Storing excess daytime solar energy to heat greenhouse at night

Russell Benoy
March 21, 2014

Having built a well insulated greenhouse, I was amazed at how often the exhaust fan ran to maintain a reasonable inside temperature during sunny days, even on the coldest winter days. The greenhouse has enough mass to prevent freezing on the inside, but I wanted to be able to grow summer vegetables in the winter. I had three options. One was electric or gas heat, two was barrels in the greenhouse, the third was to store the excess heat being wasted by the exhaust fan. I didn't have room for barrels and couldn't stand wasting all that free energy, so I opted for the challenge of storing it.

The greenhouse is small, 8 by 12 feet, with 96 square feet of floor space and the same area of glazing. The floor has about 6 inches of cellulose insulation under sub-flooring with brick laid on that. The walls are framed with 2x4's and the ceiling is framed with double joists to obtain a 6 inch thickness. The exterior walls are covered with Hardiepanel siding, and the roof in galvanized tin. I designed the roof on a 30º tilt, 90º from the glazing, to facilitate the cuts during construction. The walls and roof are also filled with cellulose insulation and covered on the interior with 1/4 inch OSB. The glazing is corrugated polycarbonate. The entire structure rests on a 2x6 treated wood frame, which is supported by concrete blocks. I wanted to be able to move it if necessary.

The glazed side is oriented due South. In order to optimize the energy from the sun in the winter and minimize energy absorbed in the summer, I decided on a 60 degree tilt for the glazing. I'm located at about 35 degrees latitude in the sand hills of North Carolina. The 'rule of thumb' for the slope on the glazing would be 35 plus 10 to 15 degrees (45-50º). I used 35 plus 25 degrees (60º) which is the angle of the sun when it's at it's lowest, December the 21st. The sun will hit the glazing at a right angle at noon on this day and will be at a sharper angle in the summer allowing more rays to be reflected and not absorbed into the greenhouse.

Planning

I based my decision regarding the orientation of the greenhouse on the following data from the Weather Bureau Army Navy (WBAN) for Charlotte, North Carolina. There is some excellent information on this site.

30-Year Average of Monthly Solar Radiation, 1961-1990

Weather Bureau Army Navy (WBAN)

City: Charlotte
State: NC
WBAN No: 13881
Lat (N): 35.22
Long (W): 80.93
Elev (m): 234
Pres (mb): 991
Stn Type: secondary

Table 1

Solar radiation for flat-plate collectors facing south at a fixed-tilt (kWh/m2/day)

