An ASABE Meeting Presentation
Paper Number: 074011

Evaluating Energy Savings Strategies Using Heat Pumps and Energy Storage for Greenhouses

A.J. Both

David R. Mears

Thomas O. Manning

Eugene Reiss

Peter P. Ling

Written for presentation at the
2007 ASABE Annual International Meeting
Sponsored by ASABE
Minneapolis Convention Center
Minneapolis, Minnesota
17 - 20 June 2007

Abstract. As energy costs are increasing, many greenhouse operators are re-evaluating energy consumption and savings strategies. In most cases, updating older heating systems to more efficient units in addition to the use of double layer glazing, insulation materials, and energy curtains significantly reduces fuel consumption. Insulating greenhouses must not conflict with the need for high light transmission through the structure. Since solar radiation loads often significantly exceed the instantaneous heat requirement of a greenhouse, many ideas have been proposed to capture this excess heat and store it for later greenhouse heating. Heat pumps are promising for use in an integrated cooling and heating system. In the study described in this paper, a simple spreadsheet approach was used to evaluate the performance of a system utilizing a heat pump and water storage. The evaluation bases its calculations on historic hourly weather data to determine hourly cooling and heating rates and storage status. The calculations allow for evaluations of the appropriate size of the heat pump, storage device, and heat exchangers. The calculations are used to investigate storage capacities that are sized for one to a few days harvest of surplus heat from the greenhouse for a range of percentages of peak cooling requirement. The model includes the option of utilizing a geothermal source for the heat pump to charge the storage during periods when greenhouse cooling is not required. The first study presented examines the impact of increasing thermal storage capacity on heat utilization from a generic co-generation system. The second considers a specific, natural gas fired, fuel cell system for various sizes of greenhouse at two different locations and includes the utilization of CO_2 from the reformer section. The heat pump study looks at the relationships between capacities of the heat pump and storage for two different locations. Provided hourly weather data are available for other sites, the spreadsheet approach can be used for other locations across the world.

Keywords. *Alternative energy, co-generation, fuel cell, simulation, spreadsheet, weather data*

Introduction

Recent increases in the costs of oil and natural gas combined with increasing uncertainty in the reliability of supply are regenerating interest in developing further advances in greenhouse energy conservation and alternative sources. There was some significant progress in developing alternative energy sources in the energy crisis of the 1970's. More importantly significant advances were made in energy conservation and management that have been widely adapted by the commercial greenhouse industry. The challenge now is to find alternative energy sources that can provide a significant portion of the requirement for modern greenhouses already adopting the best conservation practices currently available. Simulation modeling, even with relatively simplistic modeling techniques, can provide a preliminary analysis of the expected contribution of a variety of proposed alternative energy scenarios.

In a survey of greenhouse energy use conducted by Ohio State University in 1979, it was found that the fuel consumption of glass greenhouses in Ohio averaged the equivalent of about 935,390 L of fuel oil per ha of greenhouse (Short et al., 1979). With typical heating system efficiencies at the time, this rate of fuel oil consumption would result in approximately 0.26 GJ/ha delivered to the greenhouse. At the time, the greenhouses in that survey would include small single span glass and polyethylene glazed greenhouses and larger gutter connected greenhouses operating at a variety of temperatures depending on the crops being grown.

In Table 1 and Figure 1, the annual heat requirement for an acre of growing space maintained at temperatures ranging from 10.0 to 21.1^{o}C have been calculated based on a 10-year composite hourly weather data set from the Philadelphia International Airport (PHL). The basic greenhouse dimensions were seven bays each 9.14 m by 64 m with 3.7 m to the gutter and 5.2 m to the ridge. The heat transfer coefficients for glass, polyethylene and IR absorbing polyethylene are based on values presented in Bartok (2001) and the glass plus curtain data are based on tests done in The Netherlands for modern curtain materials. The coefficients for regular and IR absorbing polyethylene film in combination with modern curtain materials were estimated from the other values.

It is useful to note that for many crops the use of curtains and/or root zone heating systems can result in optimal night air temperatures significantly lower than would otherwise be the case. In the case of a crop where these measures could result in reducing the thermostat setting from 18.3 to 12.8^{o}C in a gutter connected greenhouse glazed with IR film and a curtain system, energy consumption could be about one tenth that required in a single span glass house without curtain or root zone heating. These figures are useful for comparative purposes but it is important to note that specific building designs, location and exposure to wind, installation of glazing and curtain systems, heating system design, and other factors all affect actual fuel consumption.

Table 1. Annual heat requirements in MJ per hectare for greenhouse set point air temperatures ranging from 10.0 to 21.1°C.

	Set point air temperature (^{o}C)				
Greenhouse Construction	10.0	12.8	15.6	18.3	21.1
Small single-span Glass (SG)	127	180	243	320	421
Large gutter-connected Glass (LG)	79	111	154	210	280
Gutter connected regular Polyethylene (PP)	47	68	95	130	172
Gutter connected IR absorbing Poly (IR P)	30	44	63	86	114
Gutter connected Poly + Curtain (PP+C)	34	50	71	97	129
Gutter connected IR Poly + Curtain (IR P+C)	23	34	48	65	86
Gutter connected Glass + Curtain (LG+C)	34	49	70	96	127

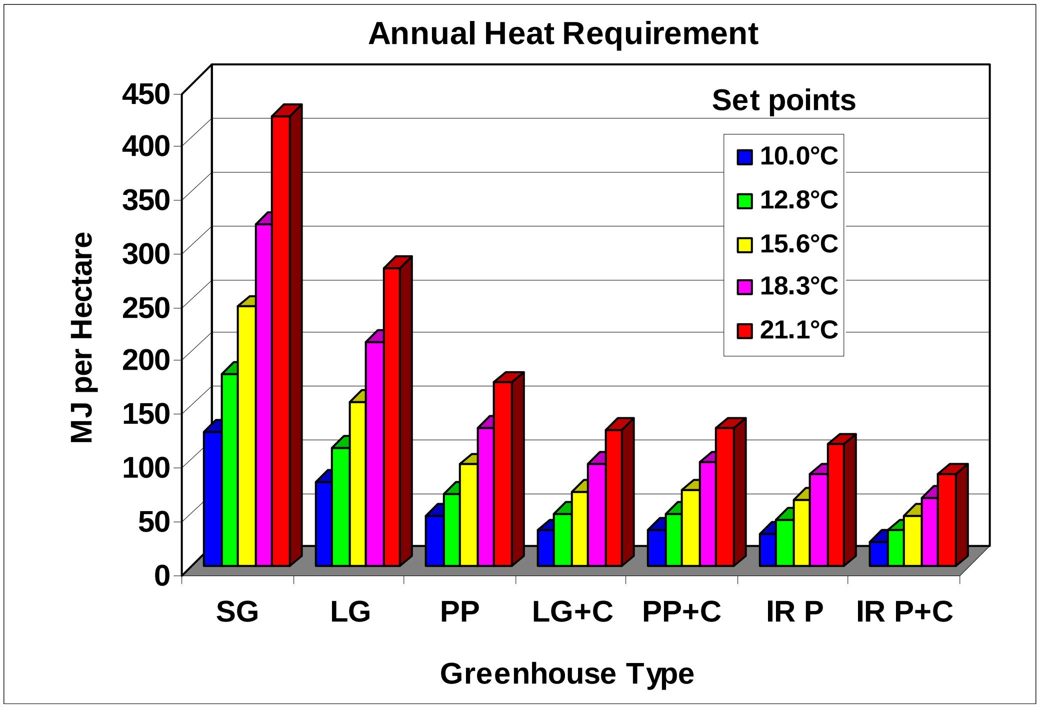

Figure 1. Annual heat requirements in MJ per hectare for greenhouse set point air temperatures ranging from 10.0 to 21.1°C (see Table 1 for greenhouse type abbreviations).

Materials and methods

Traditionally, greenhouse environmental control systems are designed based upon the characteristics of the structure and the expected extreme weather conditions for the location and the requirements of the crop being grown. For a heating system, the heat loss from the structure (walls, roof and infiltration) can be calculated for the maximum expected temperature difference between outdoor design temperature and desired inside conditions. The capacity of the heating system is then determined based upon this calculation and a reasonable factor of safety. Annual heating energy requirements can be estimated based on reported heating degree data for the region, but the actual requirement in any year will depend on the specific weather conditions that do occur. A well-designed heating system and control strategy with modulated heat delivery should maintain set points acceptably.

