AC 2008-1842: DESIGN OF A CARBON NEUTRAL GREENHOUSE FOR GREENFIELD COMMUNITY COLLEGE

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abstract

This paper describes the research, development and design of a carbon neutral 25 by 40 foot greenhouse designed by Wentworth Institute of Technology for Greenfield Community College (GCC). The greenhouse will be used for environmental science and horticultural lab experiments and for the study of energy conservation and renewable energy technologies. The system is designed to have a zero net energy impact on their campus. The system will be an active pilot demonstration for energy conservation and renewable energy technologies. When in operation in the Fall of 2008, it will achieve the optimum use of the various technologies.

The greenhouse will have a significant southerly exposure using double pain insulating glass. The north sloping roof, back and each side will be enclosed and insulated to preserve heat. The south facing roof will be at a 45 degree angle for near optimum solar heating in the winter.

The maximum use of direct and passive solar heating will be used. Sixty-nine 55 gallon drums filled with water (in the cooler months) will be stacked three high against the rear wall to absorb maximum daily solar energy. This energy will then be transferred to the greenhouse enclosure at night. A moveable thermal blanket will be drawn over the top and down the sides of the greenhouse on cold nights to further preserve heat.

A geothermal closed loop ground coil heating system will be furnished for supplementary heating with radiant hot water as required. This system will basically transfer heat from the ground and discharges it into the greenhouse in the cold weather. It is 50% more efficient than a standard gas fired heater. The yearly electricity requirement for geothermal system will be offset with the electricity provided by a 7.5 KW solar voltaic system installed on the south facing roof of the adjacent laboratory building.

Monthly heat loss charts have been developed for the greenhouse for maximum loss, loss with passive thermal storage added, loss with thermal blankets added and geothermal heating requirement. Our calculations have shown that the 7.5 KW solar voltaic system will provide the yearly electricity that we estimate will be required by the compressor, motors, controls, fans, pumps and lights of the greenhouse system with an ample safety factor.

GCC has secured the required funding for the project and anticipates obtaining bids in early Summer 2008. The goal is to complete construction in the Fall of 2008.

project description

In 2006 a preliminary design for a sustainable greenhouse for GCC was created. The project was designed to allow the school to both practice and teach the concept of a highly energy efficient building. The greenhouse was designed to have a 40 by 25 footprint and serve as a showcase for renewable and sustained energy technologies.

This greenhouse used power created from both solar cells and the school's traditional power grid. While in some peak hours of use it drew energy from the school's power grid, the energy it put back into the grid when the greenhouse did not need it more than compensated for the energy drawn out.

In early 2007, the original design was revisited by WIT and it was determined the greenhouse's design could be improved to further increase its energy efficiency and to make the structure carbon neutral. This paper describes the alternative design.

original design overview

The proposed greenhouse was to be located adjacent to an existing laboratory building. The original designed greenhouse extended 40 ft. from the building and only shared a 25 ft. common wall on the north side. All the sides of the greenhouse were made with single pained glass and thermal storage was in the form of 25 ten foot clear tubes filled with water. A thermal storage blanket was also used to retain heat during the night. The longest sides of the greenhouse were the east and west sides. A geothermal ground loop and heat pump system was used to supplement passive heating technologies.

new design overview

The new greenhouse is oriented parallel to the building with the 40 ft. length facing south. The south facing slanted side of the greenhouse will be made of double pane insulated glass. The east, west and north sides will be made of traditional construction materials with insulation being the maximum priority. The two sides, front and back walls will be finished with the same type and color brick used for the adjacent building. The foundation will be set at a maximum depth of five feet into the earth. The slab will be extra thick with slate flooring to act as a large heat sink and take advantage of the earth's constant temperature. Thermal mass in the form of water will be used to collect heat during the day and disperse it in the cooler evenings to reduce demands on the heating system. The supplementary heating and cooling system for the greenhouse will be in the form of closed loop geothermal heat pump system powered by a 7.5 kW photovoltaic system.

project design

The proposed greenhouse will be a south facing structure with a 25 ft. by 40 ft. footprint, as shown in Figure 1. The north wall of the greenhouse was moved away from the existing lab building wall to make room for an exiting stairway at the east end of the building. The floor of the greenhouse will be sunk approximately 5 ft. below the grade of the western side of the greenhouse. See Figure 1 for western and southern elevations and a plan view of the greenhouse.

