389.62 \frac{Btu}{hr} = \boxed{20.681 \frac{MBtu}{hr}}$$

Calculations and results throughout this report will be given in both gigajoules per hour (GJ/hr) and mega-Btus per hour (MBtu/hr).

2.2. Monthly Average Hourly Heating Energy Available

Available heating energy were calculated for winter based on monthly flow rates. Temperature difference and specific heat remained the same while mass flow rate varied. Monthly flow rates and their resulting available heat energy can be found in Table 1.

Table 1. Monthly Available Heat Energy

Month	Volumetric Flow Rate [Mgal/day]	Mass Flow Rate [kg/hr]	Resulting Heat Energy [GJ/hr]	Resulting Heat Energy [MBtu/hr]
September	2.95	462,085.5	32.19	30.51
October	3.54	554,502.6	38.62	36.61
November	1.74	272,552.1	18.98	19.99
December	1.32	206,763.7	14.40	13.65
January	1.62	253,755.4	17.68	16.75
February	1.75	274,118.5	19.09	18.10

All other months were evaluated based on the annual average flow rate 2.0 Mgal/day.

3. EnergyPlus Model

State-of-the-art energy simulation software – EnergyPlus(2015), developed by Department of Energy, was used as the simulation engine. OpenStudio Plug-in in SketchUp was employed to create the greenhouse geometry model for energy simulation. In this task, we created an EnergyPlus model for the greenhouse (300'L x 150'W x 30', pitch roof with 20' high walls) using standard greenhouse construction material as a baseline case for this study.

3.1. Greenhouse Construction

Modern greenhouses are made of a variety of materials, each with a range of advantages and disadvantages. In addition, there are a variety of forms a greenhouse can take, including an A-frame shape to a Quonset style. In an A-frame greenhouse, there are four components in its construction to consider: the roof, gable, wall, and curtain wall (Nelson 2012). For the purposes of this report, the curtain wall will be referred to as the base. A diagram of this construction is shown in Figure 2.

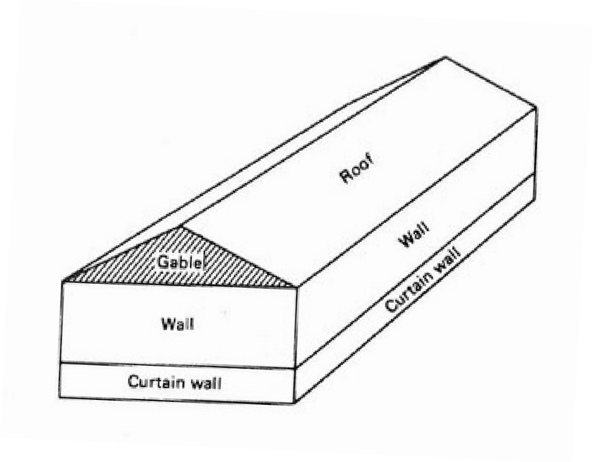
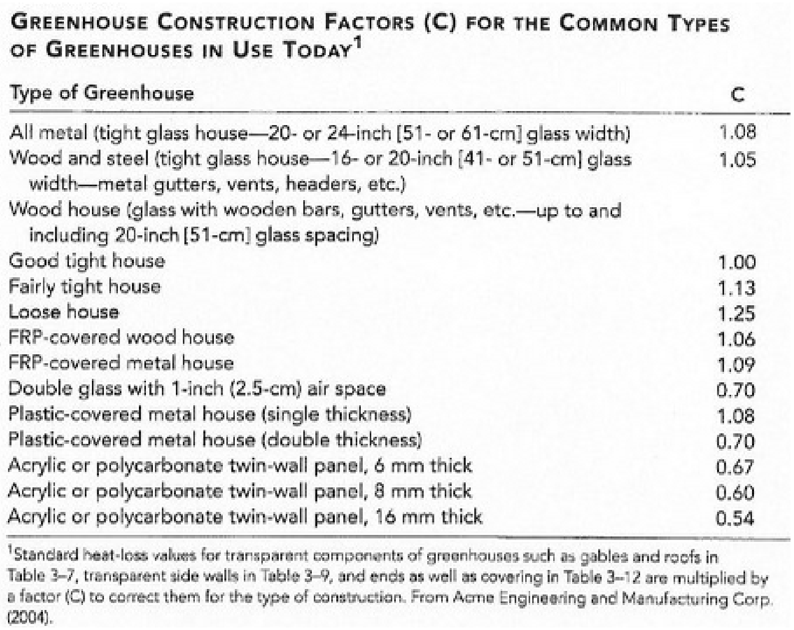


Figure 2. A-frame Greenhouse Construction
Source: (Nelson 2012)

Common greenhouse construction materials and base materials are shown in Table 1 and Table 2, respectively. Because the amount of heat lost through each component of the greenhouse construction is multiplied by the construction factor corresponding with the material, a smaller construction factor is desired (Nelson 2012). A smaller construction factor yields a greater reduction in heat loss, therefore less energy needed to heat the structure. The most efficient greenhouse construction material is a 16mm acrylic or polycarbonate twin-wall panel, and the most efficient base construction materials are 8in concrete blocks (Nelson 2012).