Simulations of greenhouse climate have been widely used to study a variety of issues. Manning and Mears (1981) designed a 1.1 ha greenhouse facility utilizing waste heat from an electric power generation station. For their model development, they used historical hourly data on ambient temperature and the temperatures of the station's cooling water (Manning et al., 1983; Mears and Manning, 1996). Ekholt et al. (1983) used a simulation approach to optimize the sizing of a co-generation system designed to utilize landfill methane to generate electricity for crop lighting and recapture waste heat for climate control using a floor heating system. More recently, Takakura and Fang (2002) discussed a number of simulation examples. They noted that simulation models could be particularly useful as an evaluation or optimization tool in the design of climate control systems utilizing mixed energy sources where the energy costs vary between sources. Both et al. (2005) used a simple spreadsheet approach to modeling to design environmental control systems and strategies for orchid production based on weather conditions in New Jersey and Taiwan. The basic structure of that model has been adapted to the several studies discussed in this paper.

Historical weather data can be useful in comparing the annual contributions to environmental control of various heating, cooling and shading options. However, these results only give estimates that can reasonably be expected as actual contributions depend not only on the actual weather experienced in the future but also can depend significantly on greenhouse management and the control strategies used. Hourly time increments can be too coarse to model detailed dynamic response of the internal climate to changing environmental conditions and to analyze the performance of control systems that influence air temperature. Nevertheless, the results can be useful in evaluating relative performance of proposed system designs, alternative energy resources and control strategies.

The spreadsheet, described in some detail in Both et al. (2005) is set up with the main calculations page having several rows at the top for headings and for cells to contain the constants needed for the calculations. The first five columns contain the time and basic weather data, 8760 rows for the year. Additional columns are used to indicate control states for the operation of the heating and venting systems and the energy flows of interest. Another descriptive data sheet is set up to describe the basic characteristics of the greenhouse including dimensions and the heat transmission coefficients of the various components. The capacity of any given thermal storage system and the basic parameters for the alternative heating sources being considered are also defined on this sheet. The calculations of energy inputs and energy flows on the main calculations page are all done on a per unit area basis. Therefore the important parameters developed on the descriptive data sheet are also computed on a per unit area basis for referencing on the main calculations page.

Previous work on the optimization of waste heat systems, (Manning and Mears, 1981; Manning et al., 1983; Mears and Manning, 1996), and on solar energy systems for greenhouses (Mears et al., 1980), clearly indicated the importance of designing in the best available greenhouse structure and insulation system as the costs associated with these measures are far less than the amortized cost of equipment needed for any alternative to fossil fuel as an energy source. Therefore, the greenhouse structures used in the simulations discussed in this paper are all based on a large, gutter connected commercial greenhouse glazed with double layer IR polyethylene film with a movable curtain insulation system to reduce nighttime heat loss as well as provide environmental shade during peak solar daytime conditions.

To calculate the heat required for any hour to maintain a given minimum inside temperature, the need for heat can be determined by computing an energy balance based on the desired inside temperature, the outside temperature and the amount of heat being transmitted into or out of the greenhouse. Since most heating is required at night, the shade/energy conserving curtain material can be pulled to reduce heat loss at night. For the calculation of internal greenhouse temperature during the daytime, it may be important to consider that the radiation contributing to heating the greenhouse is the radiation received at the crop canopy plus a portion of the radiation intercepted by the shade curtains that may be deployed, so a coefficient for that is needed. For the heating calculations, this is only a factor when it is very cold and overly bright compared to the desired light setting. If the predicted energy input is not adequate to maintain minimum desired temperature, the temperature is set at that level and the amount of energy that needs to be added to maintain this temperature computed.

For cooling, three columns were set up to indicate control at three rates of airflow and a fourth to indicate the use of evaporative cooling. To determine the needed stage of ventilation, the internal temperature was calculated using an energy balance based on the desired internal temperature, the current outside temperature and the radiation received at the plant canopy as well as absorbed by any curtains deployed. After the required stage of ventilation was determined, the canopy temperature was calculated by an energy balance based on the airflow associated with the ventilation rate but without evaporative cooling. Based on this temperature, a decision could be made as to the need to turn on the evaporative cooling, and if that was the case another column was calculated to determine the internal air temperature with evaporative cooling based on the wet bulb depression and the efficiency of the evaporative cooling system.

The three stages of ventilation were set to initiate at 21, 24 and 27°C predicted internal temperatures, respectively. The airflow rates were set at 0.31 m^3/min per m^2 of floor area for the first stage and an additional 1.24 and 0.93 m^3/min per m^2 of floor area for the second and third stages, respectively, for a total capacity of 2.48 m^3/min per m^2 of floor area at full ventilation. When under full ventilation, the predicted inside temperature was predicted to be above 29°C, evaporative cooling would be turned on and assumed to operate at an efficiency of 80%. A check on radiation levels was used to avoid having evaporative cooling still operating at solar radiation levels at the canopy of under 236 W/m^2. This practice will allow some time to reduce humidity in the greenhouse late in the afternoon, even when temperatures are higher than desired.

Cases considered in this paper

The first case being considered is the use of a co-generation system to provide electricity and heat for the greenhouse with surplus electricity used elsewhere in the production system or sold back to the grid. The issues to be considered are the relationship between the size of the co-generation unit relative to the area of greenhouse utilizing the heat and whether or not thermal storage is used and if so the size of the thermal storage relative to the capacity of the co-generation unit. This comparison is done for the PHL database.

The second case being considered is the use of a commercially available fuel cell utilizing natural gas. The unit considered had an electrical capacity of 200 kW and a thermal output of 212 kW when the fuel cell stack is new. The modular unit is modeled with increasing sizes of greenhouse and increasing amounts of thermal storage for two weather databases, the Philadelphia database and one for Bonita, Arizona to compare different geographic regions.

The third case being considered is the use of a relatively small water-to-water heat pump sized to provide roughly enough cooling to match up with a normal heat output for first stage ventilation. With high capacity heat exchangers in the greenhouse and two water storages for warm and cold water, the unit can provide daytime cooling with the stored heat used for night heating. With access to a groundwater well, the unit can deliver increased heat by charging the storage from the well during periods when cooling is not required. These models are run for the PHL database and for an actual one-year record from a location in Bellville, Ohio that is significantly colder in the wintertime.

Co-generation for greenhouse heating

One option for utilization of a co-generator for greenhouse heating is to look at the unit as the first stage of a heating system and utilize the heat from the unit upon demand while dumping any heat not needed when the unit is running for electricity production. An alternative is to add thermal storage so heat can be stored during generation of electricity for later use in heating. To investigate the impact of varying amounts of thermal storage relative to the size of the co-generation unit, simulations were run on the same double layer polyethylene greenhouse used for the analyses presented in Table 1. In this case the greenhouse was considered well insulated with a good curtain system and the overall heat loss coefficient per unit area of floor was assumed as 4.13 W/m^2K. For simplicity it was assumed the various storages were very well insulated so heat loss would be negligible.

Simulations were run using the PHL weather database to calculate the annual contribution to the heating requirement per unit area with co-generators of various thermal outputs up to 63 W/m^2, which is significantly under the maximum heat requirement of 114 W/m^2 for this database and greenhouse. For each co-generator size, simulations were run for no storage capacity and for storage systems with a storage capacity up to the maximum daily heat requirement of 7.91 MJ/m^2. While the use of this idealized storage concept does not enable the simulation to address the issues associated with storage heat loss, maximum and minimum storage temperatures, or how heat is delivered from storage to the greenhouse, the results do demonstrate the effect of changing these capacities on system utilization.

Figure 2 shows the seasonal heat contributed by the co-generator for the various storage sizes as a function of the thermal output of the unit, Figure 3 shows the seasonal heat requirement of the backup system and Figure 4 indicates the increase in the utilization of the output of the unit with increasing storage capacity for different size co-generators. These figures clearly illustrate that while increasing the capacity of the unit increases the energy provided and decreases the amount of backup required, the utilization of thermal output is decreased at higher capacities. Storage does enable smaller units to provide a greater portion of the thermal requirement and Figure 4 clearly shows this increase.

