FEASIBILITY OF USING AN AUGMENTING SOLAR ARRAY FOR A GREENHOUSE IN NORTHWEST OHIO

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Abstract

The idea of growing plants in environmentally controlled areas has existed since Roman times. By the first century A.D., the Romans were growing fruits and vegetables in simple greenhouses or cold frames. A green house is an example of a green building, making use of renewable energy and sunlight to grow plants during winter, when the temperature is too cold to grow the plants out in the open at northern latitudes. However, there is often not enough sunlight to sufficiently warm the greenhouse in some areas without additional heating. Such is the case in Northwest Ohio. One such greenhouse uses natural gas to provide this additional heating. The burning of natural gas incurs extra costs, and is a non-renewable energy source that emits carbon dioxide, thereby contributing to global warming. Therefore, there is a need to eliminate or reduce the use of natural gas for this greenhouse. One solution proposed by the owners of the greenhouse was to use a solar collector array placed by the side of the green house. In this paper, the authors describe an analysis carried out in collaboration with the greenhouse owners to evaluate the feasibility of using a solar array. The analysis involved using the design provided to the owners by a consulting company. The study evaluated the design from the perspective of cost savings per year, due to reduced gas usage and against the cost of installation and maintenance of the solar array system. The results were then used to calculate the payback period.

Introduction

An agricultural greenhouse consists of frames of metal or wood covered with a transparent material, which provides a suitable environment for the intensive production of various crops. All greenhouses collect solar energy. The basic operational principles of greenhouses include: collection of light and conversion to heat; storage of thermal energy; release of thermal energy; temperature moderation; a controlled environment; and, protection from severe weather and animals. A greenhouse is essentially an enclosed structure that traps short-wavelength solar radiation and stores long-wavelength thermal radiation to create a favorable microclimate for plant growth. It is not a problem to maintain the temperature inside the greenhouse when there is sun during most times of the day, except in the Northwest Ohio location, where there is a lot of snowfall during the winter and there are fewer sunny days. Hence, there is a need for additional thermal energy to heat the greenhouse and maintain the required temperature for plants to grow.

Different renewable energy sources can be applied in heating the greenhouse, such as geothermal, solar, and biomass instead of using fossil fuels, which have predominantly been used thus far. The intent of this study was to analyze the new design of a greenhouse located at the J.C. Reuthinger Memorial Preserve on Oregon Road in Perrysburg, Ohio. The heat demand in the greenhouse was provided by heaters that burn natural gas. The main problem with this type of heater is the cost of the fuel. That is why the owners decided to utilize a solar energy storage system in the greenhouse. As only low-temperature heat was needed for preheating the air in the greenhouse, the use of solar panels was proposed in order to partially reduce heating demand of the heater, thereby reducing the amount of fuel consumption. The purpose of this study was to evaluate a design of a new heating system for the greenhouse that incorporated solar panels for economic viability.

The Greenhouse

The greenhouse was 30' x 96' and used predominantly for growing perennial plants. Figures 1 and 2 show how the greenhouse was built with an aluminum frame system that was shrouded by clear plastic sheets. It was a double poly structure with air pumped between two layers. The temperature maintained inside the greenhouse for these plants was 60°F. Greenhouse use starts the first week of January and goes until the first week of June. Since this area of the country faces a severe climate during the winter, which starts from December and lasts until March, the greenhouse needed to be heated during this period. In the proposed design, solar panels would be used to collect the heat from sun as the first stage of heating. Solar energy collected by solar panels would then used to heat the fluid stored in a drain-back tank, which would then give power to a natural gas heater to operate and heat the tube in the heat exchanger, thereby heating the floor of the greenhouse.

Description of the System

Figure 3 shows a schematic diagram of the proposed heating system. The proposed design consisted of five flat-plate solar thermal collectors manufactured by Alternate Energy Technologies (AET). The selected solar collector system was chosen based on the availability in the local market and domestic demand. Aluminum flat-plate solar collectors were popular because of their low investment costs. The number of solar thermal collector panels was determined according to the ground surface area of the greenhouse.