Table 2. Common Types of Greenhouse Materials
Source: (Nelson 2012)

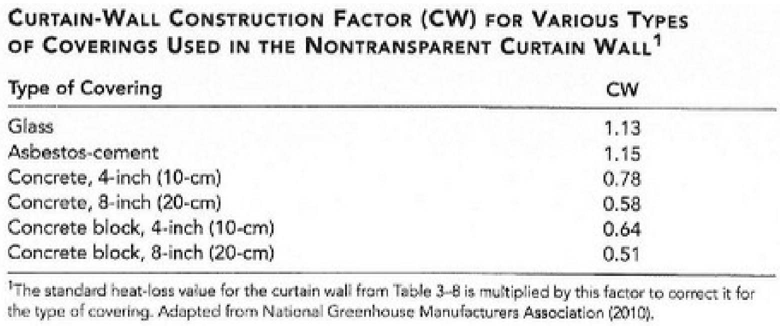


GREENHOUSE CONSTRUCTION FACTORS (C) FOR THE COMMON TYPES OF GREENHOUSES IN USE TODAY[1]

Type of Greenhouse	C
All metal (tight glass house—20- or 24-inch [51- or 61-cm] glass width)	1.08
Wood and steel (tight glass house—16- or 20-inch [41- or 51-cm] glass width—metal gutters, vents, headers, etc.)	1.05
Wood house (glass with wooden bars, gutters, vents, etc.—up to and including 20-inch [51-cm] glass spacing)	
Good tight house	1.00
Fairly tight house	1.13
Loose house	1.25
FRP-covered wood house	1.06
FRP-covered metal house	1.09
Double glass with 1-inch (2.5-cm) air space	0.70
Plastic-covered metal house (single thickness)	1.08
Plastic-covered metal house (double thickness)	0.70
Acrylic or polycarbonate twin-wall panel, 6 mm thick	0.67
Acrylic or polycarbonate twin-wall panel, 8 mm thick	0.60
Acrylic or polycarbonate twin-wall panel, 16 mm thick	0.54

[1] Standard heat-loss values for transparent components of greenhouses such as gables and roofs in Table 3–7, transparent side walls in Table 3–9, and ends as well as covering in Table 3–12 are multiplied by a factor (C) to correct them for the type of construction. From Acme Engineering and Manufacturing Corp. (2004).

Table 3. Curtain Wall (base) Construction Materials
Source: (Nelson 2012)



CURTAIN-WALL CONSTRUCTION FACTOR (CW) FOR VARIOUS TYPES OF COVERINGS USED IN THE NONTRANSPARENT CURTAIN WALL[1]

Type of Covering	CW
Glass	1.13
Asbestos-cement	1.15
Concrete, 4-inch (10-cm)	0.78
Concrete, 8-inch (20-cm)	0.58
Concrete block, 4-inch (10-cm)	0.64
Concrete block, 8-inch (20-cm)	0.51

[1] The standard heat-loss value for the curtain wall from Table 3–8 is multiplied by this factor to correct it for the type of covering. Adapted from National Greenhouse Manufacturers Association (2010).

It was decided that the greenhouse for this project would be A-frame and would use 8in concrete blocks for its base and twin wall polycarbonate panels for the walls, roof, and gables.

The material properties of the chosen greenhouse materials are shown in Table 3. 10mm polycarbonate panels were used because of their wider availability and favorable thermal properties. The properties shown in Table 3 were incorporated into the EnergyPlus model.

Table 4. Greenhouse Material Properties

Material	**Thickness [m]**	**Conductivity [W/m K]**	**Density [kg/m-3]**	**Specific Heat [J/kg K]**	**Thermal Absorptance**	**Solar Absorptance**	**Visible Absorptance**
Polycarbonate Panels	0.01	0.205	0.12	1200	0.9	0.15	0.2
Concrete Blocks	0.2033	1.7296	2243	837	0.9	0.65	0.65

Thermal conductivity of the 10 mm polycarbonate panels was found to be 0.205 W/m K by averaging the range of values given for polycarbonate material (Professional Plastics n.d.).

$$k = \frac{0.19 + 0.22}{2} = 0.205 \frac{W}{m\,K}$$

Where

k = Thermal Conductivity [W/m K]

Density of the polycarbonate material was found to be 1.2 g/cm3 with the following conversions (BPI Boedeker.com n.d.).

$$1.2\ \frac{g}{cm^3} \times \frac{1\ kg}{1000\ g} \times \left(\frac{100\ cm}{1\ m}\right)^3 = 0.12\ \frac{kg}{m^3}$$

Specific Heat of the polycarbonate panels was found to be approximately 1200 J/kg K (Professional Plastics n.d.).

Thermal Absorptance was assumed to be the default value given by EnergyPlus. Solar reflectance and visible reflectance properties of polycarbonate were not found so solar and visible absorptance were approximated as 100% minus the solar or visible transmittance. Because the polycarbonate panel material is used minimally in the model, this approximation will not have a large effect. See below for further explanation. It was found that the Solar Absorptance of polycarbonate panels was 0.15 and the Visible Absorptance is 0.2 (General Electric Company n.d.).

A simple glazing system of polycarbonate panels was also incorporated into the model with the properties found in Table 5 (AmeriLux International 2013) and (General Electric Company n.d.). The glazing system was incorporated as sub surfaces of the base, Polycarbonate Panel.

Table 5. PC Panel Fenestration Properties

Name	U-Factor	Solar Heat Gain Coefficient	Visible Transmittance
PC Panel	0.52	0.8	0.8

Property values for the 8 in concrete blocks were kept at the EnergyPlus default values for concrete blocks.