The frame of the greenhouse will be made of metal and the walls will be finished with 3 inch wide brick and 3.25 inch thick fiberglass insulation on the inside covered with plywood. The resulting thermal resistance (R-Value) of these walls will be 12.12 ft^2-h-°F/BTU. The vertical South facing side will be made of similar material. The northern slant will have at least 3.25" of fiberglass insulation having an R-Value of 10.9 ft^2-h-°F/BTU. A reflective material will be attached to the interior side of the northern slant to reflect incoming solar radiation downward. The south facing slanted wall will be made from insulating glass with an R-Value of 1.54 ft^2-h-°F/BTU. Aside from determining structural support as a function of loading, snow is not expected to impact operation of the greenhouse.

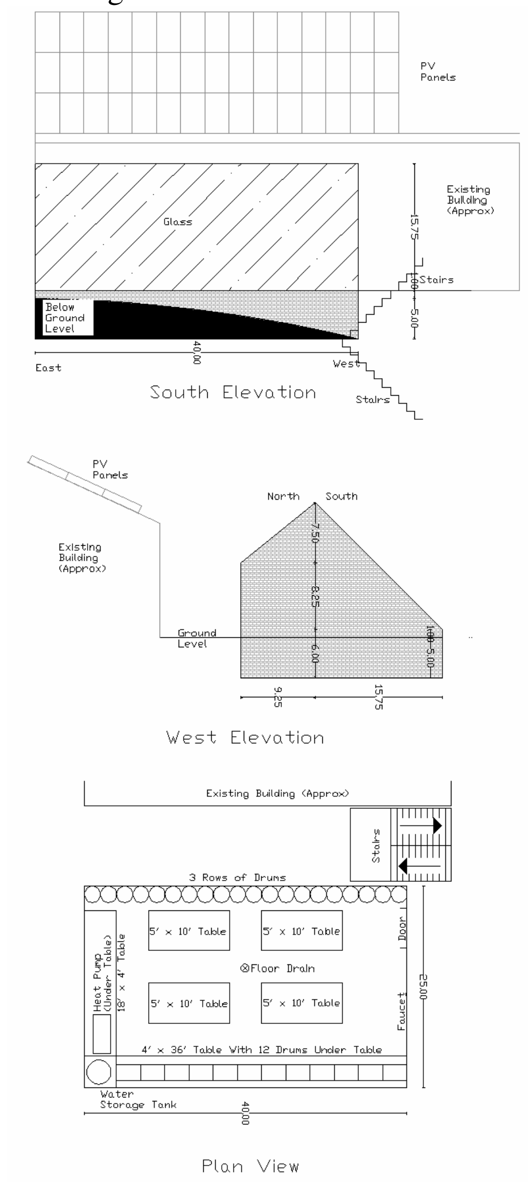

Figure 1: South and West Elevations and Plan View

heating demand

Solar radiation will be the primary source of heating for the greenhouse. The original design called for the axis of the roof to run north-south. The new design will have the axis of the roof running east-west, which will result in up to 25% more solar radiation entering the greenhouse.[1] The angle of the south facing slope is 45° above the horizontal. While the range of angles for optimum heating by solar radiation roughly approaches 63° for our latitude[2], the resulting height will be too tall for construction purposes. Monthly heating requirements for the greenhouse were calculated to determine the size of the geothermal heat pump.The following table summarizes data used for heating demand calculation.

Table 1: Average Monthly Temperature and Degree Days for Worcester MA[3]

Month	Average Temp. (F)	Heating Degree Days (F)
Jan.	22.82	727
Feb.	24.8	626
Mar.	33.62	539
Apr.	44.42	343
May.	55.58	167
Jun.	64.22	38
Jul.	69.62	3
Aug.	68	14
Sep.	60.26	87
Oct.	50	258
Nov.	39.38	427
Dec.	27.32	648

Conductive heat loss for the greenhouse was calculated for the sides of the greenhouse. The basement slab was not considered for the purposes of heating calculations and thermal storage purposes. Any of the side walls below ground surface were treated as above ground sides.