Figure 1. Exterior View of the Greenhouse

Figure 2. Interior View of the Greenhouse

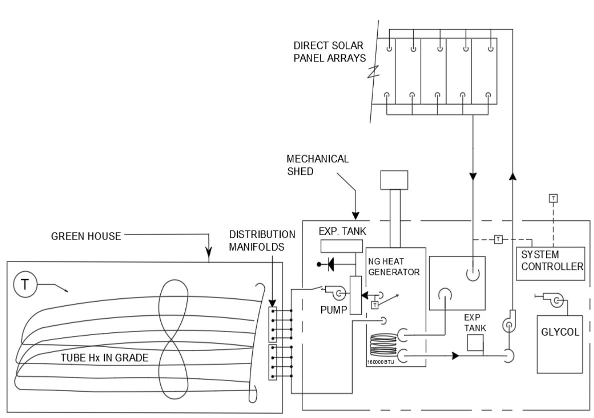

Figure 3. Proposed System Flow Diagram (Source: greenhouse owners)

Theory of Operation

As the sun starts to shine on the solar collectors, the collectors begin to heat up. This system had a differential controller that sensed temperature differences between water leaving the solar collector and the coldest water in the tank. When the water in the collector was about 12°F warmer than the water in the tank, the controller turned on the pumps. When the temperature difference dropped to about 3 -5°F, the pump turned off. In this way, the water always gained heat from the collector when the pump was operating. The solar installer manually set the differential temperature of the controller at the time of system installation. The pumps were very quiet.

The system collected heat by circulating the water in the collector loop through the collectors, the drain-back reservoir, and a heat exchanger. When the pumps turned on, the water in the collector loop was circulated through the solar collectors where it was heated. The return water from the solar collectors passed through the drain-back tank and to the heat exchanger. The heat exchanger gave up the collected heat to the water in the main underground heat exchanger. The now cooler water was returned to the collectors to continue to collect heat. When there was no longer a marked difference between the temperature at the solar collector and at the solar storage tank (4°F), the controller automatically turned the pumps off—since there was no heat to be gained. This process was repeated continuously throughout the day. This was all done automatically and required no interaction on the part of the system owner. Drain-back systems provide a fail-safe method of ensuring that collectors and collector-loop piping never freeze, by removing all water from the collectors and collector-piping loop when the system is not collecting heat. Freeze protection is provided when the system is in the drain mode. Water in the collectors and exposed piping drains into the insulated drain-back reservoir tank each time the pump shuts off. A slight tilt of the collectors is required in order to allow complete drainage. A sight glass attached to the drain-back reservoir tank showed when the reservoir tank was full and the collectors had to be drained. For this reason, the drain-back system was protected from freeze damage at all temperatures.

Methodology

The basic idea was to compare two greenhouse heating systems: a conventional fossil-fuel system and a hybrid system in which part of the heating demand was covered by solar collectors, heat storage, and a heat pump. The economic feasibility of heating the greenhouse using these two methods was analyzed.

Data Collection

The data collection for the evaluation of the project involved the following areas:

- The monthly averaged, mean maximum, and mean minimum temperatures from January 2014 to July 2014 were collected. These data were used to calculate the greenhouse's thermal need. These data were obtained from a commercial database and from the Internet source AccuWeather.
- The price of natural gas during the recommended period of time was also obtained from Columbia Gas of Ohio, the local gas supplier company.
- Equipment prices for the installation of solar panels were obtained from the manufacturer recommended by the designer. For all of the systems, mean costs with reference to a greenhouse ground-surface area of 2700 sq. ft. were used. This was the actual ground surface of the greenhouse that was being analyzed.
- For the evaluation of the proposed design, the solar system costs, installed collector surface area, and operating costs were obtained from the manufacturer and the suppliers.

Using all of the parameters mentioned, the total thermal needs, the parts covered by the solar panel system and the lifecycle costs of two heating systems were calculated. The lifecycle cost is the sum of all the costs associated with an energy system; in this case, investment, fuel, electricity, and maintenance, during its lifetime at current dollar value.

Analysis and Results

Table 1 shows the average temperature during the six months and the remaining temperature increase needed to be attained in order to keep the greenhouse at 60°F. Figure 4 shows the location of the two gas heaters currently used to heat the greenhouse in winter. Figure 5 shows the fuel consumed for the six months of 2014. The information about the fuel consumed was obtained from monthly gas bills for 2014. It was also found that the unit price of the gas supplied by Columbia Gas of Ohio varied from month to month. Data on the fuel consumed every month and the estimated unit rate of natural gas were used to calculate the cost incurred each month for the consumption of gas (see Table 2). February, the coldest month during that year, had the highest consumption of fuel.

Only about 80-85% of the heat produced by the heaters was used for heating the space; the remaining 15-20% was lost through the ground, covering material, and other related avenues [1]. Since the greenhouse being analyzed had two layers of plastic covering, based on published literature [1], it was assumed that 15% of the heat was wasted. Using the information on the temperature required, the actual temperature, the fuel consumption, the heat-loss percentage, and the amount of gas used and its cost were determined to maintain the temperature regardless of the fuel used for heat loss, as shown in Table 3. The actual gas used, A, was 85% of the total gas used, *T*.