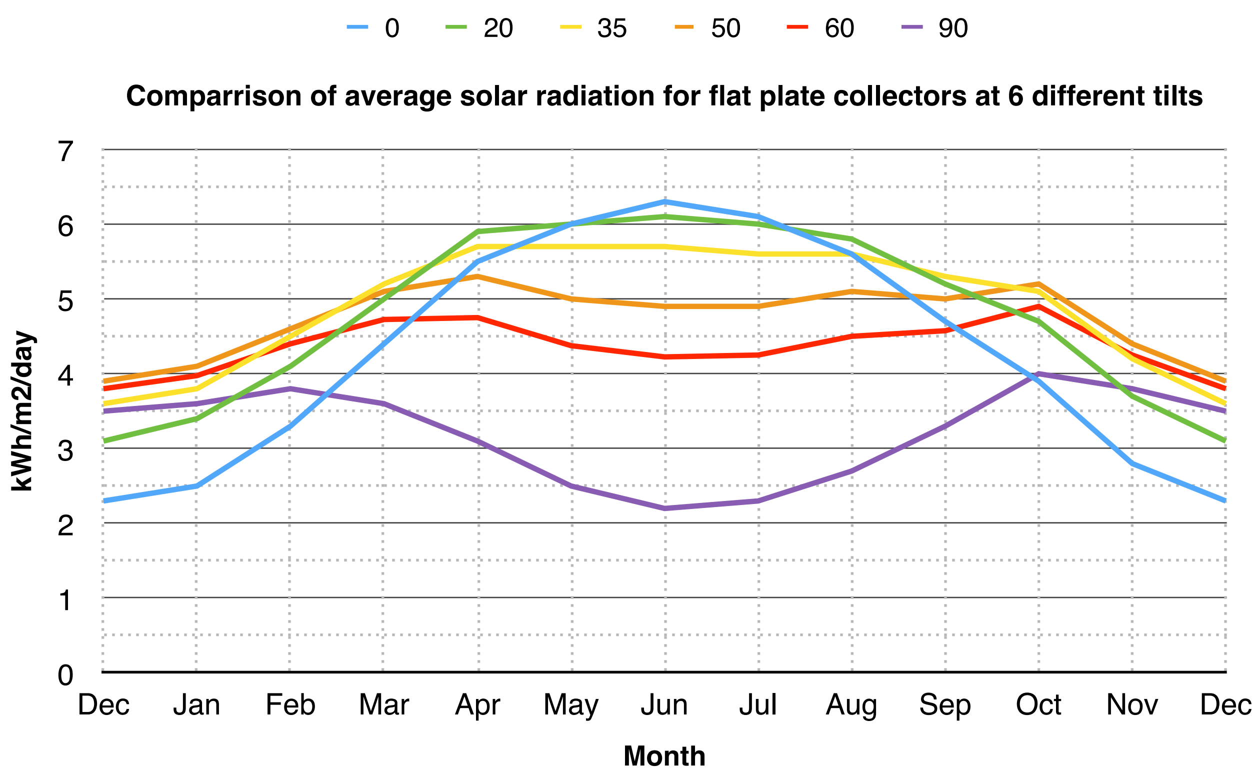
Tilt (deg)		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec		Year
0	Aver	2.5	3.3	4.4	5.5	6.0	6.3	6.1	5.6	4.7	3.9	2.8	2.3		4.4
	Min	2.0	2.8	3.6	4.7	5.5	5.5	5.3	4.9	4.0	3.3	2.0	2.0		4.2
	Max	2.8	3.8	5.2	6.4	6.6	7.1	6.9	6.3	5.4	4.5	3.3	2.6		4.6
Lat - 15	Aver	3.4	4.1	5.0	5.9	6.0	6.1	6.0	5.8	5.2	4.7	3.7	3.1		4.9
	Min	2.5	3.4	4.1	4.9	5.5	5.3	5.2	5.0	4.3	3.9	2.3	2.6		4.6
	Max	4.0	5.1	6.1	6.9	6.6	6.9	6.8	6.6	6.1	5.7	4.6	3.9		5.1
Lat	Aver	3.8	4.5	5.2	5.7	5.7	5.7	5.6	5.6	5.3	5.1	4.2	3.6		5.0
	Min	2.7	3.6	4.1	4.8	5.2	4.9	4.8	4.8	4.3	4.1	2.4	2.9		4.7
	Max	4.7	5.7	6.3	6.8	6.2	6.4	6.3	6.4	6.3	6.2	5.3	4.6		5.2
Lat + 15	Aver	4.1	4.6	5.1	5.3	5.0	4.9	4.9	5.1	5.0	5.2	4.4	3.9		4.8
	Min	2.8	3.7	4.0	4.5	4.6	4.3	4.3	4.4	4.1	4.1	2.5	3.1		4.5
	Max	5.1	5.9	6.3	6.3	5.6	5.5	5.6	5.8	6.0	6.3	5.7	5.0		5.1
90	Aver	3.6	3.8	3.6	3.1	2.5	2.2	2.3	2.7	3.3	4.0	3.8	3.5		3.2
	Min	2.3	3.0	2.8	2.7	2.3	2.1	2.1	2.4	2.6	3.0	2.0	2.7		2.9
	Max	4.6	4.9	4.4	3.6	2.7	2.3	2.5	3.0	4.0	4.9	5.0	4.6		3.4

Table 2

Averages taken from table 1 (60 degree tilt was interpolated)

Tilt (deg)	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0	2.3	2.5	3.3	4.4	5.5	6.0	6.3	6.1	5.6	4.7	3.9	2.8	2.3
20	3.1	3.4	4.1	5.0	5.9	6.0	6.1	6.0	5.8	5.2	4.7	3.7	3.1
35	3.6	3.8	4.5	5.2	5.7	5.7	5.7	5.6	5.6	5.3	5.1	4.2	3.6
50	3.9	4.1	4.6	5.1	5.3	5.0	4.9	4.9	5.1	5.0	5.2	4.4	3.9
60	3.8	4.0	4.4	4.7	4.8	4.4	4.2	4.3	4.5	4.6	4.9	4.3	3.8
90	3.5	3.6	3.8	3.6	3.1	2.5	2.2	2.3	2.7	3.3	4.0	3.8	3.5

Chart 1



As you can see from table 1, the best yearly gain is with the glazing oriented on a tilt equal to the Latitude (35°), 5 kWh/m²/day. That's the yellow graph in chart 1. The blue graph at 0° tilt (horizontal) gives the most radiation in the summer and the least in the winter months. The purple graph is just the opposite, at 90° (vertical) it gives a reasonable amount of radiation in the winter and the least in the summer. I was interested in the maximum possible radiation in the winter, but not so much in the summer. A 60° tilt, the red graph, seems to be the best for my application. I get maximum radiation in the winter months and a reasonably reduced amount in the summer. A byproduct of this tilt is more head space inside the greenhouse.

