ENERGY SAVINGS OF EVAPORATIVE COOLER VENT COVERS:

Feasibility Analysis for Orchard Park Greenhouses

AN PROJECT ENERGY ASSESSMENT BY:

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Executive Summary

The Orchard Park Greenhouses operated by UC Davis are functional but outdated. They lack vent covers that help to regulate internal temperatures and allow heated air to escape through evaporative cooling pads. We conducted an economic analysis with a theoretical air flow model to determine the feasibility of vent cover installation given a 5 to 10 year greenhouse lifetime.

Each greenhouse, studied at different set points from 15 to 30 degrees C set point, was projected to save between $300 and $2,000 annually while requiring an upfront cost of $3,380 per greenhouse. It was found that the potential energy savings will give a return on investment for a 5+ year lifetime, with the potential for over $1M savings for a 10+ year lifetime. A vent cover retrofit of the 69 greenhouses in Orchard Park was found to be economically feasible, but we recommend further research to better estimate potential upfront costs and validate the theoretical model. Future work would include obtaining a contractor estimate of installation costs and volume discounts, a blower door test to better estimate conditioned air losses through the vent, and a characterization of the Orchard Park greenhouse set-points.

This project was carried out by: Omar Samara, a 1st year PhD student in Biological Systems Engineering with extensive experience modeling and designing automated irrigation systems and unmanned aerial vehicles for agricultural use; Caitlin Walker, a 5th year BS student in Chemical Engineering with experience in transport phenomena and ventilation rate analysis; and Carrie Ng, a 3rd year BA student in Environmental Policy Analysis and Planning with experience in cost benefit analysis and energy service company economic feasibility analysis.

Introduction/Background

Greenhouses are required to maintain temperatures 24/7 for proper propagation, and are constantly running. On Orchard Park Drive, there are 69 greenhouses that lack vent covers, as they are older facilities. These greenhouses use evaporative cooling pads to bring cool air into and through the greenhouses. While modern greenhouses have covers installed over these pads to reduce air leakage, the greenhouses in question do not. This creates an open system during heating, and an opportunity for energy savings. The majority of the greenhouse's energy costs can be attributed to steam heating through conduction, and minimizing air flow out of the system during heating hours could result in energy savings that justify installation and maintenance of vent covers.

In support of the UC Davis research mission, a substantial portion of campus energy usage is delegated to greenhouse operation. In addition to the high energy usage, being tied into the grid presents other logistical constraints depending on the varying demands of campus. The greenhouse managers, Garry Pearson, Ronald Lane, and Chris Durand have noticed and wish to address this issue at hand. With a grant of $2 million dollars, they are also working with another team to discover other potential sources of energy consumption to upgrade greenhouses and reduce energy consumption. As such, increasing energy efficiency in the greenhouses could help lower operating expenses, simplify logistical management, and support the UC Davis's sustainable climate goal for 2020. Our team's efforts focused specifically on the economic feasibility of installing vent covers on up to 70 greenhouses in Orchard Park.

Methodology

Major Considerations:

The feasibility of installing vent covers was largely governed by the lifetime of the project, as the potential energy savings would need to at least breakeven with the upfront installation costs. We also wanted to help the greenhouse managers to efficiently spend their grant money by providing a recommendation on whether this retrofit would be a worthwhile investment that also maintains the facility's energy savings goals without compromising their research mission.

Literature Review:

As the heating system is specifically modeling the energy lost through air leakage via the open ventilation cover, studying air leakage is important in creating a model. Takeshi (2002) analyzes air leakage with both mathematical models and through computational fluid dynamics and aims to calculate pressure differentials and air losses in a greenhouse specifically. The model further referenced Fernandez's (1992) paper of environmental factors which affect air flow rates in a system and explains the relevance with math.

Procedure:

We conducted a literature review to gather information about existing greenhouse technologies as well as ongoing research pertaining to vent covers specifically. There was very limited information on this topic, but the majority of sources concluded that most modern greenhouses are equipped with vent covers [2]. There were a lot of useful articles on modelling procedures to estimate the greenhouse air flow and heat exchange, which we incorporated into our theoretical model [3,4,5].