Table 1. Temperature Difference Each Month

Months (2014)	Temperature needed to maintain (°F)	Actual average temperature (°F)	Remaining temperature needed to be raised (°F)
January	60	25.84	34.16
February	60	18.92	41.08
March	60	29.75	30.25
April	60	49.75	10.25
May	60	61.69	-1.69
June	60	72.25	-12.25

Figure 4. Location of Heaters inside the Greenhouse (Source: J.C Reuthinger Preserve, Oregon Road, OH)

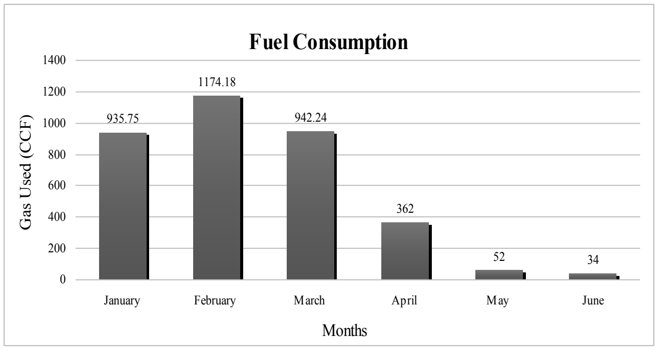

Figure 5. Fuel Consumption for the First Six Months of 2014

Table 2. Historic Rates in $/CCF (Source: Columbia Gas of Ohio, 2014)

Billing period end date (2014)	Rate ($/CCF)	Fuel consumed (CCF)	Total amount ($)
January	$0.5697	935.74	$533.09
February	$0.6547	1174.18	$768.73
March	$0.6145	942.24	$579.00
April	$0.5984	362	$216.62
May	$0.5821	52	$30.26
June	$0.58	34	$19.72

Table 3. Temperature and Fuel Consumption Considering Heat Loss

Month	Temper-ature required to raise (°F)	Total Gas used = T (CCF)	Actual Gas used for raising tempera-ture = A (CCF)	Cost incurred in actual Gas (A) used to raise temp.
January	34.16	935.74	795.37	$ 453.12
February	41.08	1174.18	998.05	$ 653.42
March	30.25	942.24	800.90	$ 492.15
April	10.25	362	307.7	$ 184.12
May	-1.69	52	44.2	$ 25.72
June	-12.25	34	28.9	$ 16.76

Table 3 shows how much fuel was needed to raise the required temperature to 60°F in each month, assuming a 15% heat loss. It is clear from Table 3 that February, being the coldest month, required the most fuel, whereas June, being the hottest month, had the least amount of fuel consumption. No fuel was used for heating during the months of May and June; the numbers for cost and fuel consumption associated with these months were the lowest cost the owners had to pay, even when no fuel was used at all. These data were used in further calculations and analyses during the later part, where the heating was partially replaced by the solar panels.

Heat Calculations Using the Solar Panels

The use of five 4' x 8' solar panels was based on the ground coverage of the greenhouse, which was about 2700 sq. ft. The storage capacity of the 150-gallon drain-back tank was also based on the surface that required heating (i.e., 27,000 sq. ft.). To calculate the reduction in fuel due to the use of solar panels, it was necessary to determine how much heat one solar panel could produce. This information was provided by the expert engineers from Radiant Tech Flooring, who have worked in the industry for more than 20 years. According to them, an AET 4' x 8' solar panel, when exposed to continuous sun for five hours a day, can produce about 30,000 BTUs of energy. Being in Northwest Ohio, it is impossible to get that amount of sunlight every day during winter.

From 1961 to 1990, the National Renewable Energy Laboratory monitored the hourly values of direct beam and diffuse horizontal solar radiation in various cities across the United States. They published a table for various cities to show how much direct sunlight a solar flat-plate collector received for a given tilt per day [2]. The values for Toledo, which is adjacent to Perrysburg, are given for each month. Values for Toledo were used in this study. Figure 6 shows the amount of heat generated each month and how it could be calculated.