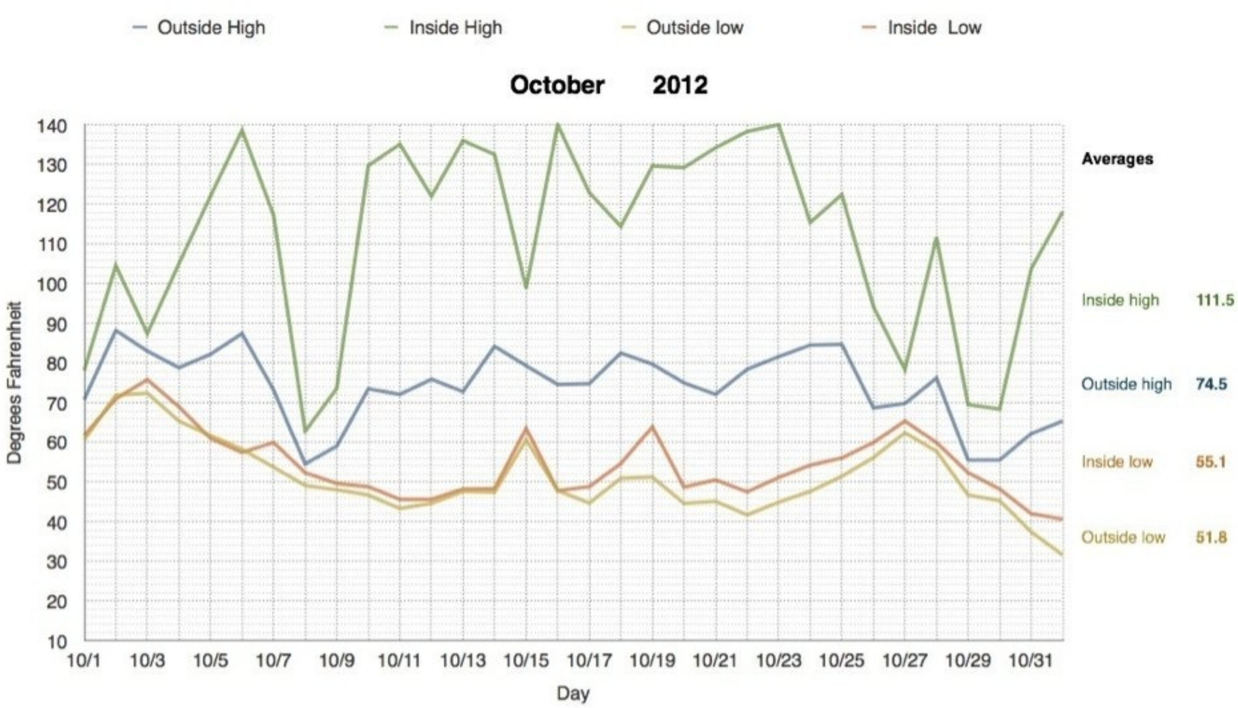
The information above, along with weather data for the same period can be found for any region of the US at http://www.nrel.gov/rredc. The specific page for data on solar radiation for flat-plate collectors facing south at a fixed-tilt (kWh/m^2/day) is:

http://rredc.nrel.gov/solar/old_data/nsrdb/1961-1990/redbook/sum2/state.html

Before installing the exhaust fan, inside temperatures were reaching 140ºF in October of 2012. The chart below shows the potential for heat storage. Considering I wanted to keep the inside high somewhere near 90ºF and the average inside high was 111ºF, I had an average daily difference of 21 degrees to work with.

As you can see in chart 2, the inside and outside low were running very close together at the beginning of the month. That's due to very little mass in the greenhouse. I completed insulation on October 17th, 2012, and began the brick floor on the same day, I completed the floor on the 25th. You can see in the chart where the spread between the two increased during this period.

Chart 2



The glazing on my greenhouse, as I mentioned before, is 8' by 12', or 96 ft^2. That calculates to 8.92 m^2. I'll round that down to 8 m^2 to compensate for framework blocking part of the sun. The yearly average, not shown on the chart, for a 60º tilt is 4.4 kWh/m^2/day. That times 8 m^2 is 35 kWh per day of radiation into the greenhouse. There would be an average of 39 kWh per day in October, and 30 kWh per day in December. That's a substantial amount of energy.

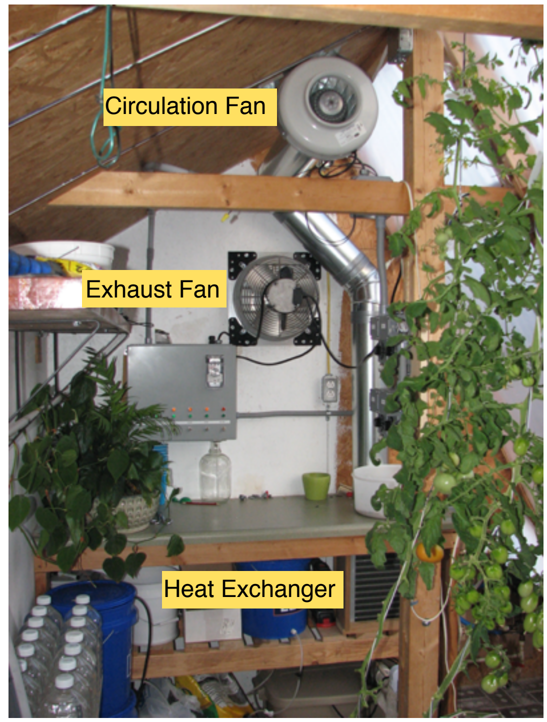
The electric backup heater I used in January, plus exhaust fan and some machines I used in the shop, consumed 100 kWh. I have no way of determining what percentage of that was used by the heater, but I would guess 80 to 90%. That figures to about 3 kWh per day. Using December's figure of 30 kWh/day, I would only have to store 10% of the heat entering the greenhouse to be able to heat it during the coldest part of the year. The trick is to be able to accumulate enough to last through cold and cloudy days.