Next, we conducted a site visit with the greenhouse managers to gather nameplate information and collect temperature and power data. This was done using data loggers and kW meters to compare against data previously collected from the greenhouse ARGUS control system. A month's worth of temperature and hot water heating data was salvaged after a server crash, but ultimately this data was deemed incomparable for further analysis due to 607 operation around 20 C at night while 608 was operating at 10 C. We concluded that the due to nonlinearities in physical operations (i.e. the intensity and duration of heating as demonstrated in Figure 1) as well as nonlinear governing physics, the two greenhouses were not directly comparable.

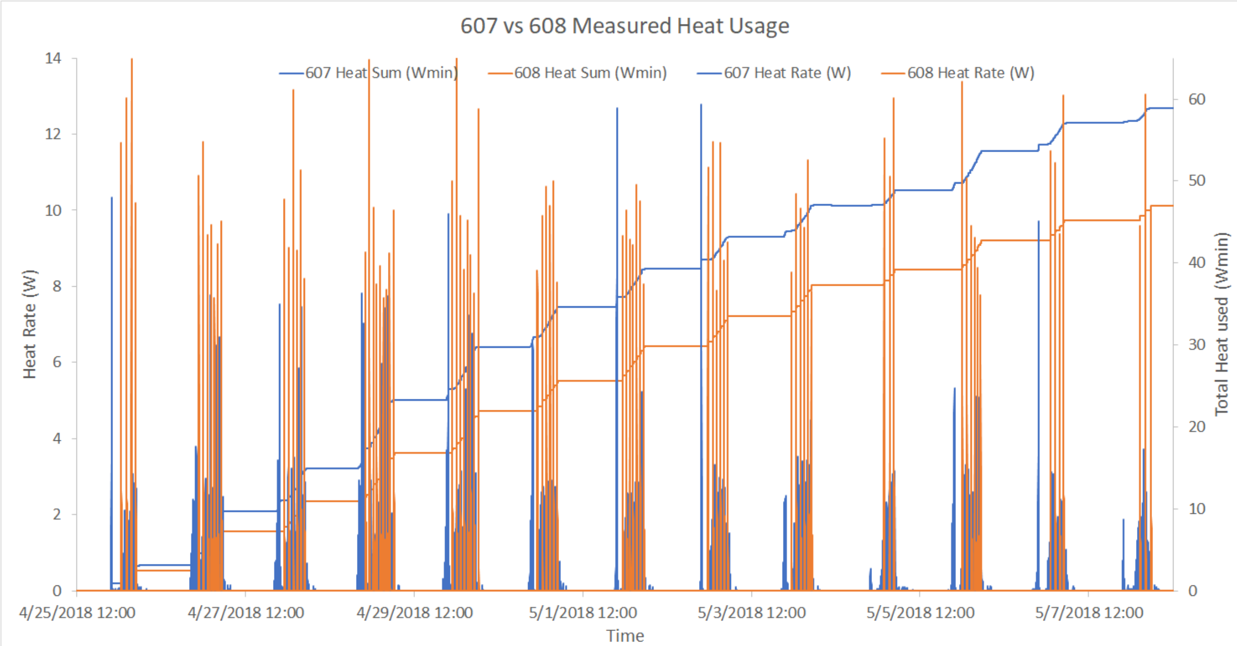

Figure 1: Measured Heat Usage in Greenhouse 607 and 608

Instead, a theoretical air flow model was used to calculate and compare the theoretical heat loss (and therefore potential energy savings) of each greenhouse. This estimate was combined with contractor estimates of the materials cost, and implemented in a simple payback period to extrapolate the potential energy savings to the entire Orchard Park facility. Additionally, the rate of return was explored over a project lifetime of 1 to 10 years.

Analysis & Model:

A theoretical airflow model (Figure 2) was used to estimate the volumetric flow rate of conditioned air being lost from the greenhouse through the open vent.