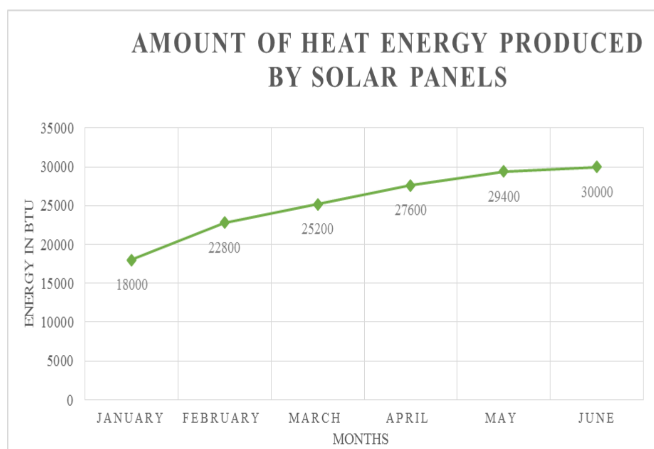

Figure 6. Amount of Heat Energy Produced by the Solar Panel Each Month

The next step was to calculate the amount of heat energy that was required every month to heat the water in the drain back tank in order to maintain the required temperature. An example of this calculation for the month of January is as follows:

Temperature required to maintain (T) = 60°F
Amount of water needed to be heated ($W1$) = 150 gallons
1 gallon of water = 8.33 pounds (lbs.)
150 gallons of water (W) = 1249.5 lbs.
Initial temperature in January ($T0$) = 25.84°F
Temperature differences (ΔT) = T-$T0$ = 60-25.74 = 34.16°F
Percentage of heat loss to be considered ($H0$) = 15%

Let the energy required to heat the water to the desired temperature without heat losses = Z
$Z = W * \Delta T$

hence, Z =1249.5 * 34.16 = 42682.92 BTUs

Let the energy required to heat the water to the desired temperature with heat losses = P. Adding the 15% heat loss factor, P = 49085.35 BTUs

This was the actual amount of heat required in January to maintain a temperature of 60°F. On the other hand, Figure 6 shows that the amount of energy produced by the solar panel during this month was only 18,000 BTUs. The gas heaters provided the rest of the energy—31,085.35 BTUs. From the calculation shown below, it is clear how many degrees 18,000 BTUs can raise the temperature, which is the amount the solar panel could produce in January.

Energy produced (E) = 18,000 BTUs
Water weight (W) = 1249.5 lbs.
Temperature = TT
$TT = E/W$ = 18,000/1249.5 = 14.40°F

For January, the average temperature was 25.84°F (from Table 1). So the temperature achieved through solar panels = Average temperature + TT = 5.84+14.40 = 40.24°F

It was clear that 18,000 BTUs could only raise the temperature to 40.24°F from 25.84°F, and the temperature still needed to be raised an additional (60-40.24) = 19.76°F. To achieve this, additional heat was then supplied by the existing natural gas heaters. The amount of gas and the associated costs were then determined to be 460.01 CCF for a cost of $262.06. Table 4 shows the energy required for the remaining months and the associated costs. Using the findings noted above, the costs and savings would be comparable if a solar heating system were installed. Table 5 shows a summary of the data, and Figure 7 shows a graphical representation. From Table 5, it is clear that after the installation of the solar panels, the amount of fuel consumption decreased and, in six months, the owners were able to save $1036.43 on their gas bills. However, the installation costs of the solar panel and its components need to be taken into account to calculate the payback period. Figure 7 shows the comparative chart.

The cost of the project, which in this case was the installation cost of the solar panel and its components, was obtained from the manufacturers, as shown below:

Five 4' x 8' solar collectors	$7826
Mounting hardware and strut	$600
150-gallon storage tank	$1500
Plumbing mechanical package	$525
Pumps	$500
Passive solar heat exchanger	$2500
Labor costs for installation	$4500
Miscellaneous components	$1549
Total	= $19,500

Table 4. Heat Energy Required, Fuel Consumed, and the Associated Costs for Each of the Six Months

Month	Heat required to maintain the temp. + 15% heat loss (BTUs)	Actual heat produced by Solar Panel (P) (BTUs)	Temp. raised by Heat P (°F)	Remaining temp. (Tr) (°F)	Fuel consumed to raise Tr (CCF)	Cost associated with fuel ($)
Jan.	49,085.35	18,000	40.24	19.76	460.01	262.06
Feb.	51,329.46	22,800	37.16	22.84	554.78	362.82
Mar.	37,797.37	25,200	49.91	10.09	267.08	163.98
Apr.	12,807.37	27,600	71.83	-11.83	0	0
May	-2428.40	29,400	85.21	-25.21	0	0
June	-17602.33	30,000	96.25	-36.25	0	0