All of my designs, of the greenhouse and the storage system, planed for solar collectors and a PCM (phase change material) storage system. After certain observations, mostly from data I collected along the way, I decided to try this system before adding a collector. The advantage to this system is the lower temperature of the storage tank. The higher the temperature, the more potential heat loss. If I used the PCM system, I could use a smaller storage tank, but would have to maintain temperatures at 140º for the PCM to store the heat. Temperatures in this region usually don't get below about 20º, so the heat loss would be much greater at a temperature difference of 120º than at 60º.

I'm undecided on the type of backup heat to use. I originally thought of an electric element at the heat exchanger, but considering the storage tank maintains heat levels fairly well, I think an electric element in the storage tank itself would be the best for this system. I'm also considering a rocket furnace as a manual backup. I can use the same hydraulic system to circulate the water from the tank through a copper coil in the furnace. The advantage to this type setup would be the option to heat the store above it's normal temperature to allow for a longer heating period during consecutive cloudy days.

After analyzing the information on the performance of the greenhouse, I decided on a system that would remove the heat from the peak of the greenhouse that the exhaust fan was just waisting, and use an air to water heat exchanger to store this heat in an insulated storage tank. At night the stored heat would be returned to the greenhouse by way of the same heat exchanger.

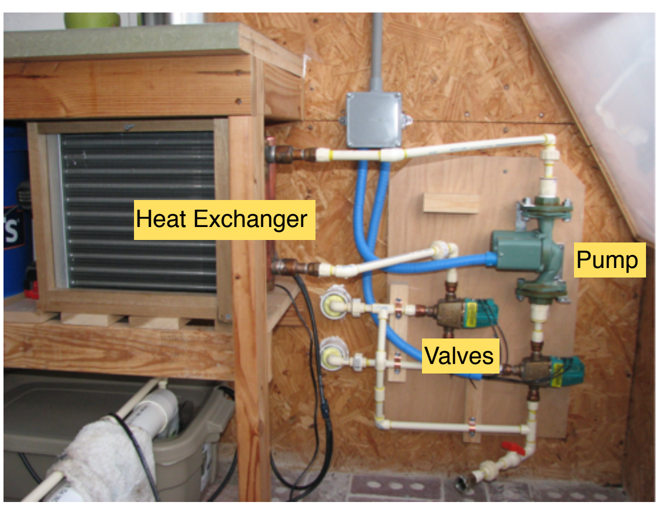
Construction



It took me quiet a while to decide where to locate the storage tank. Inside the greenhouse seemed the ideal location. Any heat lost from the tank would help warm the greenhouse. Space issues finally dictated the location to be on the exterior. Since the East end of the greenhouse is reserved for a work bench and anything else that gets in the way, I decided that a shed on that exterior wall would be the best place.

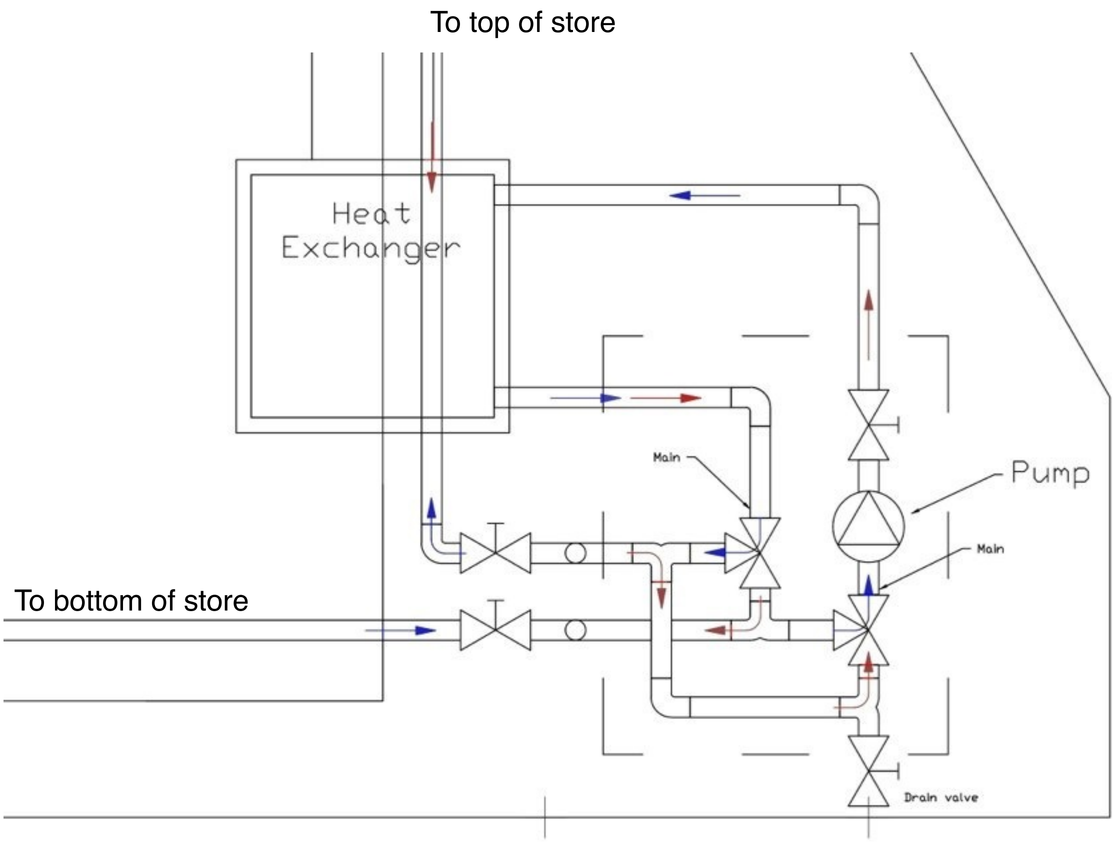
I built the storage tank shed with the same roof pitch as the greenhouse to allow for a solar collector to be mounted on the shed. The shed was built against the East wall of the greenhouse, but not connected to it. I didn't want the weight of the tank causing settlement in the foundation of the greenhouse.