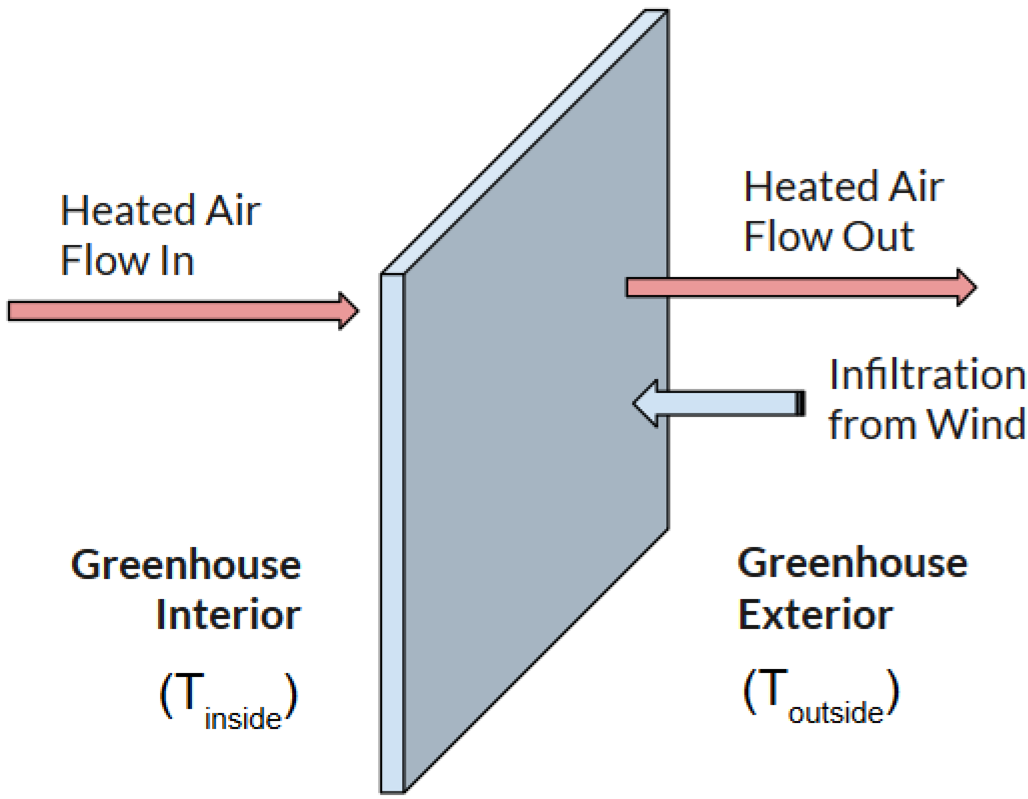

Figure 2: Air Flow Model

Using a constant internal temperature (set-point) as well as meteorological data for Davis from the CIMIS database, the following equation was used to model the system:

$$Q_{ventilation} = \frac{A_L}{1000}\sqrt{C_s \Delta T + C_w U^2} \quad \text{(Eq.1)}$$

$Q_{ventilation}$ = air leakage flow rate [m^3/sec]; A_L = effective vent area [cm^2]; U = wind velocity [m/s]; ΔT = interior/exterior temp difference [°C]; C_S = stack coefficient $(L/s)^2/cm^4$-K, 0.0001453; C_W = wind coefficient, 0.0000323 $(L/s)^2/cm^4$-$(m/s)^2$ [1]

The theoretical flow rate was used to estimate the heat losses of the open system (no vent cover) via Equation 2 [1]. These potential heat losses were combined with UCD utility rates [source] to estimate potential energy savings per greenhouse.

$$Q_{ventilation\ loss} = C_P \times \rho_{air} \times Q_{ventilation} \times (\mathrm{T_{inside}} - \mathrm{T_{outside}}) \qquad \text{(Eq.2)}$$

$Q_{ventilation\ loss}$ = heat loss via ventilation [W]; C_P = specific heat of air [J/kg-°C]; ρair = density of air [kg/m^3]; $Q^{ventilation}$ = air leakage flow rate [m^3/sec]

Results

Discussion of Relevant Results:

The theoretical model using Eq. 1 and Eq. 2 predicts two main contributors to the loss of conditioned air: (1) stack effects, driven by the temperature difference between the greenhouse interior and exterior; and (2) wind driven infiltration, driven by exterior wind through gaps in the greenhouse envelope. The contribution of wind driven filtration to the air leakage is constant across all greenhouses, but the stack effect varies with greenhouse set-point. A sensitivity analysis was performed on the greenhouse set-points, varying the set-point from 15 deg C to 25 deg C. The effect of greenhouse set-point on heat loss and energy savings is shown in Figure 3.