Conductive Heat Loss[4]

$$Q_c = \sum\left(\frac{1}{R}\times A\right)\times\left(\frac{24hours}{Day}\right)\times(\#DD)$$

R = R Value of a side (ft^2-h-°F/BTU)

A = surface area of a side (ft^2)

DD= degree days. (°F)

Table 2: Monthly Conductive Heat Losses

Month	Q_c (BTU/month)
Jan.	1.312E+07
Feb.	1.130E+07
Mar.	9.728E+06
Apr.	6.190E+06
May.	3.014E+06
Jun.	6.858E+05
Jul.	5.414E+04
Aug.	2.527E+05
Sep.	1.570E+06
Oct.	4.656E+06
Nov.	7.706E+06
Dec.	1.169E+07

Additional heat losses were calculated for air infiltration. It was assumed there would be one change of volume of air in the greenhouse per hour, resulting in 24 changes per day.

Infiltration Heat Loss[5]

$$Q_{\text{inf}} = 0.018 \times V \times K \times \Delta T \times t$$

V = volume of the greenhouse (ft^3)
K = number of changes per day (day^{-1})
ΔT = difference in temperature between indoor and outdoor temperatures (°F)
t = number of days in each month (days/month)

The following table contains the heat losses by infiltration on a monthly basis using 65°F as an internal temperature. The table to the right of it contains a total heat loss value for each month.

Table 3: Monthly Infiltration and Total Heat Losses

Infiltration Heat Loss

Month	Q_{inf} (BTU/month)
Jan.	7.668E+06
Feb.	6.557E+06
Mar.	5.441E+06
Apr.	3.110E+06
May.	9.116E+05
Jun.	0
Jul.	0
Aug.	0
Sep.	0
Oct.	2.062E+06
Nov.	4.115E+06
Dec.	6.740E+06

Total Heat Loss

Month	Q (BTU/month)
Jan.	2.079E+07
Feb.	1.785E+07
Mar.	1.517E+07
Apr.	9.300E+06
May.	3.926E+06
Jun.	0
Jul.	0
Aug.	0
Sep.	1.518E+06
Oct.	6.719E+06
Nov.	1.182E+07
Dec.	1.843E+07

A removable nighttime thermal curtain is employed to reduce heating demands. A retractable nighttime curtain with an R Value of at least 10 ft^2-h-°F/BTU will be drawn against the south facing slant. This blanket increases the R Value of the south facing slant (the largest of all the sides) from 1.54 to 11.54. These two R Values will be weighted for daily usage for the south facing side. For the conductive heat loss equation mentioned above, the conductive heat loss for the south facing slant was calculated by weighing the daytime R Value as 1/3 of the daily heat loss and the night time R Value as 2/3 of the daily heat loss. These two weighted values added together form a basis for the cumulative heat loss for the southern slant. New monthly heat losses (heating demands) were calculated using the weighted R Value for the curtain. Table 4 contains the newly calculated monthly heating demands which include both infiltration and conductive losses. This table replaces the total heat lost data in Table 3.

Table 4: Monthly Heating Demand with Nighttime Curtain

Month	Q (BTU/month)
Jan.	1.496E+07
Feb.	1.284E+07
Mar.	1.085E+07
Apr.	6.551E+06
May.	2.587E+06
Jun.	0
Jul.	0
Aug.	0
Sep.	8.211E+05
Oct.	4.651E+06
Nov.	8.400E+06
Dec.	1.324E+07