The tank shed was framed and finished the same as the greenhouse except for insulation. I built the shed 9" larger on all sides than the 275 gallon IBC (Intermediate Bulk Container) I used for storage. The supporting floor frame is made of treated 2x6's with their voids filled with cellulose insulation. I then placed a sheet of 1/2" treated plywood on that, 2" larger on all sides than the tank. On that, I placed 2" polystyrene rigid insulation with foil facing to reduce heat loss by radiation. Then another 1/2" piece of plywood the same size as the tank covers that. The tank was then placed on the plywood and 2" polystyrene was placed on all four sides of the tank and on the top. The polystyrene on the sides rests on the bottom sheet of plywood that extends 2" beyond the tank. I initially thought of gluing the polystyrene together, but decided on duct tape to seal the corners. I then used Great Stuff foam insulation to seal the holes where the inlet, outlet and overflow pipes go through the polystyrene.



All of the data I have acquired so far is with the 2" polystyrene insulation only. The other 7 inches have yet to be filled with cellulose insulation. When done, I will have obtained an R value of about 35.

To transfer heat from the greenhouse to the storage tank in the day and back to the greenhouse at night, I used a fan blowing across a heat exchanger, and a pump to circulate water from the tank, through the heat exchanger, and back to the tank. During the day, the pump draws water from the bottom of the tank and pumps it through the heat exchanger, and then back to the top of the tank. I call this ‘Cool 1’. At night, I needed to reverse the flow of water, so I installed two three way valves. This allows the pump to draw from the top of the tank, across the heat exchanger, and back to the bottom of the tank. This is ‘Heat 1’. A separate thermostat controls each of these stages. The following drawing shows the setup that reverses the flow between cooling and heating.



The fan is mounted on the ceiling to draw the warmest air in and by way of duct work, blows it across the heat exchanger located under the work bench, which is a couple of feet from the floor. At night the fan mixes the warmer air from the top of the greenhouse with heat from the tank, and returns it near the floor. The blue arrows in the drawing show the direction of flow when the system is cooling (daytime), and the red arrows show the direction of flow when the valves are energized or the system is heating the greenhouse (nighttime).

The system is controlled by four thermostats. I wanted to be able to independently control each temperature. Here’s how they are setup. During the day, Cool 1 thermostat turns the circulator fan and pump on to remove and store heat from the greenhouse when the temperature goes above 80^{o}. Cool 2 thermostat turns the backup exhaust fan on if the temperature gets above 90

- 95°. Cool 1 continues to operate in this case. At night, when the temperature falls below 55 - 60°, the Heat 1 thermostat turns the circulator fan, pump and valves on to heat the greenhouse from the store. If the temperature falls to 50°, Heat 2 thermostat turns Heat 1 off and turns a backup heater on.

<u>Table 3</u>

Proposed Thermostat Settings for Solar Storage System

Thermostat	Description	Proposed Temp Setting (°F)
Cool 1	Controls pump to remove heat from greenhouse to store	80
Cool 2	Backup cooling (exhaust fan)	90 - 95
Heat 1	Controls pump and valves to heat greenhouse from store	55 - 60
Heat 2	Backup electric heat	50

The temperature settings I'm using will vary depending on outside conditions. For example, if the weather is warm and sunny, I may raise the inside temperature to use some of the heat in the tank. This allows for more efficient cooling during the day. The pump is more economical to run than the exhaust fan. On the other hand, if I'm expecting very cold or cloudy days, I may lower the inside temperature to use less heat from the store.

The following table shows the equipment I used for this system. I considered using two pumps, one for each direction of flow, but wasn't sure if I would have adequate flow (one pump pumping through the other). Two pumps would eliminate the need for the more expensive 3-way valves. I purchased the valves for half price, but I'm showing the full price in the table.