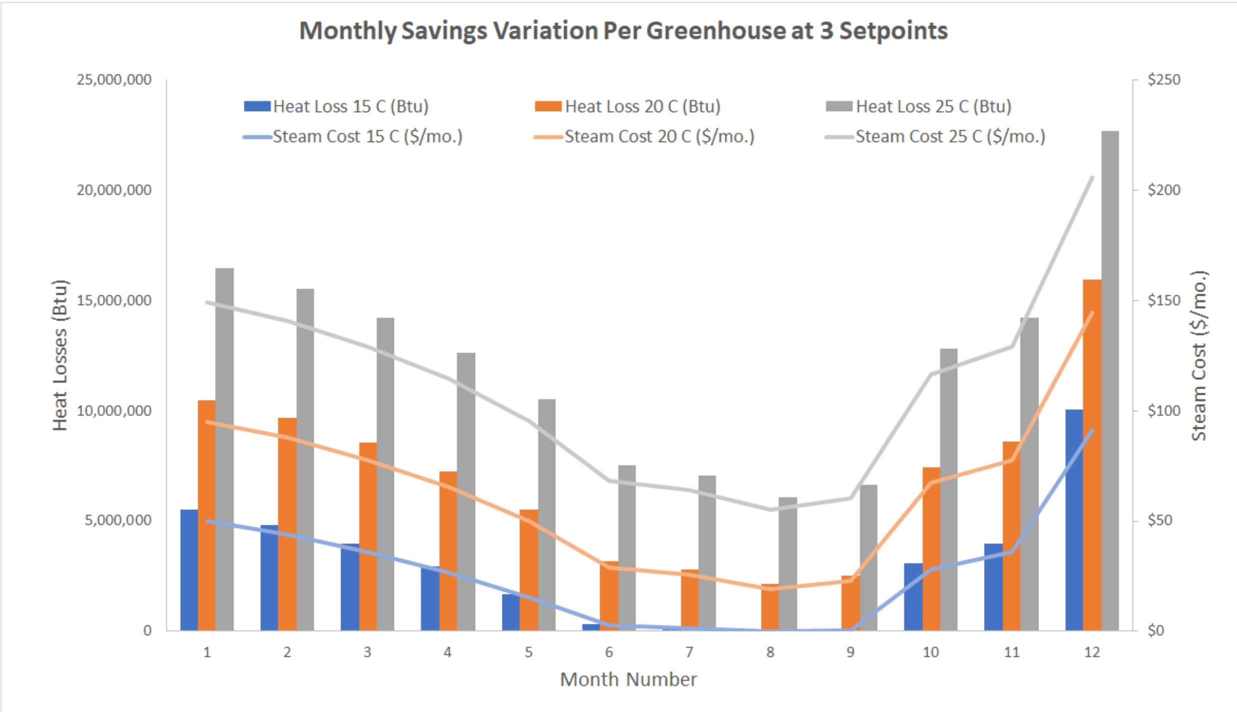

Figure 3: Sensitivity of Monthly Savings as a Function of Greenhouse Setpoint

The sensitivity analysis in Figure 4 shows that annual energy savings are most sensitive to greenhouse set-point, with the highest set-points yielding the largest savings. As the temperature difference between the greenhouse interior and exterior increases, the rate of heat transfer through the vent also increases. This gives the greatest losses during colder autumn/winter months, with the least losses occurring in the spring/summer. While the wind driven infiltration varies month-to-month, the relative magnitude of the wind coefficient combined with small annual variations in Davis wind speed make this contribution much smaller than variations in set-point.