Table 5. Comparison between the Two Heating Systems

Month	Conventional heating system (A)		Solar panel-based heating system (B)		Total savings
	Fuel consumed	Total cost	Fuel consumed	Total cost	Saving cost (A-B)
Jan.	795.37 Ccf	$453.12	460.01 Ccf	$262.06	$191.06
Feb.	998.05 Ccf	$653.42	554.78 Ccf	$362.82	$290.60
Mar.	800.90 Ccf	$492.15	267.08 Ccf	$163.98	$328.17
Apr.	307.7 Ccf	$184.12	0	0	$184.12
May	44.2 Ccf	$25.72	0	0	$25.72
June	28.9 Ccf	$16.76	0	0	$16.76
	Total				$1,036.43

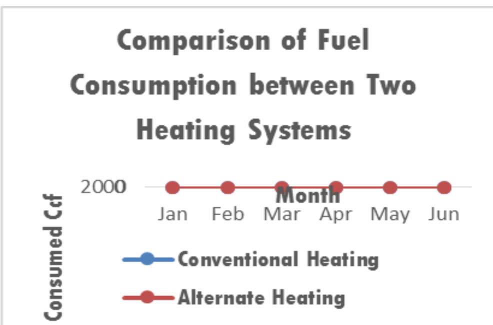

Figure 7. Comparative Chart of the Fuel Consumed

In general, the discounted payback period is the amount of time it takes to break even, based on the initial investment, the profit being generated, and taking into account the time value of money. The time value of money is accounted for by a discount rate, or the rate at which the value of money decreases in the future. The discounted cash inflow for each period can be calculated using Equation (1) [3]:

$$\text{Discounted cash flow} = CF/(1+i)^n \quad (1)$$

where, CF is actual cash flow; i is the discount rate; and, n is the period to which the cash inflow relates.

The rest of the procedure is similar to the calculation of simple payback period except that the discounted cash flows, as calculated above, need to be used instead of actual cash flows. The cumulative cash flow was replaced by the cumulative discounted cash flow [3]. Discounted payback period was calculated using Equation (2):

$$A + \frac{B}{C} \quad (2)$$

where,
A = the last period with a negative discounted cumulative cash flow
B = the absolute value of discounted cumulative cash flow at the end of period A
C = the discounted cash flow during the period after A

Now, calculating the discounted payback period using these values,

Initial investment = $19,500
Annual saving each year = $1036.43
Discount rate/interest rate = 5% (most commonly used)
Years = 18 years (from simple payback period)

Figure 6 shows the calculated discounted cash flow of each period and the cumulative cash flow. From Table 6, the last period with a negative discounted cumulative cash flow was (A) = 17 years. The absolute value of the discounted cumulative cash flow at the end of period A (B) = $7823.57. The discounted cash flow during the period after A (C) = $430.118. The discounted payback period Equation (2). So, the discounted payback period was 17 + (7823.57/430.118) = 35.18 years. Thus, the discounted payback period was about 35 years.

Conclusions

With the installation and operation of solar panels, it can be seen that for the first three months of 2014, the owners were able to reduce overall fuel consumption. But since the temperature rose after April, there was a need to vent excess heat to maintain the temperature. Thus, it may be better to start heating with the solar panels from November instead of heating the greenhouse from January, given that tempera-

Table 6. Cumulative Discounted Cash Flow

Year (N)	Cash flow (CF) ($)	Present value factor ($) PV= $1/(1+i)^n$	Discounted cash flow = CF x PV ($)	Cumulative discounted cash flow
0	-19,500	1	-19500	-19500
1	1036.43	0.952	986.6814	-18513.31864
2	1036.43	0.907	940.042	-17573.27663
3	1036.43	0.863	894.4391	-16678.83754
4	1036.43	0.822	851.9455	-15826.89208
5	1036.43	0.783	811.5247	-15015.36739
6	1036.43	0.746	773.1768	-14242.19061
7	1036.43	0.71	735.8653	-13506.32531
8	1036.43	0.676	700.6267	-12805.69863
9	1036.43	0.644	667.4609	-12138.23771
10	1036.43	0.613	635.3316	-11502.90612
11	1036.43	0.584	605.2751	-10897.631
12	1036.43	0.556	576.2551	-10321.37592
13	1036.43	0.53	549.3079	-9772.06802
14	1036.43	0.505	523.3972	-9248.67087
15	1036.43	0.481	498.5228	-8750.14804
16	1036.43	0.458	474.6849	-8275.4631
17	1036.43	0.436	451.8835	-7823.57962
18	1036.43	0.415	430.1185	7393.46117

ture starts to fall in Northwest Ohio from these months. However, the payback period of more than 35 years is excessive, and so the owners may not want to invest in this venture.

References

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Biographies

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