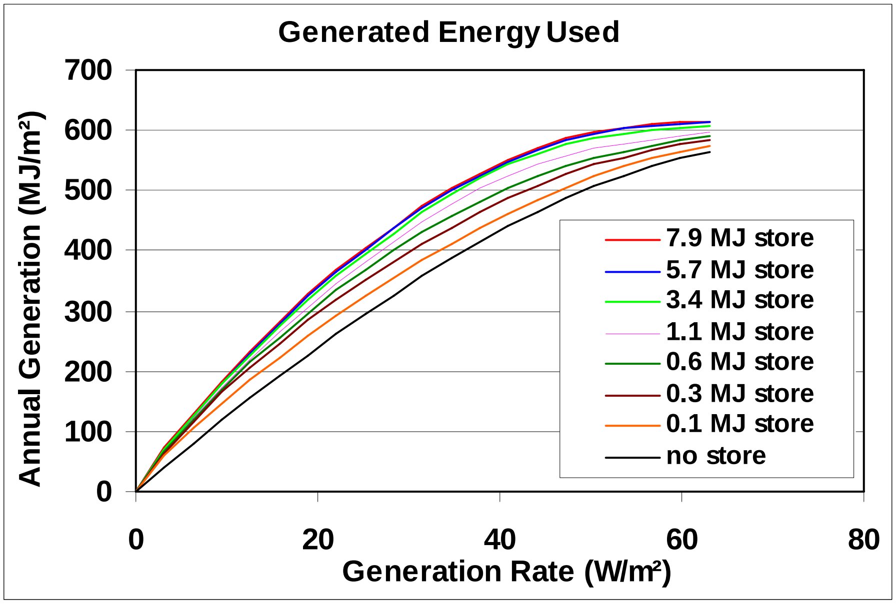

Figure 2. Energy provided by different sized co-generation units with increasing storage.

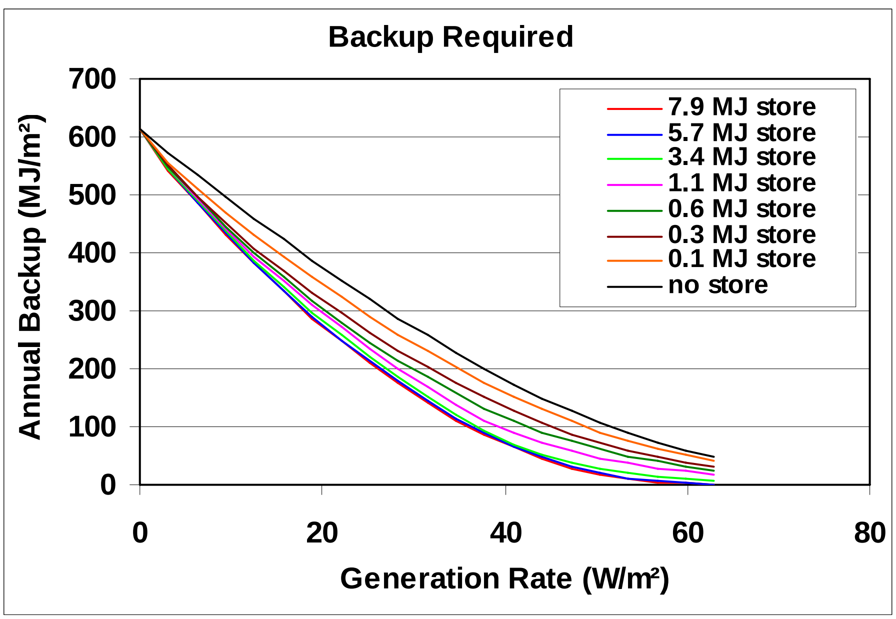

Figure 3. Backup required for different sized co-generation units with increasing storage.

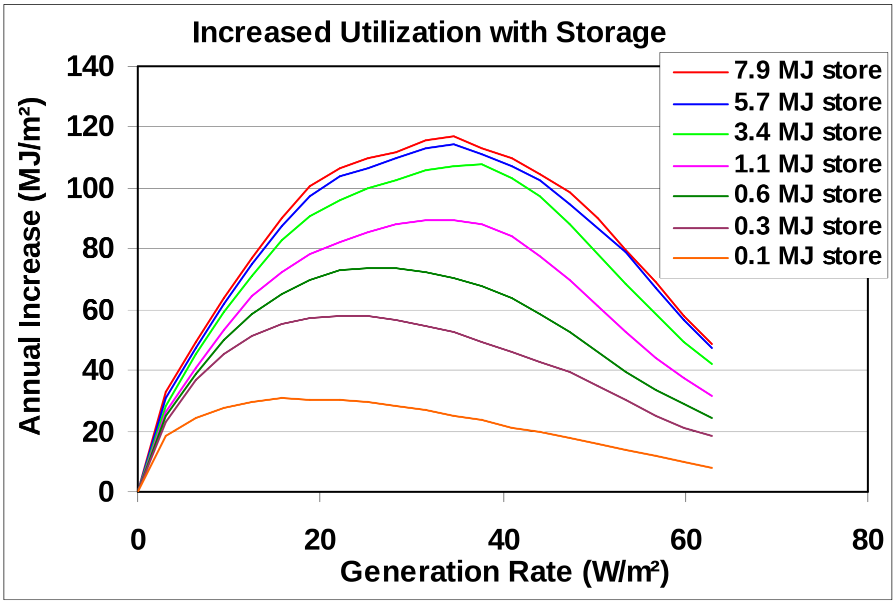

Figure 4. Increased utilization of different sized co-generation units with increasing storage.

A fuel cell as co-generator plus CO_2 source

Technically a fuel cell is an attractive co-generator as it provides a relatively large proportion of the output energy as electricity and a fuel cell utilizing natural gas also provides a source of clean carbon dioxide from the reformer section. Given the high cost of this technology it will be important to carefully optimize the use of all outputs to amortize investment costs: electricity, heat and CO_2. To investigate the match of outputs to greenhouse needs, the operating characteristics of a commercially available fuel cell have been utilized. The unit chosen is the 200 kWe PureCell from UTC Power (Note: mention of specific commercial equipment does not constitute endorsement). In addition to the 200 kW electrical output the unit generates 98 kg/hr of CO_2 and up to 0.76 GJ/hr of heat at the beginning of stack cell life. Up to 0.29 GJ/hr of this is available from 121°C to 60°C, with the remainder available from 60°C to 27°C, assuming the return temperature can be brought down to this level.

Previous projects utilizing waste heat from power plants have demonstrated useful heat can be extracted from relatively low temperature sources utilizing floor heating systems and/or appropriate air/water heat exchangers (Mears and Manning, 1996), with return temperatures at or below 27°C. For the purposes of this study it is assumed that segregated storages can be utilized that will enable energy to be stored over a temperature range of 49°C with the amount of energy stored within that range dependent on the thermal mass of the selected storage. For simplicity in modeling for this first stage evaluation, a single storage unit was assumed. It is assumed that heat requirements of the greenhouse were met from storage first with backup heat providing the balance in each hour and the fuel cell unit recharging storage.

Storage units were of several sizes and assumed located outdoors and insulated to reduce heat loss to 0.28 W/m^2K for calculating heat loss from storage during the simulation. For this study, the three storages were modeled on simple backyard swimming pools of 1.22 m depth and of 3.0, 6.1 and 9.1 m diameters, respectively for the PHL location, and 1.22 m by 6.1 and 9.1 m, and 2.44 m by 9.1 m for the largest tank for the Bonita, AZ location. When being charged by the fuel cell at full thermal output and no withdrawals being made, the rate of increase of temperature for these four storage sizes were: 20.5, 5, 2.2 and 1.1°C per hour, respectively. Thus the time it would take to fully charge the storage over a temperature range of 67 ^{o}C would range from just over 4 hours for the smallest tank to 60 hours for the largest.

To evaluate the benefit of CO_2 utilization it is assumed that the greenhouse can utilize up to 50 kg/hr per hectare when there is significant light for plant growth and when there is either no ventilation or only first stage ventilation operating but there is no provision for storage of CO_2 so it is only utilized as produced under the stated conditions. The results of the simulation for two weather databases, PHL and the complete 2006 hourly database from Bonita, AZ are presented to indicate the difference in heat and CO_2 utilization as affected by local weather. The greenhouse construction and heat loss characteristics were similar to those of the previous co-generation simulation but the specific heat loss values per unit area depend on greenhouse size, decreasing slightly for the larger sizes due the reduced influence of sidewalls.