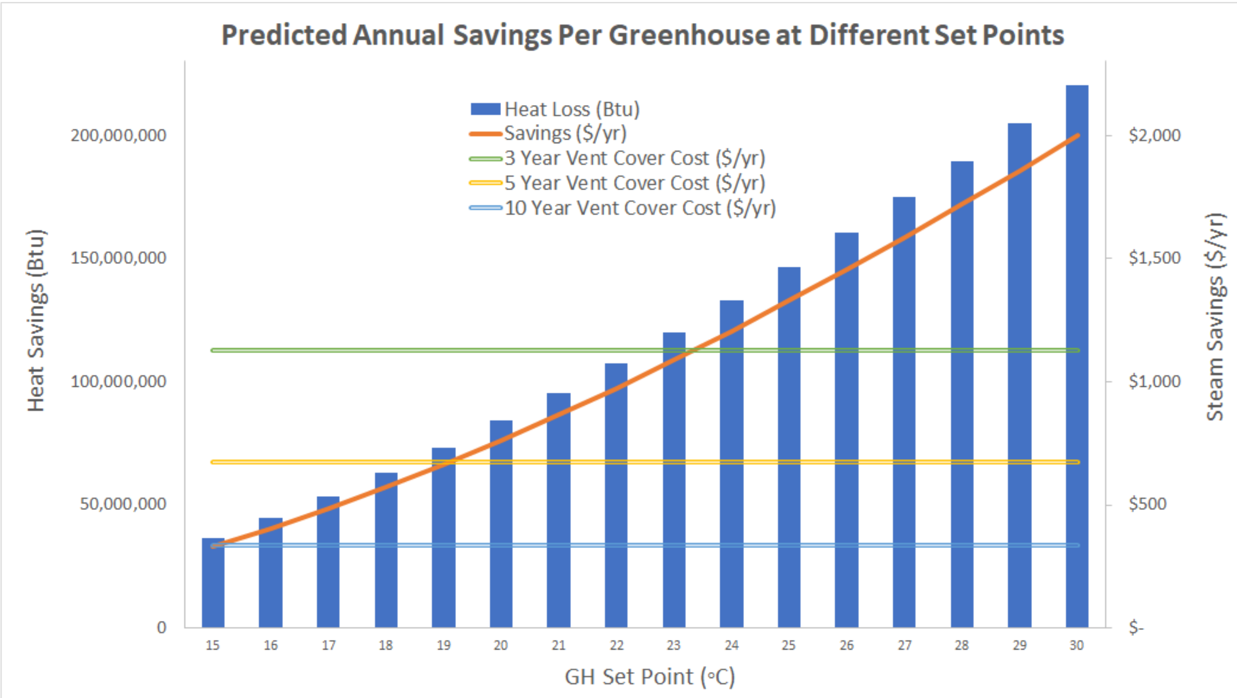

Figure 4: Sensitivity of Annual Savings as a Function of Greenhouse Setpoint

Figure 4 shows a direct relationship between greenhouse set-point and annual potential savings. When compared to the upfront project costs for various project lifetimes, there is an inverse relationship between rate of return and greenhouse set-point. This means that greenhouses that require a higher interior temperature will benefit the most from vent cover installation, and will pay for themselves in the shortest amount of time. Greenhouses with lower set-points (such as 15 deg C) will not be able to pay themselves back within the 10 year lifetime, but the high savings of warmer greenhouses will likely mitigate those loses.

<u>Economic Analysis:</u>

Using the theoretical model, estimated savings due to monthly energy losses in steam were calculated. A sample calculation can be found in Appendix 1. The boiler efficiency was assumed to be 80% [6]. As the heating load is more intensive during the colder winter months and less intensive during the warmer summer months, potential savings vary month-to-month. For initial calculations at a greenhouse setpoint of 25 C, savings ranged from $73 to $230 per month. This came to an annual saving of $1,580 for a single greenhouse. Given a total of 69 greenhouses that are suitable for a vent cover retrofit, an aggregate amount of $109,000 could potentially be saved in a year. Once calculated at setpoints of 15, 20 and 25 C, monthly savings varied from $0.40/month during summer, to $206/month in the height of winter.

Contact with the sales representative, Kent Wright, of the contractor Agra-Tech provided a rough estimate of $2,600 per vent cover [7]. This figure is incomplete due to the lack of volume discounts. Installation costs from Ag-Con Construction Inc. are still pending, and a 30% labor cost - an amount of $780 - was assumed. This puts the total at $3,400 per vent cover installation. The upfront project cost is $233,000 for the overall facility, and has a simple payback period of 2.5 years to recover costs (for a 25 deg C set-point). For a project lifetime of 10 years, there is potential for close to $1 million in energy savings. Tables 2-4 in Appendix 2 show a breakdown of lifetime savings and costs over different project lifetimes, as well as rates of return.