3.2. Modelling Assumptions

For the purposes of this engineering study, it was assumed that the greenhouse would be A-frame. It was also assumed that the greenhouse, rather than having one large pitch, would have a series of pitches, or gables, forming 5 bays. These gables are located at the top of the 20 foot wall, are 30 feet wide and 10 feet tall. Figure 3 shows the geometry of the A-frame bays.

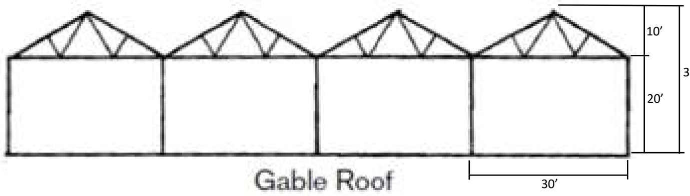


Figure 3. A-frame Bays

The greenhouse was oriented so that the 150 foot dimension is North/South and the 300 foot dimension is East/West. Each of the 30 foot bays run North/South along this orientation.

Materials of the greenhouse include 10 mm clear twin wall polycarbonate panels for the roof, gables, and walls and concrete for the base. It is assumed that the base will be 3 feet in height at the bottom of the greenhouse and will surround the building on all sides.

For modelling purposes, polycarbonate surfaces were separated into opaque “Polycarbonate Panel” material and transparent “PC Panel” material. Each polycarbonate panel surface consists of Polycarbonate Panel material with a PC Panel subsurface that cover nearly all of the base surface. This allows for the simulation of transparent materials and a more accurate energy analysis.

The assumption that the greenhouse will not have a floor, but rather be open to the ground, was made. An “air wall” was used at the base of the greenhouse model to simulate the building being open to the ground.

Specific internal loads such as lighting and equipment are not included within the EnergyPlus model. The energy results specified within this document do not account for these loads.

It was assumed that “daytime” hours take place from 7 am to 5:59 pm and “nighttime” hours take place from 6 pm to 6:59 am.

The given daytime and nighttime temperature requirements for the greenhouse were converted to degrees Celsius using Equation 1.

$$T_d = (80°\text{F} - 32°\text{F}) \times .5556 = 26.67°\text{C}$$

$$T_n = (70°\text{F} - 32°\text{F}) \times .5556 = 21.11°\text{C}$$

Where

T_d = Daytime Temperature [˚C]

T_n = Nighttime Temperature [˚C]

3.3. Geometry Model

Figure 4 shows the geometry of the greenhouse in SketchUp.

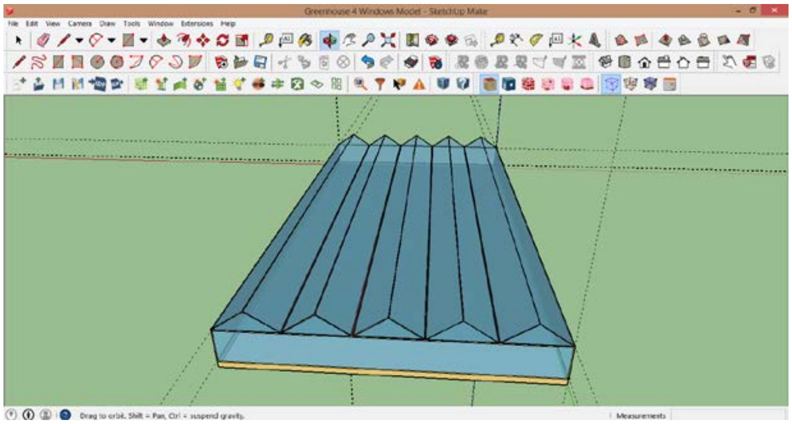


Figure 4. Geometry of Greenhouse

Figure 5 shows the greenhouse as divided by thermal zones. The base and walls form Thermal Zone 1 and the gables and roof form Thermal Zone 2.

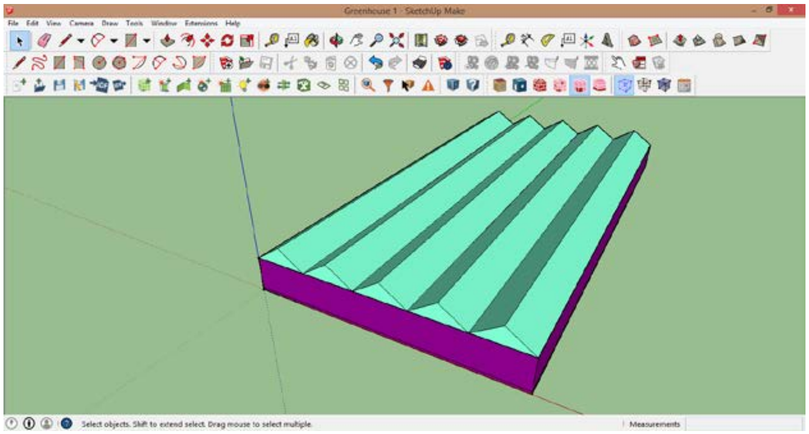


Figure 5. Thermal Zones

Surfaces dividing Thermal Zone 1 and Thermal Zone 2 include skylights. 10 skylights were modelled, 5 on Thermal Zone 1's roof and 5 on Thermal Zone 2's floor. Each skylight measured 149' x 29' and was centered in each of the 5 bays. These skylights are open at all times, allowing a boundary for the thermal zones, yet still allowing air flow between the two zones.