<u>Table 4</u>

Equipment Used For Solar Heat Pump

		Model #	Rate CFM	Rate GPM	HP	Amps	Volts	Watts	Each $	Quant	Total $
Circulator Pump	Taco	005-F2		0 - 18	1/35	0.53	115	61	78.75	1	78.75
3-Way Valve	Taco	560-5		1 - 4.25		0.90	24	22	165.75	2	331.50
Thermostats	J & D	CT-VC15					24 - 120		46.00	4	184.00
6" Centrifugal Fan	Can-Fan	RS6	269		?	0.69	115	79	108.56	1	108.56
Heat Exchanger			700	6					83.00	1	83.00
IBC Tote									100.00	1	100.00
Total								184			885.81

Taco manufactures a pump for systems with a solar collector and one or two storage tanks. I thought it worth mentioning because it's the only one I've seen so far that has all the controls necessary, including variable speed motor and sensors, to optimize the system. It's the 006-VTF4 model. This pump could also be adapted to this system, although it wouldn't be as effective as with a collector which produces higher temperatures. The pump operates according to the differential between the two temperatures instead of the actual temperatures. With a sensor measuring the greenhouse temperature and the store temperature, the differential can be set so that the pump will extract the optimal amount of heat by controlling the flow of water through the heat exchanger. This would eliminate the need to adjust thermostat temperatures according to the outside temperatures.

Analysis

I was pleasantly surprised with the efficiency of the system. Chart 3 below shows the results of the first five days of operation. In the chart, you can see that the inside temperature for the first two days was set at 54° and held for 4 hours on the first night and 7 hours on the second night. The temperature was raised to 60° for the remainder of the tests, and held for as much as 9 hours on the 4th night. The system didn't heat on the fifth day due to higher outside temperatures. The interesting thing is that the gain in tank temperature for each day was greater than the loss due to heating.

Chart 3

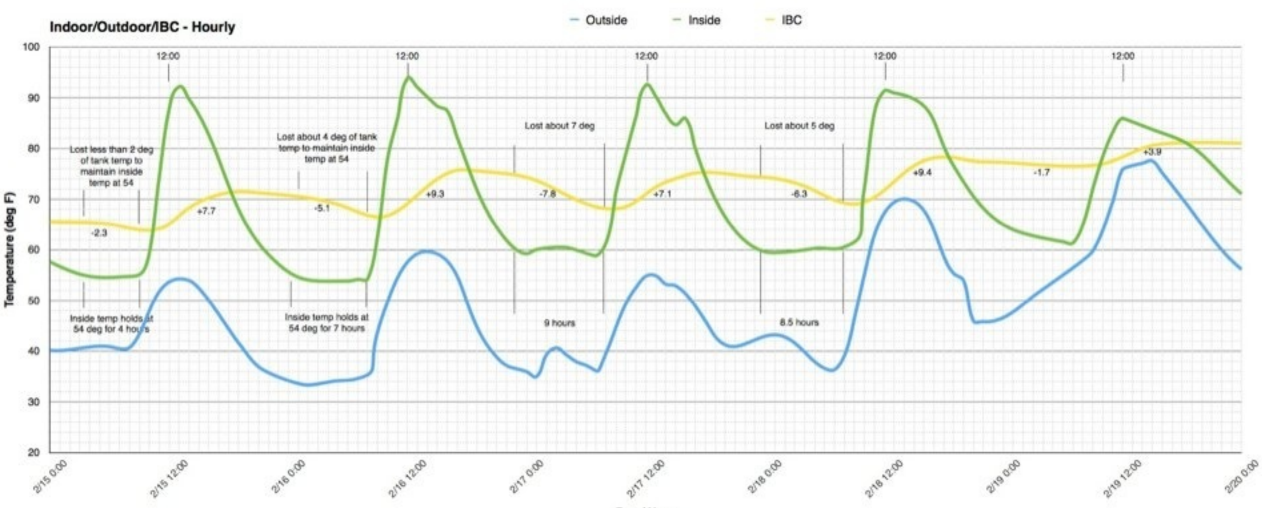


Chart 4 shows some interesting details. On February 26, the system started heating at 4:00 am and heated through the day and through the next night until 8:30 am on February 27. It was cloudy and cold, and the outside temperature didn't get above 45° on the 26th. The system had to heat for more than 28 hours non stop. At about 9:00 pm, the tank temperature dropped to a point that it couldn't maintain an inside temperature of 60°. As the tank temperature dropped, the inside temperature also dropped. The inside temperature held at about 10° below the tank temperature and took ten hours to drop 6°. The inside temperature dropped below 60° for a few hours the next morning also. The storage tank was able to recuperate enough the next day to hold for about seven hours that night.