Sources of Uncertainty:

The ventilation rate model was calculated using ASHRAE parameters for a small, one-story house with similar neighboring structures. While consultation with faculty on campus confirmed this is a good assumption, it still creates some uncertainty. Additionally, atmospheric data was gathered from the Davis CIMIS station, which provides accurate data at its location, but doesn't perfectly match local environmental conditions at Orchard Park. This data was also averaged to provide monthly wind and night-time temperatures, but hourly data would provide a better estimate. Lastly, the contractor would not provide a finalized quote, so final cost had to be assumed.

Not included in the analysis of costs and benefits include maintenance and operation and positive externalities, such as the rebate programs for carbon reduction and energy efficient measures. Further research into the lifetime maintenance costs of the vent covers, as well as external incentives for their installation should be conducted.

Follow-Up Work

Moving forward, having a typical set-point range and estimate of envelope tightness for all of the greenhouses at Orchard Park would be useful. This can be done by placing data loggers inside, or by analyzing seasonal data collected by the ARGUS control systems. Our data only corresponded to summer heating usage - which is likely the lowest of the year - and collection of winter data would better inform the potential savings. Additionally, a blower door test will directly measure the envelope tightness of the greenhouse. This will give more accurate airflow rates, and can be used to confirm the results of the theoretical model by testing the airflow rate with the vent cover open as well as closed.

In terms of the economic estimate, obtaining a quote for labor costs would provide a better estimate of the upfront costs. Our analysis assumed that labor costs were about 30% of the material cost, but a site visit with a contractor would be far more accurate. Ray from Agra Tech has done work at the facility before, and is a good future contact for this work.

Conclusions & Recommendations

Based on the above analysis, it can be determined installing greenhouse vent covers has the potential of between $115,000 to $500,000 in energy savings over 5 years (Appendix 2, Tables 2-4). The Orchard Park Greenhouses are scheduled for demolition in the next 5 to 10 years, but in the event the Orchard Park Greenhouses are not demolished the savings will only increase over time. Extension of the project lifetime is a distinct possibility due to the logistics and social considerations of removing 70 greenhouses.

To conclude, it has been found that there is high potential that installing vent covers at the remaining 69 Orchard Park Greenhouses will yield economic returns in addition to providing better climate control and functionality to these greenhouses. The exact yields are dependent primarily on three factors: cost of purchasing and installing vent covers, infiltration/exfiltration through the greenhouse envelope, and the night time set points per greenhouse.

Our recommendation is to further investigate these three factors in order to better model the conditioned air losses through the open vent. This would involve a) receiving a finalized quote including volume discounts and installation costs; b) running a blower test on greenhouses 607 and 608 to determine actual ventilation rates through the uncovered evaporative cooling pad; and c) characterizing the typical set points of the Orchard Park Greenhouses throughout the year for more accurate annual savings.

References

[1] American Society of Heating, Refrigerating and Air-Conditioning Engineers. *ASHRAE handbook: Fundamentals*. Atlanta, GA: American Society of Heating, Refrigeration and Air-Conditioning Engineers (2017): Ch. 16.

[2] Bucklin, R. A., et al. "Fan and pad greenhouse evaporative cooling systems. Circular 1135." (2004).

[3] Kuroyanagi, Takeshi. "Investigating air leakage and wind pressure coefficients of single-span plastic greenhouses using computational fluid dynamics." *Biosystems Engineering* 163 (2017): 15-27.

[4] Fernandez, J. E., and B. J. Bailey. "Measurement and prediction of greenhouse ventilation rates." *Agricultural and Forest Meteorology* 58.3-4 (1992): 229-245.

[5] Jain, Dilip, and Gopal Nath Tiwari. "Modeling and optimal design of evaporative cooling system in controlled environment greenhouse." *Energy Conversion and Management* 43.16 (2002): 2235-2250.

[6] Morejohn, Josh. (June 3, 2018). Email correspondence with Joshua Morejohn, Energy Manager of UC Davis Facilities Management.

[7] Wright, Kent. (June 4, 2018). Interview with Kent Wright, Sales Engineer of Agra-Tech [Online interview]

Appendix 1: Heat Loss Calculations

A sample calculation using Eq. 1 and Eq. 2 combined with utility rates from UCD Facilities is shown in Table 1 below.