An Airflow Network was used in order to simulate natural ventilation through the skylights mentioned above.

Figure 6 shows a view from the interior of the model. The model allows the viewer to see through the air wall below to the ground and above through the skylights to the gables and roof of the building.

Figure 6. Interior View of Greenhouse Model

4. Heating and Cooling Load Analysis

Predict annual heating and cooling loads (monthly daytime average, monthly nighttime average, peak) to maintain required indoor environment conditions (daytime 80F and nighttime 70F) for Cody winter when factoring in the solar gains including result analyses.

4.1. Heating Load Results

Once the building of the greenhouse model was complete, hourly heating loads were extracted and analyzed. As expected for northern Wyoming, heating loads are larger during the winter months and smaller during the summer months. Table 6 shows the monthly average heating loads for the greenhouse building. Data was divided by month and by hour in order to determine the monthly averages of daytime and nighttime loads. Figure 7 illustrates the average monthly heating loads.

Table 6. Monthly Average Heating Load for Daytime and Nighttime

Month	Average Heating Daytime [GJ/hr]	Average Heating Daytime [MBtu/hr]	Average Heating Nighttime [GJ/hr]	Average Heating Nighttime [MBtu/hr]
January	1.46	1.38	1.67	1.58
February	1.33	1.26	1.64	1.55
March	0.94	0.89	1.42	1.35
April	0.85	0.80	1.23	1.17
May	0.73	0.70	1.09	1.04
June	0.64	0.60	0.93	0.88
July	0.52	0.50	0.75	0.71
August	0.61	0.58	0.80	0.76
September	0.84	0.79	1.07	1.01
October	1.08	1.03	1.31	1.24
November	1.33	1.26	1.49	1.41
December	1.50	1.42	1.60	1.52

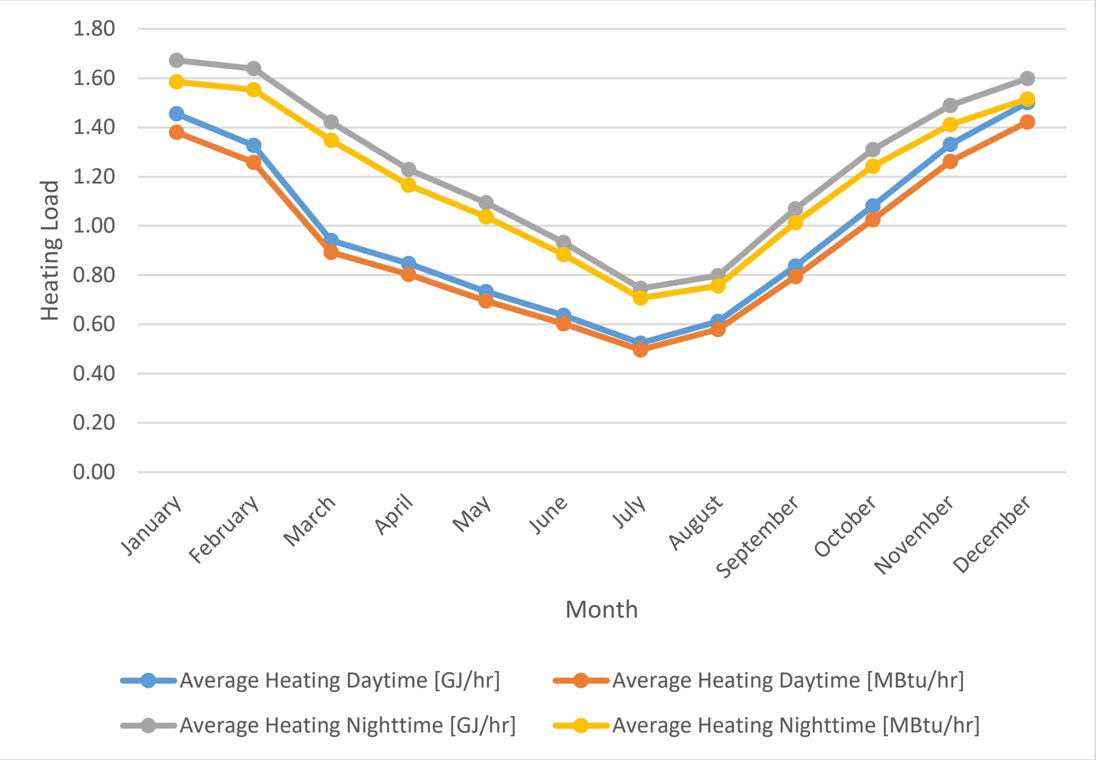


Figure 7. Monthly Average Heating Load

In order to determine whether the available heating energy is sufficient to heat the greenhouse, a peak load for daytime and nighttime is required. The highest simulated heating load was 4.335 GJ/h, which is well below the 21.82 GJ/h available. Table 7 shows the peak heating loads for both daytime and nighttime.