The results for the heat and CO_2 utilization for the Bonita, AZ and PHL locations are given in Table 2 and Figure 5 for Bonita, AZ and Table 3 and Figure 6 for PHL for the case where there is no provision for heat storage. In this case the thermal output of the fuel cell can only be used to the extent that it meets the heat needs for any given hour so as the size of the greenhouse increases the heat utilization increases. The total annual heat production potential for 8760 hours would be 6694 GJ and of course there will be no ability to use any of this during warm weather or when solar energy meets or exceeds heat requirements. At the Bonita, AZ location, the thermal energy utilization ranges from just under 21% for a 0.49-hectare greenhouse to just over 31% for a 3.44-hectare facility. For similar sizes at the PHL location, utilization ranges from 27.5% to over 36% reflecting the general colder weather at the more northerly location.

Table 2. CO_2 and heat use without thermal storage - Bonita, AZ.

Grhse Size ha	Total Required GJ	Fuel Cell Provided GJ	Percent From Fuel Cell	Excess Not Used	CO_2 kg With No vent	CO_2 kg With Stage 1	Total CO_2 kg Used	Percent CO_2 Utilized
0.49	1501	1389	93	5305	8528	13640	22169	1.2
0.98	3002	1851	62	4843	17057	27281	44338	2.3
1.47	4503	1973	44	4721	25585	40921	66507	3.5
1.97	6005	2029	34	4665	34114	54562	88675	4.7
2.46	7506	2062	27	4632	34155	54629	88784	4.7
2.95	9007	2084	23	4610	Hourly CO_2 fully used over 2 hectares			
3.44	10508	2099	20	4595				

Table 3. CO_2 and heat use without thermal storage - PHL data.

Grhse Size ha	Total Required GJ	Fuel Cell Provided GJ	Percent From Fuel Cell	Excess Not Used	CO_2 kg With No vent	CO_2 kg With Stage 1	Total CO_2 kg Used	Percent CO_2 Utilized
0.33	1510	1452	96	5242	13092	17221	30312	1.6
0.49	2265	1842	81	4852	19637	25831	45468	2.4
0.98	4530	2177	48	4517	39275	51662	90937	4.8
1.47	6795	2289	34	4405	58912	77493	136405	7.2
1.97	9060	2352	26	4342	78550	103324	181873	9.6
2.46	11325	2390	21	4304	78646	103451	182097	9.6
2.95	13590	2414	18	4280	Hourly CO_2 fully used over 2 hectares			
3.44	15856	2433	15	4261				

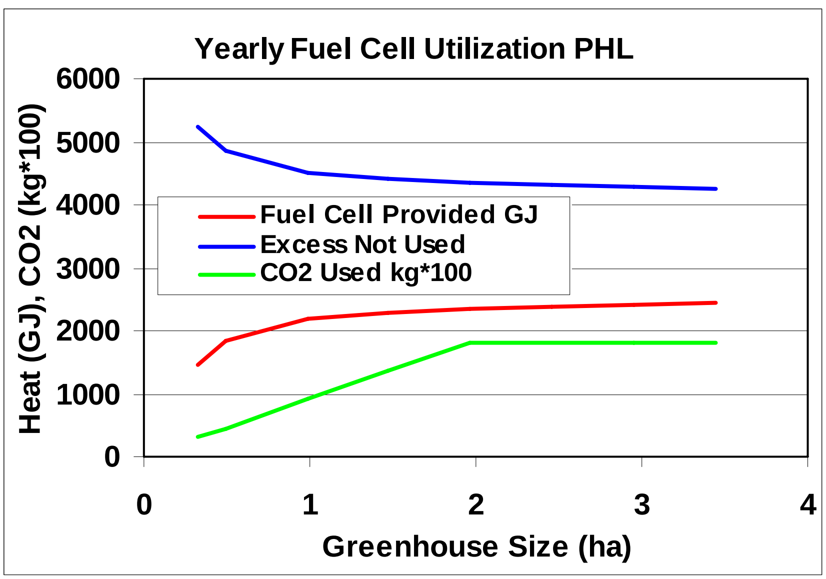

Figure 5. Effect of greenhouse size on heat and CO_2 utilization without heat storage for the PHL database.

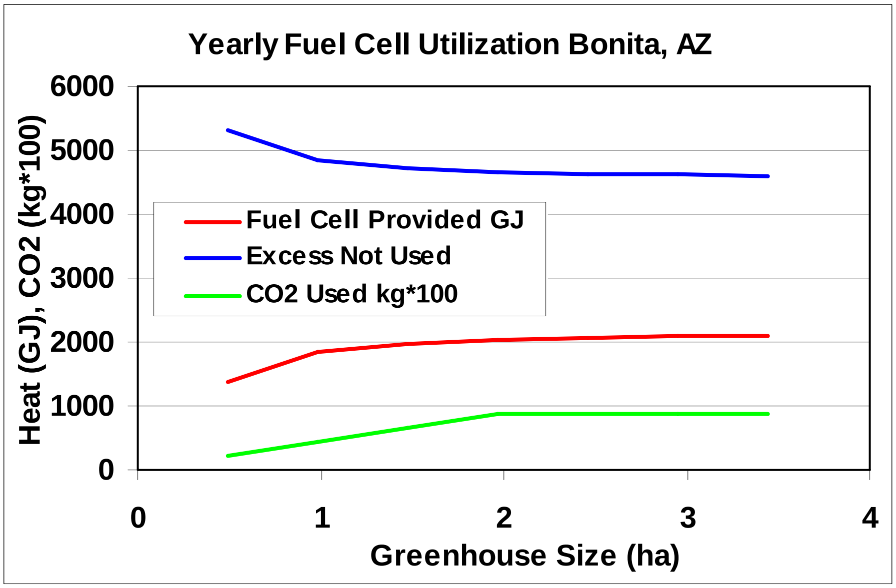

Figure 6. Effect of greenhouse size on heat and CO_2 utilization without heat storage for the Bonita, AZ database.

The utilization of CO_2 does not depend on thermal storage but simply the relationship between light levels and the requirement for ventilation at the two sites. At the Bonita, AZ location, there were 347 hours of light with no ventilation and 555 hours with light during first stage ventilation. At the PHL location, there were 799 hours of light with no ventilation and 1051 hours with light during first stage ventilation. The main reason there is so much more potential for CO_2 enrichment at the PHL location is that there are so many more hours of the year where second and third stage ventilation is required at the Bonita, AZ location reducing the effectiveness of purchased CO_2 during those periods. There were 3569 hours of this condition at the Bonita, AZ location and only 2612 at the PHL location. This is due to the higher temperatures and higher light levels at the more southerly location. The degree to which CO_2 enrichment is beneficial during higher stages of ventilation will potentially enhance the value of this waste resource at both locations.

At both locations there was a significant increase in the utilization of the reject heat with increasing size of the greenhouse, as noted in Tables 2 and 3 above for the case where there was no thermal storage. In addition, adding some thermal storage can dramatically improve the utilization of the waste heat as energy can be banked during hours of no demand to meet an increasing percentage of the greenhouse heat requirements. In relatively mild weather, spring and fall, storage enabled the unit to meet virtually all the heating needs for even very large areas.

At the Bonita, AZ location for the smaller, 0.49-hectare greenhouse adding storage increased the thermal utilization from 93% to 100% for each of the three larger storage units (Table 4 and Figure 7). However, as the size of the greenhouse increased the added benefit of storage dramatically increased, with utilization for the larger, 3.44-hectare facility increasing from 20% for no storage to from 36 to 38 to 39% for the three larger storages, essentially doubling the utilization of the heat for the larger storages. Similarly at the PHL location (Table 5 and Figure 8), for the smaller, 0.49-hectare greenhouse adding storage increased the thermal utilization from 81% to 87 to 98 to 100% for each of the three smaller storage units. Again, as the size of the greenhouse increased the added benefit of storage dramatically increased with utilization for the larger, 3.44-hectare facility increasing from 15% for no storage to from 17 to 24 to 25% for the three larger storages, substantially increasing the utilization of the heat for the larger storages.