Chart 4

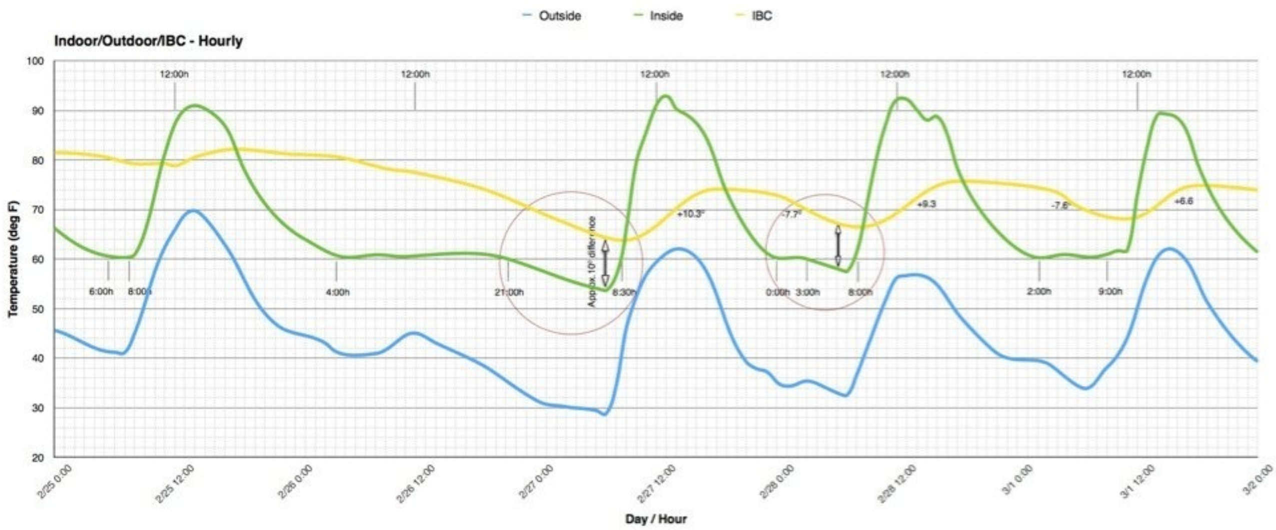


Chart 5

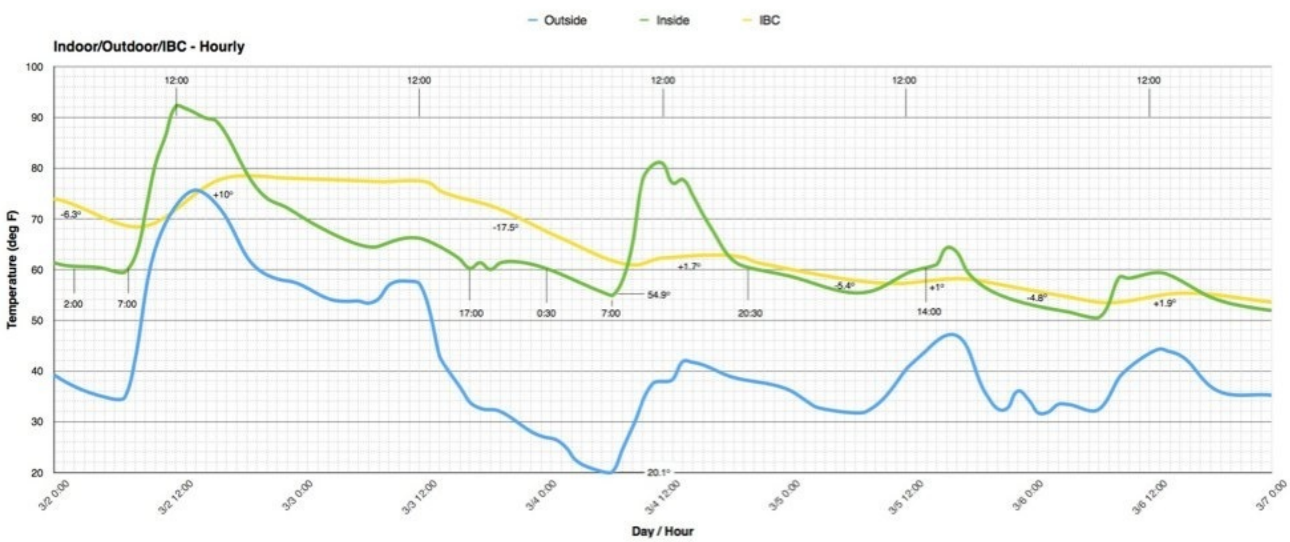
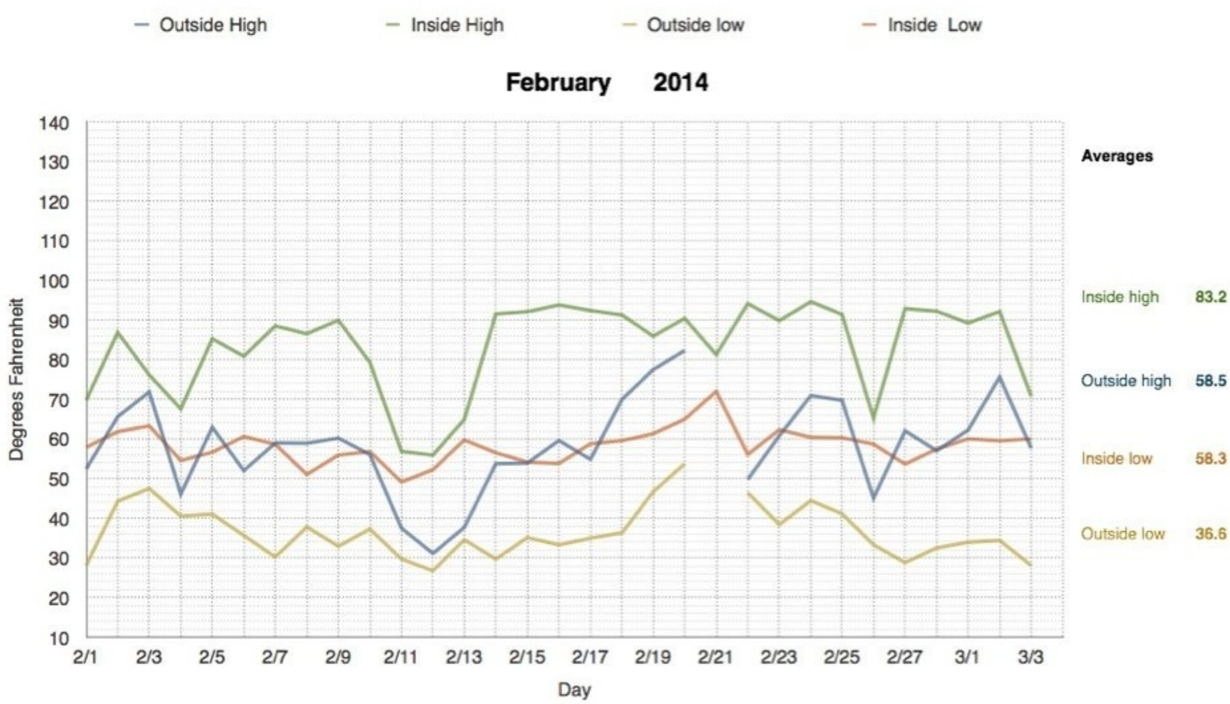