Table 7. Peak Heating Loads for Daytime and Nighttime

Peak Heating Load Daytime [GJ/hr]	**Peak Heating Load Nighttime [GJ/hr]**
4.335	3.389

4.2. Cooling Load Results

Hourly cooling loads were extracted and analyzed in addition to the heating loads mentioned above. Table 8 shows the monthly average cooling loads for the greenhouse building. Data was divided by month and by hour in order to determine the monthly averages of daytime and nighttime loads. Average monthly cooling loads are shown graphically in Figure 8. Table 9 shows the peak daytime and nighttime loads for the greenhouse.

Table 8. Monthly Average Cooling Load for Daytime and Nighttime

Month	Average Cooling Daytime [GJ/hr]	Average Cooling Daytime [MBtu/hr]	Average Cooling Nighttime [GJ/hr]	Average Cooling Nighttime [MBtu/hr]
January	0.000	0.000	0.025	0.024
February	0.020	0.019	0.025	0.024
March	0.132	0.125	0.027	0.026
April	0.199	0.189	0.031	0.029
May	0.269	0.255	0.037	0.035
June	0.343	0.325	0.047	0.044
July	0.393	0.372	0.056	0.053
August	0.326	0.309	0.044	0.042
September	0.171	0.162	0.030	0.029
October	0.047	0.045	0.027	0.025
November	0.006	0.006	0.026	0.024
December	0.000	0.000	0.025	0.024

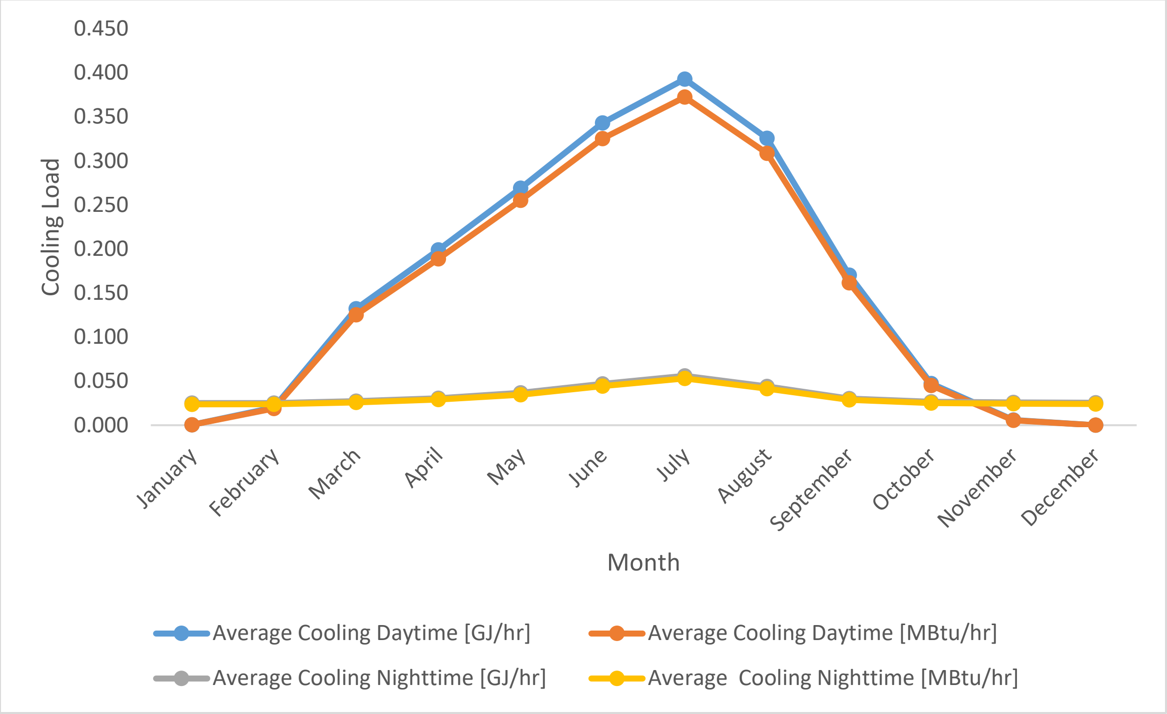


Figure 8. Average Monthly Cooling Load

Table 9. Peak Cooling Loads for Daytime and Nighttime

Peak Cooling Load Daytime [GJ/hr]	Peak Cooling Load Nighttime [GJ/hr]
0.984	0.865

5. Parametric Study of Greenhouse Size

A parametric study of greenhouse sizes was conducted for this engineering study. The greenhouse was doubled and tripled in size and energy loads were compared between the one, two, and three acre greenhouses.

5.1. Two Acre Greenhouse

Similar to the one acre baseline model, heating and cooling loads were extracted and analyzed. Tables 10 and 11 show the monthly heating and cooling loads for the two acre greenhouse, respectively. Figures 9 and 10 show the heating and cooling loads for the two acre greenhouse, respectively. Peak heating and cooling loads for this greenhouse size are shown in Tables 12 and 13, respectively.