Table 4. Effect of storage capacity and size on heat utilization - Bonita AZ.

Grhse Size ha	Fuel Cell Provided No store GJ	Percent From Fuel Cell	Fuel Cell Provided 36 m^3 store GJ	Percent From Fuel Cell	Fuel Cell Provided 80 m^3 store GJ	Percent From Fuel Cell	Fuel Cell Provided 160 m^3 store GJ	Percent From Fuel Cell
0.49	1389	93	1501	100	1501	100	1501	100
0.98	1851	62	2735	91	2807	94	2844	95
1.47	1973	44	3289	73	3420	76	3461	77
1.97	2029	34	3569	59	3700	62	3744	62
2.46	2062	27	3685	49	3850	51	3928	52
2.95	2084	23	3758	42	3955	44	4045	45
3.44	2099	20	3798	36	4013	38	4100	39

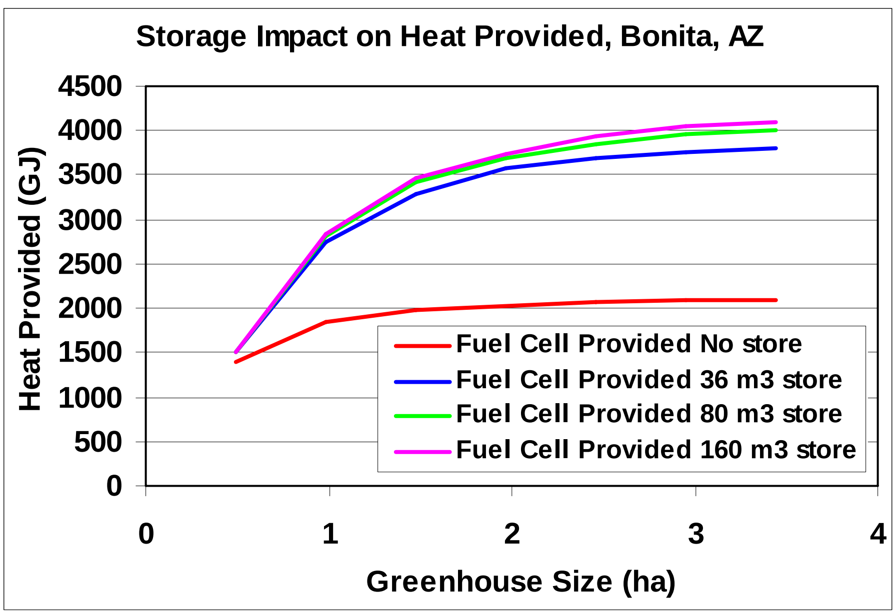

Figure 7. Increases in heat utilization with storage for the Bonita, AZ database.

Table 5. Effect of storage capacity and size on heat utilization - PHL data.

Grhse Size ha	Fuel Cell Provided No store GJ	Percent From Fuel Cell	Fuel Cell Provided 9 m^3 store GJ	Percent From Fuel Cell	Fuel Cell Provided 36 m^3 store GJ	Percent From Fuel Cell	Fuel Cell Provided 80 m^3 store GJ	Percent From Fuel Cell
0.49	1842	81	1979	87	2213	98	2260	100
0.98	2177	48	2415	53	3130	69	3228	71
1.47	2289	34	2561	38	3419	50	3545	52
1.97	2352	26	2642	29	3574	39	3707	41
2.46	2390	21	2697	24	3680	32	3811	34
2.95	2414	18	2728	20	3762	28	3898	29
3.44	2433	15	2753	17	3826	24	3969	25

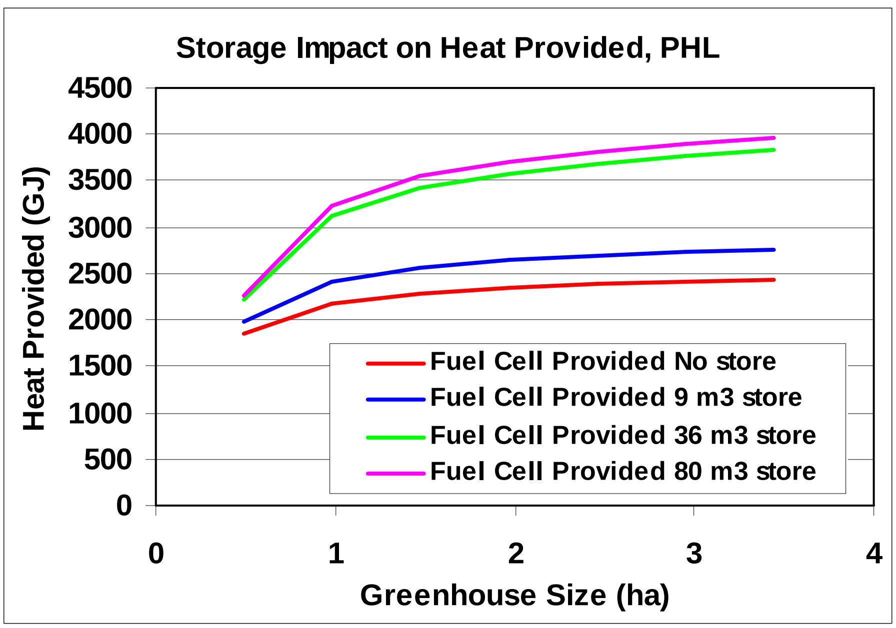

Figure 8. Increases in heat utilization with storage for the PHL database.

A heat pump with internal collection for heating and cooling

Earlier work on energy alternatives for greenhouses, particularly the activities in the late 1970's, did not seriously consider options that were strongly dependent on electricity. At the time, about 20% of U.S. electricity was generated from oil but that has shifted today to about 3%, (Woolsey, 2006), and there has been a significant shift in the cost of electricity relative to other energy resources. There are examples of commercial greenhouses installing electric boilers given the price advantage of electricity in their area. With the high coefficient of performance for water sourced heat pumps these units appear an attractive option, assuming the system will provide enough equipment utilization for the fuel savings to amortize the relatively high initial cost.

In considering a heat pump as a heating source only if one were to design a system where the heat pump was the only heating source then the capacity of the unit and the associated water source would have to match the peak heating requirement of the greenhouse and would only be fully utilized during the coldest possible weather for the site. Given the relatively high initial cost of the system, the concept of scaling down the heat pump capacity and relying on a lower cost fossil fuel based system for peaking requirements should be considered. The option of adding energy storage so a smaller unit can be utilized more hours of the year will be critical to achieving economic viability. In this regard, the relationship between system capacity and storage relative to the pattern of greenhouse energy requirements will follow the same scenario as discussed in the section on fuel cell utilization. The relationships between the system generation capacity, storage capacity, and heating load patterns will be similar for any type of co-generation unit or heat pump.

When using an air handling system with water/air heat exchangers there is the option to use the heat pump unit to provide some portion of greenhouse cooling, capturing heat in the daytime and storing it for night use. Assuming a heat pump system will have appropriately sized warm water storage it is only necessary to provide a small cool water storage, valves and controls to add this feature. When greenhouse cooling is required the heat pump will move heat from the cool to the warm tank and the chilled water will be circulated through the heat exchanger and the cooled air distributed throughout the greenhouse. When greenhouse cooling is not required, the heat pump can be used to extract heat from the water source to be stored or used. A potential advantage of adding this feature is the ability to keep the greenhouse closed with temperature and humidity control for more of the daylight hours, which can potentially extend the effective period for carbon dioxide enrichment.

The initial design considered to utilize this concept started with an assumption of acquiring a heat pump with a thermal output about 1/10 the peak heating system capacity and associating it with an air handling system recirculating interior greenhouse air at a rate roughly equivalent to 1/8 maximum ventilation design requirements of 2.48 m^3/min per m^2. For this phase of the study a 3278 m^2 - four bay section of the greenhouse, simulated at various sizes described in the preceding fuel cell discussion, was used with the assumption these are interior bays of a larger structure so there is no heat loss through the sidewalls.