Thermal mass is another passive means of reducing the daily heating demands. Water heat storage is one of the simplest forms of thermal mass. A series of 55 gallon drums will be stacked against the north wall. If a 55 gallon drum contained 50 gallons of water, there is 411.5 lb of water per drum. Water has a specific heat of 1 BTU/lb-°F, so each drum has a specific heat of 411.5 BTU/lb-°F. Assuming an average nightly drop of 8°F for each drum[6], it can be estimated that each night the thermal mass of each drum releases 3.292E+03 BTU/day. The heating value for thermal mass was established by multiplying that heating value by the number of days in a month and the number of drums within the greenhouse. That heating value is subtracted from the heating demands from the above table to produce a new monthly heating demand. There is room along the north wall to install 3 rows of drums, stacked alternately like a brick wall. The bottom row will contain 20 drums, the second row 19 drums, and the third row 18 drums. 12 drums can be stored lying horizontally along the vertical south wall. A total of sixty-nine 55 gallon drums will be used as thermal mass for the greenhouse, resulting in 2.271E+05 BTU/day available. Although solar radiation is expected to vary seasonally, for the purposes of this design, solar radiation is only considered to be able to recharge the thermal mass during the day. For 40° N Latitude, the expected solar radiation on a 45° sloping window is 1687, 1858, 2182, 2307, and 2244 BTU/(day-ft^2) for December, January, February, March, and April respectfully.[7] Assuming 30% of the radiation is lost through the windows[8] of the southern slant and 40% of the remaining radiation can enter the thermal storage[9], then an expected 4E+06 BTU/day are available in December, which is larger than the 2.271E+05 BTU/day expected to be released from the thermal storage. New monthly heating demands for the greenhouse were calculated and are presented in Table 5. Figure 2 depicts a pictorial representation of the data found in Tables 2, 4, and 5.

Table 5: Monthly Heating Demands with Nighttime Curtain and Thermal Mass

Month	Q (BTU/month)
Jan.	7.922E+06
Feb.	6.479E+06
Mar.	3.808E+06
Apr.	0
May.	0
Jun.	0
Jul.	0
Aug.	0
Sep.	0
Oct.	0
Nov.	1.586E+06
Dec.	6.201E+06

Compared to the original design, the new greenhouse requires, on an average monthly basis, less heating by non-passive techniques. Table 6 displays the percent difference for heating demand of the new design compared to the original design.

Table 6 Comparison of Heating Demands

	Original Design	New Design	
Month	Q (BTU/month)		Percent Diff.
January	4.382E+07	7.922E+06	81.9%
February	3.732E+07	6.479E+06	82.6%
March	3.021E+07	3.808E+06	87.4%
April	1.606E+07	0	100%
May	2.532E+06	0	100%
June	0	0	NA
July	0	0	NA
August	0	0	NA
September	0	0	NA
October	9.564E+06	0	100%
November	2.221E+07	1.586E+06	92.9%
December	3.815E+07	6.201E+06	83.7%