Table 10. Two Acre Monthly Average Heating Loads

Month	Average Heating Daytime [GJ/hr]	Average Heating Daytime [MBtu/hr]	Average Heating Nighttime [GJ/hr]	Average Heating Nighttime [MBtu/hr]
January	2.88	2.73	3.29	3.11
February	2.64	2.50	3.22	3.06
March	1.89	1.79	2.82	2.67
April	1.71	1.62	2.45	2.32
May	1.49	1.41	2.19	2.07
June	1.30	1.23	1.88	1.78
July	1.09	1.03	1.52	1.44
August	1.26	1.19	1.61	1.53
September	1.70	1.61	2.13	2.02
October	2.16	2.05	2.59	2.45
November	2.65	2.51	2.93	2.78
December	2.97	2.81	3.14	2.98

Table 11. Two Acre Monthly Average Cooling Loads

Month	Average Cooling Daytime [J/hr]	Average Cooling Daytime [Btu/hr]	Average Cooling Nighttime [J/hr]	Average Cooling Nighttime [Btu/hr]
January	0.001	0.001	0.051	0.048
February	0.037	0.035	0.050	0.048
March	0.246	0.234	0.054	0.052
April	0.374	0.354	0.060	0.057
May	0.507	0.480	0.070	0.066
June	0.652	0.618	0.087	0.082
July	0.744	0.705	0.102	0.097
August	0.615	0.583	0.082	0.078
September	0.318	0.301	0.060	0.057
October	0.087	0.082	0.054	0.051
November	0.010	0.010	0.052	0.049
December	0.000	0.000	0.051	0.048

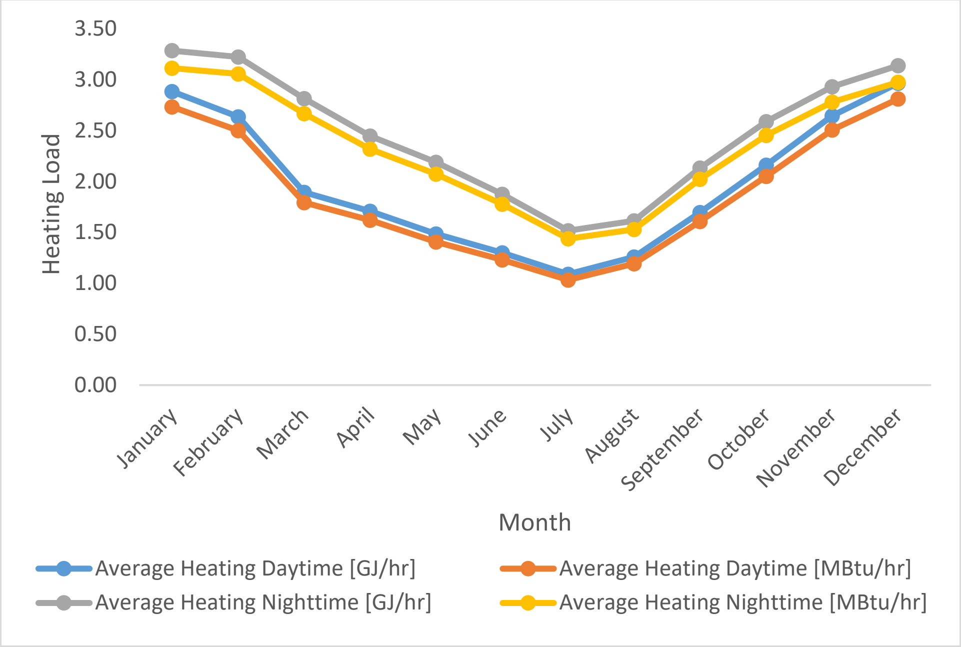


Figure 9. Two Acre Monthly Average Heating Loads

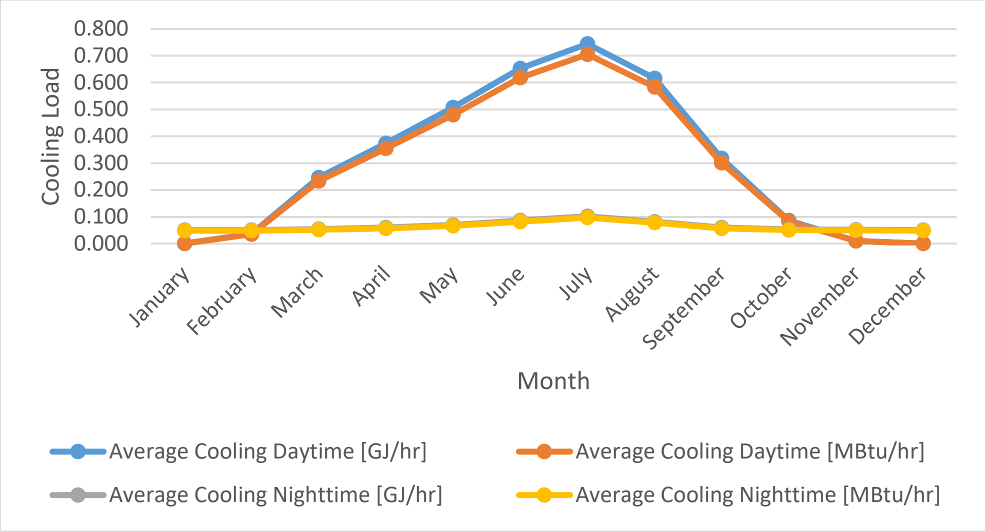


Figure 10.Two Acre Monthly Average Cooling Loads

Table 12. Peak Heating Loads

Peak Heating Load Daytime [GJ/hr]	**Peak Heating Load Nighttime [GJ/hr]**
8.533	6.700

Table 11. Peak Cooling Loads

Peak Cooling Load Daytime [GJ/hr]	Peak Cooling Load Nighttime [GJ/hr]
1.945	1.571

5.2. Three Acre Greenhouse

Tables 14 and 15 show the monthly heating and cooling loads for daytime and nighttime for the three acre model. Peak heating and cooling loads for this greenhouse size are found in Tables 16 and 17. Figures 11 and 12 show the monthly heating and cooling loads for the three acre greenhouse, respectively.