Chart 5 shows the harshest weather so far in this test. There was no sun on the second day, and the temperature dropped to 20° that night. There was a reduced amount of sun the third day, but enough to prevent the inside temperature from dropping below 55° that night. There was also no sun the forth and fifth day. The store is about depleted and still holding the inside low temperature above 50°. If the low temperature had been set at 55°, this chart may have looked somewhat different. I don't expect any sun for a couple more days, so looks like it's time for some backup heat.

If you compare chart 6 with the previous chart 2, you'll see a substantial difference in the inside and outside low temperatures. Basically, I've chopped the inside high off at about 90°, and added part of that to the inside low.

Chart 6



The greenhouse was heated with an electric heater for the first half of the month, and with the solar system beginning on about the 14th. Ignore the data from the 20th to the 22nd. The mass inside the greenhouse consists of the brick floor, a 39 gallon plastic garbage can full of water, and about 25 gallons of plastic jugs full of water. It's obvious the solar heat pump is doing the majority of the work.

Under some of the conditions shown, I would adjust the thermostats to conserve energy. If I know the inside temperature will fall below 60°, I may lower the thermostat to about 55°. This will help extend the heating potential of the store. After analyzing over a months worth of data, I've come to the conclusion that by doing this, I may not need backup heat at all for a normal winter in this region. If the heat level in the store is about depleted, I may also lower the cooling thermostat. This way I can start heating the store before the inside temperature reaches 80°. I'm using a normal setting for cooling of 80°, because the maximum store temperature is in the lower 80's. If the cooling system turns on before the greenhouse temperature reaches the same temperature as the store, the system will remove heat from the store and transfer it to the greenhouse.

For the tests I have performed, I've maintained constant thermostat settings, with the exception of the first two days at startup, to be able to make accurate comparisons. From here on, I'll make the adjustments mentioned above.

As mentioned before, the storage tank is only partially insulated, with two inches of polystyrene rigid insulation. I expect a substantial increase in performance after the tank is totally insulated, especially during colder outside temperatures.

From the results of the data I collected between February 15th to March 17th, the system has heated on the average of 7 hours per day, with an average inside to outside temperature difference of 24^{o}, and with an inside thermostat setting of 60^{o}. It gained and used approximately 104 kWh's of energy during this period.

In a nut shell, my tomatoes are thriving in the middle of the coldest winter we've had in years. Production drops off a little due to cooler than ideal nights (65^{o}), but not by a substantial amount. So far, the system has been able to maintain a temperature of 60^{o} for the majority of the time. When the store can't maintain 60^{o}, it slows the temperature decline in the greenhouse such that the lowest inside temperature so far for this test has been about 50^{o}. My goal is to maintain a temperature as close to 60^{o} as possible, and not allow it to drop below 50^{o}.

My next challenge will be to use this system to cool the greenhouse in the summer.