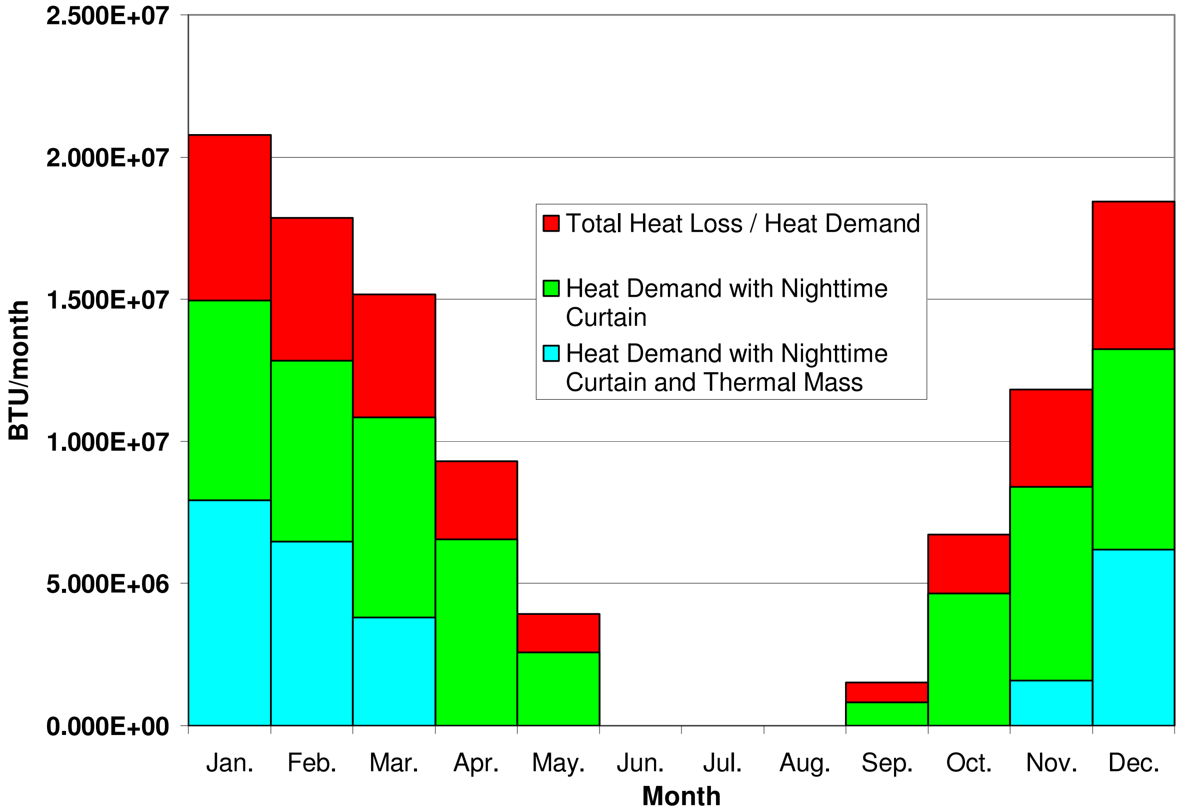

Figure 2: Graph of Heating Demands

heating and cooling system

Figure 3 shows an illustration of the three major technologies used in the greenhouse to reach carbon neutrality. The geothermal system will consist of two (2) three and a half ton units. One is for main use, and the other for back up. Each one is capable of providing 50,000 BTU/hr. The geothermal system has a main unit and a ground loop. The ground loop tubing is the portion that is placed at an appropriate depth underground. Heat transfer fluid is then pumped through the tubing and back to the main unit.

In cold weather, the main unit transfers the heat from the ground to the hot water re-circulating tank in the greenhouse. In warm weather, the main unit can utilize the cooling effect of the ground to help cool the adjacent lab building.

The main unit is basically a heat pump complete with compressor, condenser, expansion valve and evaporator. The refrigerant runs one way through the system for heating and the opposite direction for cooling. The water heated by the geothermal system will be stored in a hot water storage tank. It will be then run through a series of radiant tube heaters located in the floor of the greenhouse.

Using a coefficient of performance (COP) of 4[10], and a heating value (Q_h) of 50,000 BTU/hr, the required work of the heat pump (W_c) can be calculated.

$$W_c = \frac{Q_h}{COP} = \frac{50{,}000\frac{BTU}{hr}}{4} = 12{,}500\frac{BTU}{hr} \times \frac{1kWh}{3412BTU} = 3.66\frac{kWh}{hr}$$

automated control system

An automated temperature control system will be installed in the greenhouse. This control will maintain the internal greenhouse temperature at 65°F by regulating the required amount of heating provided by the geothermal heating system and cooling provided by automated ventilation louvers in the roof of the greenhouse. The control panel will include a data logger for temperature, heating and cooling parameters and climate data. This data will be used to calculate a carbon neutral inventory. A remote computer system will also monitor and control the greenhouse operation, as well as the photovoltaic panels.

photovoltaic panels

A 7.5 kilowatt photovoltaic system will provide the power needed for the geothermal system, venting system as well as the lighting and computer system. It will have 45 three foot by five foot panels placed on the roof of the adjoining building. The power will run from the panels through a DC-AC inverter and voltage controller. The 7.5 kW PV system can produce approximately 9000 kWh/yr. If the electricity produced by the PV system was exclusively used by the heat pump, there would be approximately 2,450 available hours of full load heat pump operation per year.

$$\frac{9{,}000\frac{kWh}{yr}}{3.66\frac{kWh}{hr}} \approx 2{,}450\frac{hr}{yr}$$

The theoretical hours of operation needed by a 50,000 BTU/hr heat pump can be approximated by using the sum of the monthly heating demand from Table 5 (23.60E+06 BTU/yr).

$$\frac{23.60E+06\frac{BTU}{yr}}{50{,}000\frac{BTU}{hr}} \approx 472\frac{hr}{yr}$$

Theoretically, the heat pump will only require 472 of the 2,450 available hours of operation provided by the PV system. The solar panels will power the heat pump and any excess electricity will be sent through the schools electrical system during the day. At night, grid electricity will power the heat pump. The system will be carbon neutral if the amount of electricity produced by the PV system at least equals the electricity withdrawn from the grid.