Table 14. Three Acre Monthly Average Heating Loads

Month	Average Heating Daytime [GJ/hr]	Average Heating Daytime [MBtu/hr]	Average Heating Nighttime [GJ/hr]	Average Heating Nighttime [MBtu/hr]
January	4.29	4.06	4.88	4.62
February	3.93	3.72	4.79	4.54
March	2.83	2.69	4.19	3.97
April	2.56	2.43	3.65	3.46
May	2.23	2.11	3.27	3.10
June	1.96	1.86	2.81	2.66
July	1.65	1.57	2.28	2.16
August	1.90	1.80	2.42	2.29
September	2.55	2.41	3.19	3.02
October	3.23	3.06	3.85	3.65
November	3.94	3.74	4.36	4.13
December	4.41	4.18	4.66	4.42

Table 15. Three Acre Monthly Average Cooling Loads

Month	Average Cooling Daytime [GJ/hr]	Average Cooling Daytime [MBtu/hr]	Average Cooling Nighttime [GJ/hr]	Average Cooling Nighttime [MBtu/hr]
January	0.001	0.001	0.076	0.072
February	0.053	0.051	0.076	0.072
March	0.361	0.342	0.082	0.077
April	0.549	0.520	0.089	0.085
May	0.745	0.706	0.103	0.098
June	0.962	0.911	0.127	0.120
July	1.096	1.039	0.148	0.140
August	0.905	0.858	0.120	0.114
September	0.465	0.441	0.089	0.084
October	0.127	0.120	0.080	0.076
November	0.015	0.014	0.078	0.074
December	0.000	0.000	0.077	0.073