The three storage sizes assumed related to the greenhouse are equivalent to 2.73, 10.8 and 24.4 L of water per m^2 of greenhouse floor area. Storage temperature was from a base of 16^oC, the greenhouse set point, to a maximum of 38^oC, above which the heat pump would be shut off. Three sizes of heat pump were considered and sized to provide 5.36, 10.7 and 16.1 W/m^2 of greenhouse floor area, respectively. The air handler properties used were taken from commercial literature (Model GLW660, Modine Manufacturing Co., Racine, WI). These units have a heat transfer rate of 3165 W times the entering temperature difference (^oC) of the air and water at flow rates of 218 m^3/min of air and 152 L/min of water, resulting in a heat transfer rate per unit of 0.97 W/($m^{2o}C$) of greenhouse floor area. Simulations were run for these combinations. Comparisons were made for two locations, one utilizing the PHL database and the other for a weather database record for one year from a commercial greenhouse in Bellville, OH that is significantly colder, requiring approximately 50% more heat than the PHL database (Fynn, 2006).

These results presented in Tables 6 and 7 show that total annual heat provided from the heat pump system does increase with increases in any of the design parameters: heat pump size, number of heat exchange units and size of storage. However, there is a diminishing improvement per unit increase with any of these parameters for each increment of increased capacity. To optimize the system economically the costs of the components and prices of electricity vs. backup fuel will be needed. In general though, some preliminary conclusions can be drawn by simple inspection of the values in the tables.

Table 6. PHL results: Total heat requirement = 520 MJ/m^2 (HEX = heat exchanger).

Heat pump capacity = 5.34 W/m^2						Heat pump capacity = 10.7 W/m^2						Heat pump capacity = 16.1 W/m^2					
Store	HEX	No	Int.	From	Comb.	Store	HEX	No	Int.	From	Comb.	Store	HEX	No	Int.	From	Comb.
L/m^2	#	Well	Rec.	Well	Total	L/m^2	#	Well	Rec.	Well	Total	L/m^2	#	Well	Rec.	Well	Total
		MJ/m^2						MJ/m^2						MJ/m^2			
2.73	1	25	24	72	96	2.73	1	20	19	129	148	2.73	1	11	10	183	193
2.73	2	25	25	73	98	2.73	2	31	29	131	160	2.73	2	21	20	186	206
2.73	4	26	25	74	98	2.73	4	31	30	132	163	2.73	4	29	27	188	216
2.73	6	Small storage limits heat exchange utility				2.73	6	34	33	133	166	2.73	6	30	29	188	217
2.73	8					2.73						2.73	8				
10.8	1	26	24	76	100	10.8	1	39	35	139	174	10.8	1	29	25	189	213
10.8	2	27	25	77	102	10.8	2	43	40	143	183	10.8	2	53	49	202	251
10.8	4	27	25	77	102	10.8	4	44	41	144	185	10.8	4	54	51	205	256
10.8	6	27	25	77	103	10.8	6	44	42	144	186	10.8	6	54	51	206	257
10.8	8	27	25	77	103	10.8	8	44	42	144	186	10.8	8	54	52	206	258
24.4	1	28	22	78	100	24.4	1	42	35	142	177	24.4	1	39	30	194	224
24.4	2	29	24	79	103	24.4	2	45	39	147	186	24.4	2	56	49	208	257
24.4	4	29	25	79	104	24.4	4	46	41	147	189	24.4	4	58	52	210	263
24.4	6	29	25	79	104	24.4	6	46	42	148	189	24.4	6	58	53	211	264
24.4	8	29	25	79	104	24.4	8	46	42	148	189	24.4	8	59	54	211	265

Table 7. Bellville, OH results: Total heat requirement = 896 MJ/m^2 (HEX = heat exchanger).

Heat pump capacity = 5.34 W/m^2						Heat pump capacity = 10.7 W/m^2						Heat pump capacity = 16.1 W/m^2					
Store L/m^2	HEX #	No Well	Int. Rec.	From Well	Comb. Total	Store L/m^2	HEX #	No Well	Int. Rec.	From Well	Comb. Total	Store L/m^2	HEX #	No Well	Int. Rec.	From Well	Comb. Total
		MJ/m^2						MJ/m^2						MJ/m^2			
2.73	1	32	31	92	123	2.73	1	26	24	170	195	2.73	1	15	13	244	257
2.73	2	33	32	93	126	2.73	2	38	37	172	209	2.73	2	27	26	248	274
2.73	4	34	33	94	127	2.73	4	39	38	173	211	2.73	4	36	35	249	284
2.73	6	Small storage limits heat exchange utility				2.73	6	43	42	174	215	2.73	6	38	37	249	286
2.73	8					2.73						2.73	8				
10.8	1	36	32	98	130	10.8	1	51	47	179	225	10.8	1	36	31	250	281
10.8	2	37	34	99	133	10.8	2	58	54	186	240	10.8	2	67	63	262	324
10.8	4	37	35	99	134	10.8	4	58	55	188	243	10.8	4	71	67	265	333
10.8	6	38	35	99	135	10.8	6	59	56	188	244	10.8	6	71	68	266	334
10.8	8	38	35	99	135	10.8	8	59	57	188	245	10.8	8	71	68	267	335
24.4	1	38	31	99	131	24.4	1	55	47	182	229	24.4	1	46	36	255	291
24.4	2	39	34	101	134	24.4	2	62	55	189	245	24.4	2	73	65	267	332
24.4	4	39	35	101	136	24.4	4	63	58	191	249	24.4	4	77	70	272	342
24.4	6	40	35	101	136	24.4	6	64	58	191	250	24.4	6	77	72	272	344
24.4	8	40	35	101	136	24.4	8	64	59	191	250	24.4	8	78	72	273	345

The rates of increase in contributed energy for the internal heat recovery alone, without the benefit of the well, do increase with increasing heat pump capacity. For the three units, the increases in performance are more significant up to: two heat exchanger units and just the small storage for the smaller heat pump, two heat exchanger units and the medium storage for the medium heat pump, and four heat exchanger units and the large storage for the larger heat pump. With these values, the increase from the small to medium and medium to large heat pump are essentially the same.

When the internal collection system is augmented with the addition of a geothermal heat source, the total energy contribution from the heat pump increases substantially, 4 to 6 fold, but the apparent break points in significant increases occur at roughly the same points. Based on these general observations, an optimal system for the PHL database with the geothermal source might be the larger heat pump with the larger storage and four heat exchange units delivering 263 MJ per m^2 or a total of 862GJ for the facility per year, just over 50% of the total requirement of 1705 GJ. With a similar choice of equipment for the Ohio location, the system is utilized more and delivers 342 MJ per m^2 or 1121 GJ for the facility per year but this is only 38% of the total requirement of 2937 GJ at this colder location.

It may be very important for some crops that the internal heat recovery system is providing cooling of the greenhouse during what would normally be first stage ventilation. In the case where CO_2 is being supplemented this will extend the period in which enrichment is not compromised by ventilation. As noted in the fuel cell simulation discussed above, the extra hours of greenhouse closure in the Bonita, AZ and PHL locations would be 555 and 1051 hours, respectively. The economic benefit of this feature will depend on the response of the particular crop being grown to CO_2 supplementation.

Conclusions

The cases presented indicate the potential for a relatively simple approach for making a first level evaluation of possible energy management scenarios. As the method is based on some historical weather database it will not precisely predict any given system and management strategies performance but does give an indication of the relative performance of proposed systems and strategies. The degree to which these predictions will actually predict performance will also depend on the accuracy of the various system parameters assumed in the simulation.

The cases examined all indicate the importance of thermal storage as a management tool to increase the utilization of the investments in the alternative energy systems where the energy to be delivered is not stored in the form of fossil fuel. In the case of an alternative system, which produces CO_2 the benefit of that product depends on the degree to which the greenhouse can be closed enough to make supplementation practical.

As the relative costs of various energy sources continue to change, opportunities for technologies based on electricity are likely to become increasingly attractive. The use of heat pumps are particularly relevant for greenhouse applications as there can be the opportunity to provide some cooling as well as base load heating. In the case where CO_2 is being supplemented, the additional hours of greenhouse closure provide benefits in addition to the provision of heating and cooling.

Literature Cited

Bartok, J.W. Jr., 2001. *Energy conservation for commercial greenhouses*. NRAES-3. NRAES, Ithaca, NY.

Both, A.J., E. Reiss, D.R. Mears, and W. Fang. 2005. Designing environmental control for greenhouses: Orchid production as example. Acta Horticulturae 691(2):807-813.