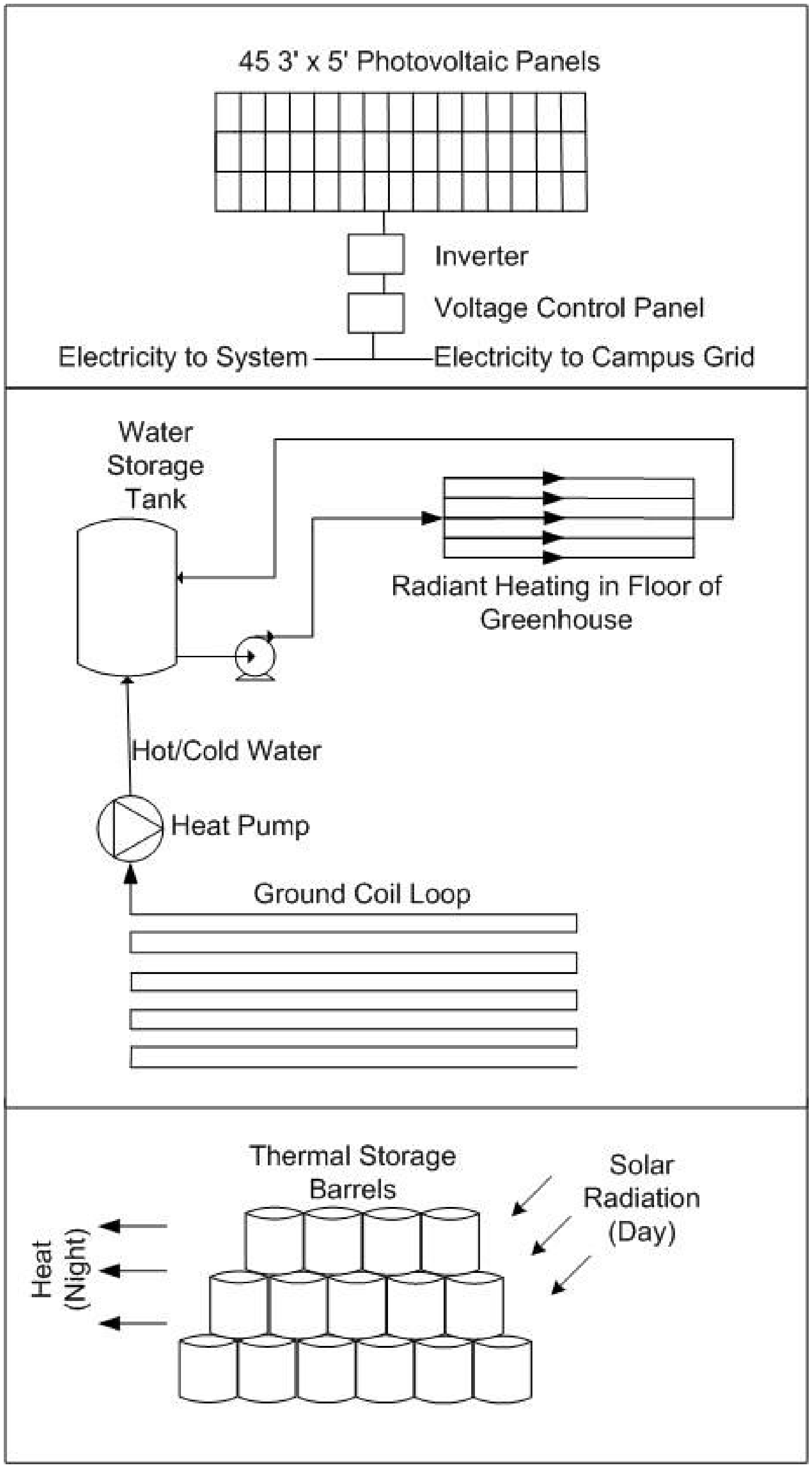

Figure 3: Process Illustration

estimated cost

The estimated total cost of the greenhouse is $400,000. The cost of construction of the greenhouse is estimated to be $180,000. The construction costs are based on adjusted previous quotes for the original design. $25,000 has been estimated for the foundation, drains, sinks, plumbing, wiring, and permitting. $20,000 has been estimated for the thermal mass system. The estimated value for the thermal mass has been inflated for the contingency that a more elegant form of thermal mass than 55 gallon drums may be used. $75,000 has been estimated for the photovoltaic system and $40,000 for the geothermal system. These values are based on preliminary vendor quotes. An additional $20,000 has been estimated for design engineering and project management. Finally $40,000 has been estimated for contingencies.