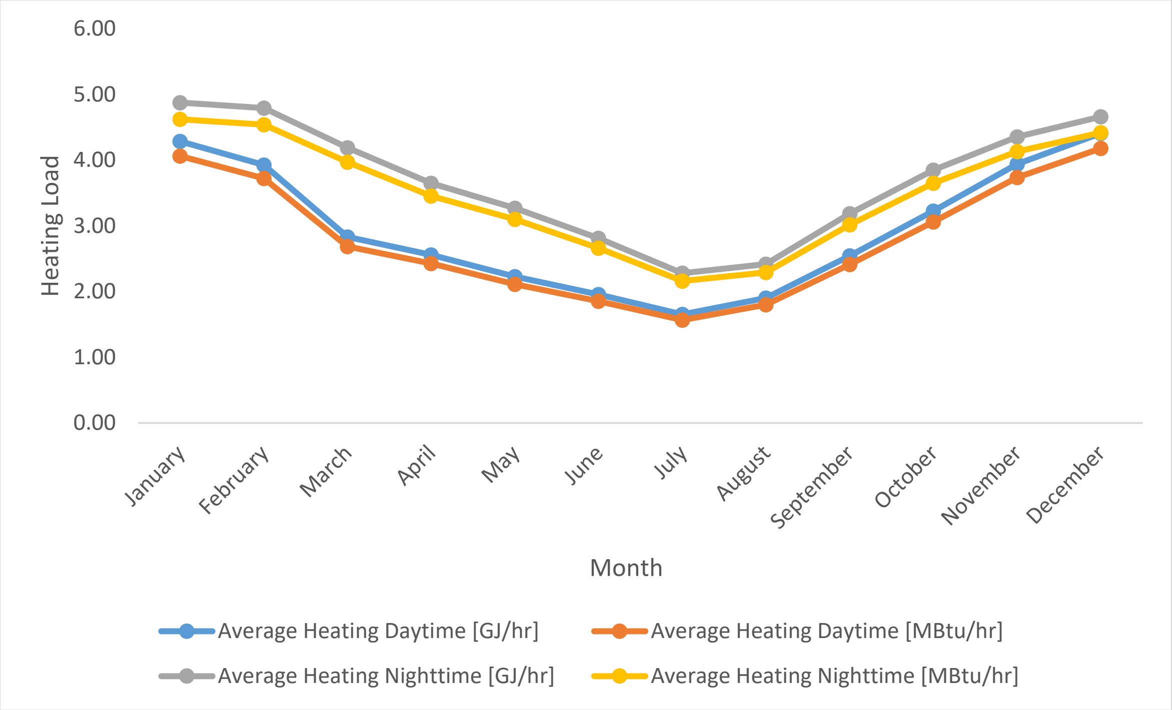


Figure 11. Two Acre Monthly Average Heating Loads

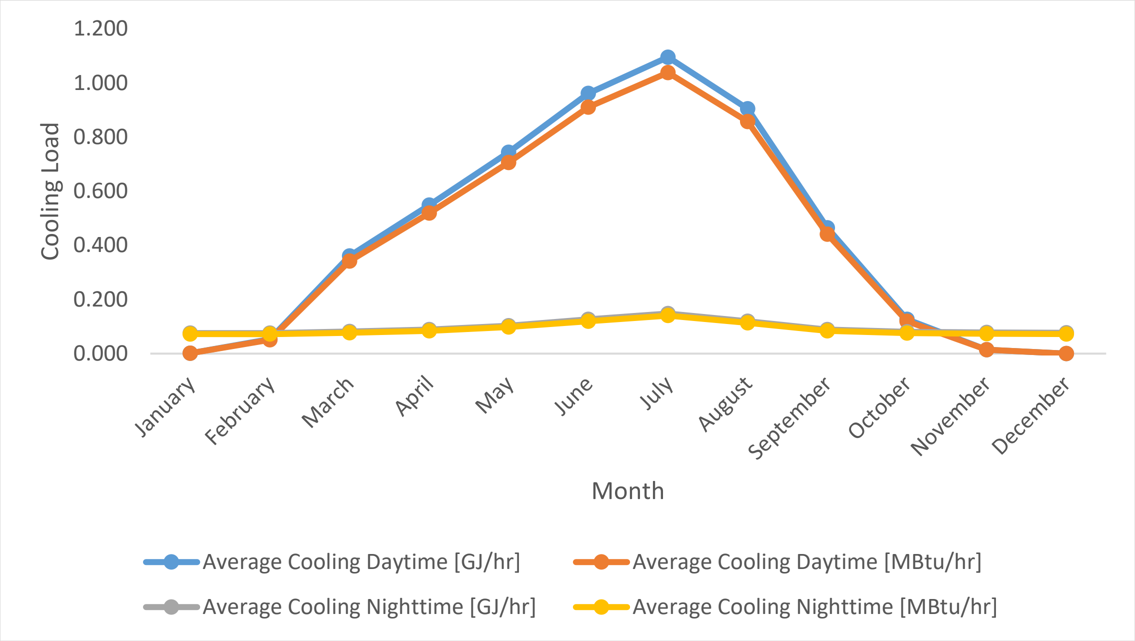


Figure 12. Three Acre Monthly Average Cooling Loads

Table 16. Peak Heating Loads

Peak Heating Load Daytime [GJ/hr]	Peak Heating Load Nighttime [GJ/hr]
12.691	9.978

Table 17. Peak Cooling Loads

Peak Cooling Load Daytime [GJ/hr]	Peak Cooling Load Nighttime [GJ/hr]
2.908	2.289

5.3. Comparison of Peak Heating and Cooling Loads

Comparing peak heating and cooling loads between the three greenhouse sizes shows how heating and cooling loads increase with increasing greenhouse size. Comparison of peak heating and cooling loads among the three different sized greenhouses are listed in Table 18 and illustrated in Figure 13.

Table 18. Comparison of Peak Loads

	Baseline (1 Acre) Greenhouse	Two Acre Greenhouse	Three Acre Greenhouse
Peak Heating Load Day	4.335	8.533	12.691
Peak Heating Load Night	3.389	6.700	9.978
Peak Cooling Load Day	0.984	1.945	2.909
Peak Cooling Load Night	0.865	1.571	2.289

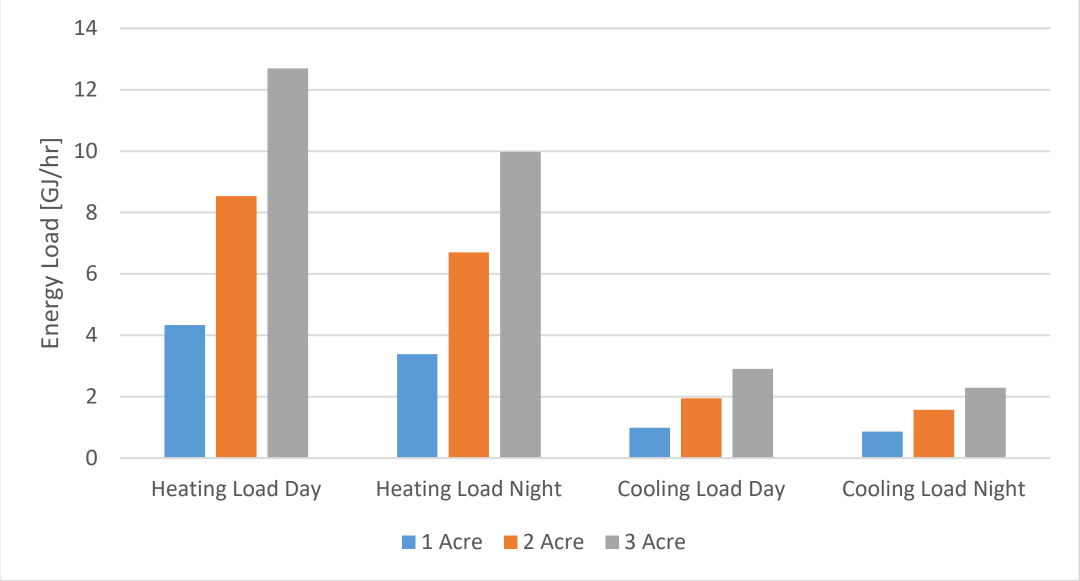


Figure 13. Comparison of Peak Loads

6. Conclusion

The lowest monthly available heating energy from the sugar plant’s discharged hot condenser water was 14.4 GJ/h as shown in Table 1. The peak heating load for all three greenhouse sizes are less than the available heating energy amount. This makes the idea of using of waste heat from the sugar plant to condition greenhouses feasible. Available heating energy from the discharged hot condenser water should be sufficient to provide enough heat for a 3-acre greenhouse.

7. References

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