Ekholt, B.A., D.R. Mears, M.S. Giniger, and T.O. Manning. 1983. Simulation of greenhouse floor heating with a co-generation unit. ASAE Paper No. 83-4018. ASAE, 2950 Niles Road, St. Joseph, MI 49085-9659, USA.

Fynn, P. 2006. Weather data from the Possum Run Greenhouse location, Bellville, OH. Personal communication.

Manning, T.O. and D.R. Mears. 1981. Computer aided design of a greenhouse waste heat utilization system. Energy in Agriculture 1:5-20.

Manning, T.O., D.R. Mears, and M.B. Buganski. 1983. Engineering performance of a 1.1 hectare waste-heated greenhouse. ASAE Paper No. 83-4020. ASAE, 2950 Niles Road, St. Joseph, MI 49085-9659, USA.

Mears, D.R., W.J. Roberts, J.C. Simpkins, P.W. Kendall, J. P. Cipolletti, and H. Janes. 1980. The Rutgers system for solar heating of commercial greenhouses. Acta Horticulturae 115:575-582.

Mears, D.R. and T.O. Manning, 1996. Redesign of greenhouse waste heat system. ASAE Paper NABEC 9642. ASAE, 2950 Niles Road, St. Joseph, MI 49085-9659, USA.

Short, T.H., M.F. Brugger, and W.L. Bauerle. 1979. Energy conservation ideas for new and existing greenhouses. Transactions ASHRAE, 86(2): 449-454.

Takakura, T. and W. Fang. 2002. *Climate under cover*, 2nd Edition. Kluwer Academic Publishers. Dordrecht/Boston/London.

Woolsey, J.R. 2006. Energy independence. Testimony for U.S. Senate Committee on Energy. March 7, 2006.

Addendum on waste heat added by D. Mears December 2007

Four waste heat use scenarios

In order to optimize the design of a greenhouse heating system using reject heat from an electric generating station Manning and Mears, (1981) used a simulation system based on actual hourly data for both the external weather and for the temperature of the water coming from the power plant which was found to vary significantly from hour to hour throughout the year. As greenhouse floor heating systems have significant thermal mass the energy storage feature can enable the system to provide somewhat more heat under varying supply temperatures than would be the case with constant temperature supply, (Manning et al 1983). However, when the pattern of variability in the waste heat resource is not known and the best available information is an estimate of the likely minimum temperature, a reasonable and conservative estimate of the contribution to total energy requirements for any given system design and set point temperature can be determined.

There has been some expression of interest in developing a greenhouse operation in the area around Regina, Saskatchewan, Canada utilizing waste heat from local industrial operations. No specific site has as yet been determined nor have there been firm decisions on what crops should be considered. As there is no firm data on variability of waste heat supply temperatures but there is an estimate of minimal supply temperature for several candidate sources of at least 30^{o}C this parameter can be used for a first approximation at some system designs. Using the same greenhouse and heat exchanger parameters used in the above studies and a historical hourly weather database for Regina, simulations were run for greenhouses kept at various possible nighttime heating set points.

Simulations were run first to determine how much total heating energy would be required for each set point temperature. Then the simulations were run to determine the backup that would be required from a boiler system to meet the heating need above what would be provided by the waste heat delivery system. The first system would utilize a floor heating system with similar heat transfer characteristics to the earlier waste heat greenhouse design. Then additional simulations could be run adding heat exchange capacity equivalent to one or more of the Modine heat exchanger units per four bay section. The results for the total heat requirement for five different set point temperatures ranging from 10.0 to 21.1^{o}C are represented in Figure 5.

The results for each hour are sorted from the coldest hour/heat requirement downwards for plotting. The highest hourly rate requirements shown on the left axis ranges from 164 to 207 W/m^2. The total seasonal energy requirements range from 231 to 431 kWhrs/m^2. To compare the system requirements with the Canadian location and others, simulations were also run for three other weather databases, the Philadelphia, Pennsylvania and Bonita, Arizona databases used for the heat pump studies and an historical hourly weather database for Tokyo, Japan. These four sites hourly and total annual requirements for the intermediate temperature of 15.6^{o}C are shown in Figure 6.

The backup required for each of the four sites after utilizing the waste heat in the floor system and then increasing numbers of heat exchanger units are shown in Figures 5-8. In the coldest location adding six units in the four bay section is required to almost eliminate the need for backup whereas in the two warmer locations virtually all of the requirement can be met with the floor alone. Note that at higher desired internal set points increased heat exchange capacity would be required. To optimize the design from the economics standpoint the costs of backup energy will need to be considered in relationship to the installation costs of the equipment.

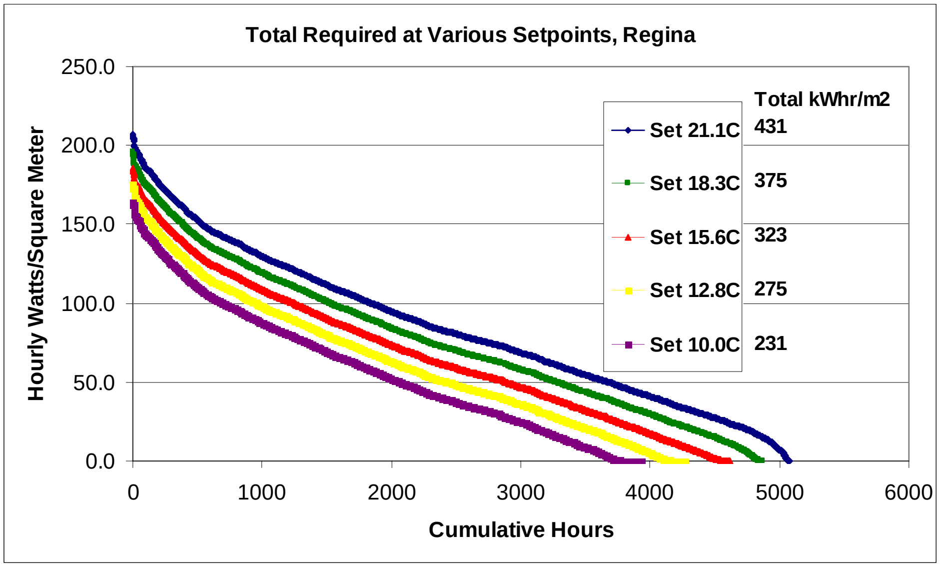

Figure 5. Hourly and total annual heating requirements for various set points, Regina, Saskatchewan, Canada

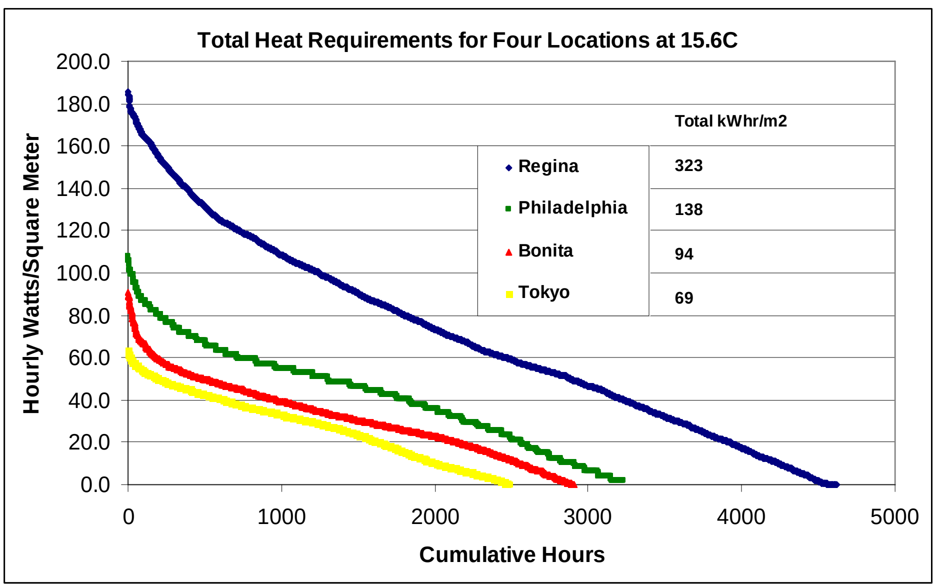

Figure 6. Hourly and total annual heating requirements for 15.6°C set point: Regina, Saskatchewan, Canada. Philadelphia, Pennsylvania, Bonita, Arizona and Tokyo, Japan