student participation and ongoing work

An Environmental Engineering student and an instructor created the original design. The client and designers revisited the design and an additional Civil Engineering student was added to the design team. The newly formed design team laid the framework for the current design. Subject matter, such as alternative energy, energy conservation, heat transfer, thermodynamics, construction materials, construction graphics and project management taught in various courses was integrated into this design. They were responsible for making changes to the original design to minimize heating demands of the greenhouse. They changed the orientation of the greenhouse and construction materials. Based on the new orientation and construction material, they re-evaluated heating demand calculations. This second design team also researched and sized the geothermal heating system and redesigned photovoltaic panels.

A third design team has been formed with the addition of at two additional Civil Engineering students. This new design team will investigate several new elements to complement the previous design. The new team will be performing a survey of the site, using skills taught in a surveying course, to finalize the location and elevation of the greenhouse. They will also be responsible for finalizing the sizing of geothermal heating system to prepare a design suitable for bidding. Students will re-evaluate the use of active solar water heating panels at the request of the client. These students have expressed interest in comparing the benefits of balancing the performance and aesthetic aspects of different forms of thermal mass, such as choosing between 55 gallon drums or tall clear tubes to hold water. Previous designs reports included basic calculations and component sizes. The new design attempts to extend the design from a conceptual state to one that can be implemented. This final definitive result will be used in the bidding process.

contribution to engineering education

The design of the greenhouse has allowed students to use skills they learned during their pursuit of an engineering education. The greenhouse benefits will extend beyond the design phase. The completed greenhouse will have two primary uses, as a greenhouse and as a teaching tool. The greenhouse can be used to demonstrate basic elements of heat transfer, energy conservation and alternative energy technologies. It also will be used in environmental science, horticultural and botany courses for laboratory studies now being developed. Heat transfer can be demonstrated by installing a small weather system near the greenhouse. This will log basic data from indoor collection instruments that demonstrate the changes of indoor temperature with the changes of outdoor conditions. Students will then be able to determine the influence of thermal mass on the system's heating demand.

The proposed design calls for 55 gallon drums to be used as the main source of thermal mass for the greenhouse. These drums can be emptied and replaced with other forms of thermal mass. Students can collect heating demand data based on actual hours of operation of the heat pump using these 55 gallon drums as thermal mass. Students can then change the thermal mass in form and material, such as using water in smaller containers or different types of thermal mass like sand, bricks, or cement blocks to determine different heating demands. Collecting various temperature and performance data for the system allows the students and faculty to maximize the operation of the greenhouse so that it minimizes outside electrical dependence. Students can establish the carbon footprint of the greenhouse on an annual basis by comparing the outside electrical dependence with the electricity generated by the photovoltaic cells.

summary

The new design is much more energy efficient than the original design. This new design will require at least 85% less heating than the original design by changing the direction of the building, reducing the number of sides made of glass, and increasing the thermal mass. Based on heating demand only, the designed system will be carbon neutral as the electricity produced will be at least three times the amount of electricity required. When fully constructed, the greenhouse will be a showcase of green technologies and provide prestige and coursework for its educational institute.

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2 McCullagh, p. 25.
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4 Hinrichs, Roger A. and Merlin Kleinbach. Energy: Its Use and the Environment. Thomson Learning, Inc., 2002 p. 137.
5 Hinrichs and Kleinbach, p. 134.
6 http://aes.missouri.edu/swcenter/sustain/Solar-heated%20greenhouse.pdf
7 McCullagh, p. 19.
8 McCullagh, p. 300.
9 McCullagh, p. 85.
10 http://acforsale.com/online/product_info.php?cPath=147_269&products_id=810