Table 1 - Sample Calculation of Estimated Heat Losses at a setpoint of 27 C

Month No.	Avg Air Temp (C)	Monthly DT	Ave Wind (m/s)	Flow Rate (m^3/s)	Heat Loss (Btu/s)	Steam (klbs/mo.)	Cost ($/mo.)	3 yr Btu Cost	10 yr Btu Cost
1	5.8	21.2	1	0.84165175	22.09541969	23.86305327	$ 173.13	$ 519.39	$ 1,731.31
2	7.1	19.9	3	0.850748039	20.96466834	22.64184181	$ 164.27	$ 492.81	$ 1,642.71
3	8	19	2.6	0.823202003	19.36841057	20.91788341	$ 151.76	$ 455.29	$ 1,517.63
4	9.4	17.6	2.8	0.799528515	17.42531304	18.81933808	$ 136.54	$ 409.61	$ 1,365.38
5	11.3	15.7	2.9	0.761953542	14.81365098	15.99874306	$ 116.07	$ 348.22	$ 1,160.74
6	14	13	2.5	0.689580124	11.10099867	11.98907856	$ 86.98	$ 260.95	$ 869.83
7	14.4	12.6	2.2	0.672311257	10.48998558	11.32918443	$ 82.20	$ 246.59	$ 821.95
8	15.4	11.6	2.2	0.647250058	9.297454263	10.0412506	$ 72.85	$ 218.55	$ 728.51
9	14.8	12.2	2.2	0.662400566	10.007244	10.80782352	$ 78.41	$ 235.24	$ 784.13
10	8.8	18.2	1.3	0.783711704	17.66288673	19.07591767	$ 138.40	$ 415.20	$ 1,384.00
11	7.6	19.4	1.1	0.806464298	19.37406887	20.92399438	$ 151.81	$ 455.42	$ 1,518.08
12	1.2	25.8	1.1	0.928456411	29.663008	32.03604864	$ 232.43	$ 697.28	$ 2,324.28
						Sum/GH	$ 1,584.86	$ 4,754.57	$ 15,848.56
						Sum 69 GHs	$ 109,355.07	$ 328,065.20	$ 1,093,550.68

Appendix 2: Return Rates with Set-Point Sensitivity

Applying a sensitivity analysis of the greenhouse set-points resulted in the following savings and rates of returns for the overall facility. These calculations assume that all greenhouses are operating at the same set-point, but a more realistic calculation would take into account the variability across the facility.

The theoretical savings can be noted in the following tables:

Table 2

Projected Savings for 69 Greenhouses at Night Time Setpoint of 15 C				
Project Years	Energy Savings	Project Cost	**Total Savings**	**Simple Return**
1	$22,855	$233,220	**-$210,365**	**-90%**
2	$45,710	$233,220	**-$187,510**	**-80%**
3	$68,565	$233,220	**-$164,655**	**-71%**
5	$114,274	$233,220	**-$118,946**	**-51%**
7	$159,984	$233,220	**-$73,236**	**-31%**
9	$205,694	$233,220	**-$27,526**	**-12%**

10	$228,549	$233,220	**-$4,671**	**-2%**

Table 3

Projected Savings for 69 Greenhouses at Night Time Setpoint of 20 C				
Project Years	Energy Savings	Project Cost	**Total Savings**	**Simple Return**
1	$52,635	$233,220	**-$180,585**	**-77%**
2	$105,270	$233,220	**-$127,950**	**-55%**
3	$157,905	$233,220	**-$75,315**	**-32%**
5	$263,174	$233,220	**$29,954**	**13%**
7	$368,444	$233,220	**$135,224**	**58%**
9	$473,714	$233,220	**$240,494**	**103%**
10	$526,349	$233,220	**$293,129**	**126%**

Table 4

Projected Savings for 69 Greenhouses at Night Time Setpoint of 25 C				
Project Years	Energy Savings	Project Cost	**Total Savings**	**Simple Return**
1	$91,662	$233,220	**-$141,558**	**-61%**
2	$183,324	$233,220	**-$49,896**	**-21%**
3	$274,986	$233,220	**$41,766**	**18%**
5	$458,310	$233,220	**$225,090**	**97%**
7	$641,634	$233,220	**$408,414**	**175%**
9	$824,958	$233,220	**$591,738**	**254%**
10	$916,620	$233,220	**$683,400**	**293%**