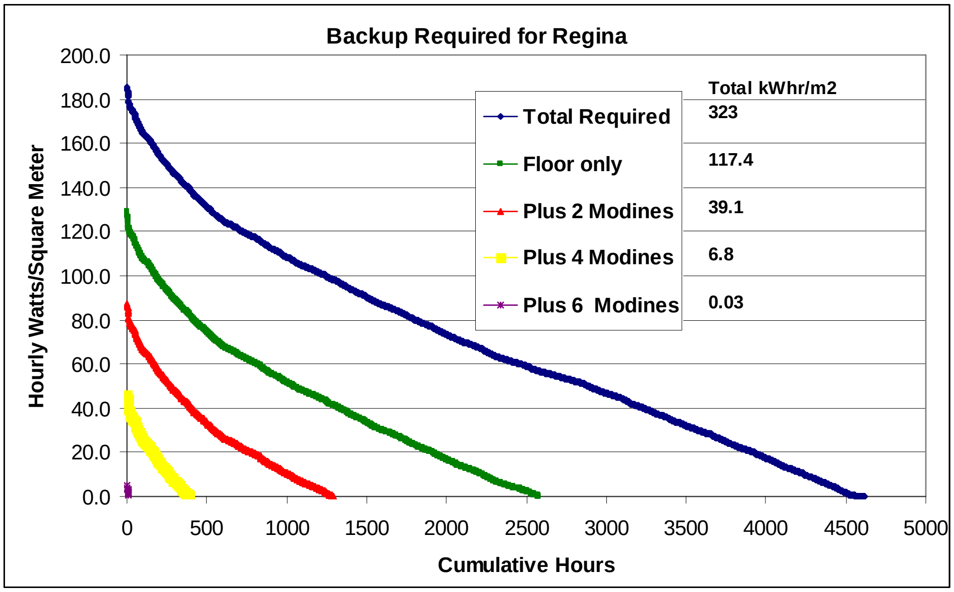

Figure 7. Hourly and total heat requirements for maintaining 15.6°C at Regina with contributions of waste heat through a floor heating system and increasing numbers of heat exchangers.

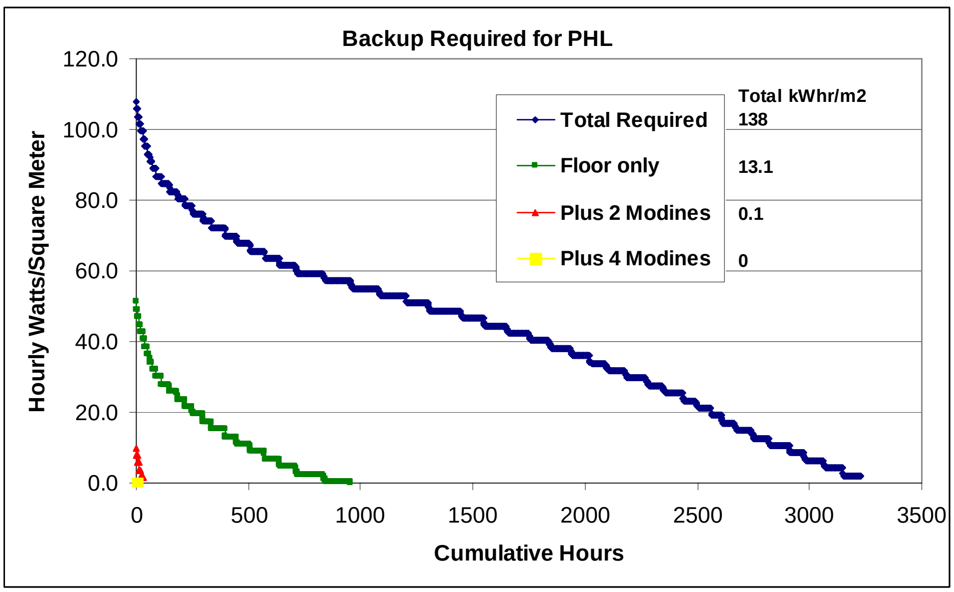

Figure 8. Hourly and total heat requirements for maintaining 15.6°C at Philadelphia with contributions of waste heat through a floor heating system and increasing numbers of heat exchangers.

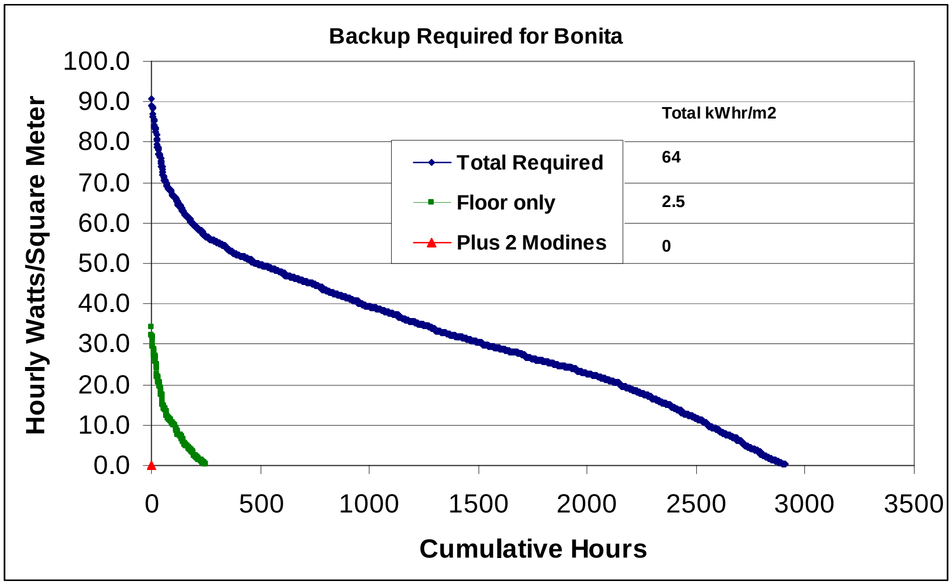

Figure 9. Hourly and total heat requirements for maintaining 15.6°C at Bonita with contributions of waste heat through a floor heating system and increasing numbers of heat exchangers.

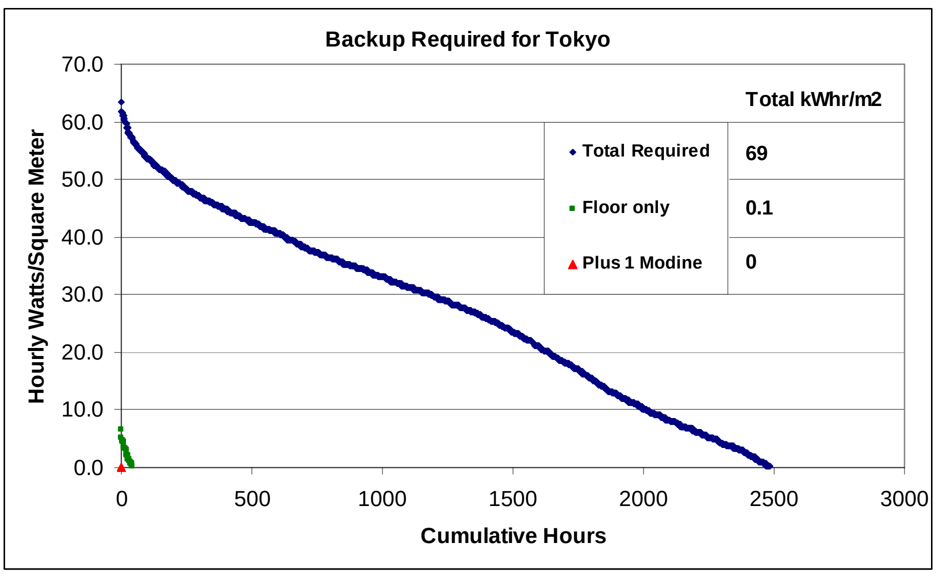

Figure 10. Hourly and total heat requirements for maintaining 15.6°C at Tokyo with contributions of waste heat through a floor heating system and floor plus one heat exchanger.