Energy Savings Analysis of a Greenhouse Heated by Waste Heat

Yara Thomas[1], Liping Wang[2], Anthony Denzer[2]
[1]University of Wyoming, Laramie, WY, United States

Abstract

Waste heat from an industrial facility is used as a heat source for a 3-acre greenhouse on site. Preliminary calculations for heat availability and simulation results demonstrate the feasibility of satisfying the entire heating load with the use of waste heat. This paper discusses the results of several greenhouse simulations using EnergyPlus. From the simulation results, the electrical heating energy consumption of a typical greenhouse heated by VAV system is compared to the electrical energy consumption of an innovative greenhouse utilizing water to air heat pumps to transfer heat energy from the waste heat to the greenhouse zones. The study concluded that there is a great potential for waste heat as a source for greenhouse heating with simulation results indicating that the WAHP system could reduce the annual heating electricity consumption from the 13,780 GJ consumed by the VAV system down to 5983 GJ.

Introduction

Global food demand is projected to double in the next 50 years (Tilman, 2002). Greenhouse agricultural operations yield 20-30 times more produce per acre than field production and have the potential to satisfy much of the growing agricultural demand. However, greenhouses are more energy intensive then open field production because of their complexity of design in terms of thermodynamic and climatic control. Designed correctly, greenhouses offer a controlled environment that is much more resilient to changing environmental factors. They have the potential to reduce water consumption, limit the use of pesticides, cut down on transportation emissions and provided greater food security. Efficient design is crucial to sustainability. Unfortunately, very little literature exists regarding greenhouse optimization and no standards of practice have been developed. There are no widely-available simulation tools or design procedures which can account for the full sophistication of the phenomena.

Due to inherent inefficiency, industrial processes lose a large percent of their productivity to waste heat. Waste heat is "heat that is either lost through the flue stack of an industrial operation, or which is rejected from a power generation station to improve the thermodynamic efficiency of the cycle" (Andrews and Pearce 2011). Although it is not technically and economically feasible to recover all waste heat, a gross estimate is that waste-heat recovery could replace 9% of total energy used by US industry (Arzbaecher, C., Parmenter, K., & Fouche, E. 2007). Instead, waste heat is often discharged into nearby streams, rivers and other heat sinks, creating many ecological issues. Utilization of this heat through greenhouse heating can offset the cost of cooling industrial equipment as well as have a beneficial environmental impact (Garton and Christianson 1970).

Modelling of greenhouses began more than fifty years ago and has continued to grow in complexity and accuracy. Although simplification is necessary to create an applicable model, there are "parameters that must be considered to achieve an accurate model. For a greenhouse these parameters include, but are not limited to plant carbon balance, photosynthesis, respiration, and allometry (Hill 2006)" (Vadiee and Martin 2012). An increase of greenhouse exploration and innovation occurred in the late 1970s when many studies sought improvements in commercial greenhouses due to the oil crises (Vadiee and Martin 2012). One of the most notable early models was created by Walker in 1965. This model used thermal inputs from solar radiation, respiration and equipment. These were balanced by losses from convection, radiation, photosynthesis, conduction and ventilation (Walker 1965). In 1973 Price and Peart combined Walkers model and a multiple reservoir model to study the use of waste heat (Rotz 1979). Degelman (1975) created a notable weather simulation. His model calculated temperature, dew point, solar insolation and wind velocity every hour for a year.

Although not specifically related to greenhouses, Degelman's model was later integrated into many studies and greenhouse models. Most pertinent to this study, Degelman's weather model was combined with a greenhouse model similar to Walkers in order to conduct a feasibility study for a potential greenhouse in Pennsylvania. In this study by Rotz (1979), simulation was used to compare the cost and energy consumption of five different heating systems. In the combined greenhouse and weather model, the heat losses and gains were balanced to find the excess or deficiency of heat in the greenhouse each hour. A traditional oil-fired boiler was used as the standard for comparison and five non-traditional systems (two hot water and three warm water) were compared. The baseline was compared with two hot water systems (one boiler assisted and one heat pump assisted) and three warm water systems assisted by heat pump, two stage condenser, and boiler. The boiler assisted, warm water system had the greatest savings at 51 percent. The boiler assisted hot water system had the lowest pay-off ratio of 4.8 (Rotz 1979). Other waste heat greenhouse studies include a Minnesota based greenhouse (Ashley et al. 1974), and Alberta, Canada (Shaw and Trimmer, 1975). Another waste heat greenhouse developmental study was conducted in Alabama on a pilot-scale greenhouse at Muscle Shoals. This study used an electric boiler to simulate condenser cooling water temperatures (Burns et al, 1976).

The increased computing power and speed of computers has allowed for a new generation of simulation and processing tools that have been applied to greenhouse technology. Most notable of these include GESKAS (Hoes et al. 2008), Simulink (Hill, 2006), The Watergy Greenhouse Model (Speetjens et al. 2005) and a Dynamic Modeling and Simulation of Greenhouses: Web-based Application (Fitz-Rodríguez et al. 2010). Other tools such as computational fluid dynamics and MatLab have also been employed for greenhouse research (Fatnassi et al. 2006), (Sase 2006), (Kacira, Sase, and Okushima 2004), (Mistriotis et al. 1997), (Reichrath and Davies 2002), (Peña, Molina-Aiz, and Valera 2005), (Villagrán et al. 2012); (Menghini et al. 2016), (Ghosal, Tiwari, and Srivastava 2003), (Ahamed, Guo, and Tanino 2015).

In this study, we use EnergyPlus to simulate the indoor environmental conditions and predict energy use of a 3-acre greenhouse located in Lovell, Wyoming. Large amount of waste heat is available from a local sugar plant. We first conducted a feasibility study on utilizing waste heat for the greenhouse and then designed mechanical systems for the greenhouse to evaluate the overall system efficiency for the greenhouse.

Simulation

During the winter beet processing campaign, the sugar plant discharges hot water at an average temperature of 115°F (46°C) and an average flow rate of two million gallons per day. Currently, the water must be cooled to below 80°F (26.7 °C) before it is discharged into the river. The waste heat represents a significant opportunity to save energy and money.

Available heating energy was calculated for the winter months based on monthly flow rates. Temperature difference and specific heat remained the same while mass flow rate varied. Table 1 shows the resulting available heat energy.

Table 1: Monthly Available Heat Energy from Western Sugar

Month	Volumetric Flow Rate [Mgal/day]	Mass Flow Rate [kg/hr]	Resulting Heat Energy [GJ/hr]	Resulting Heat Energy [MBtu/hr]
September	2.95	462,085.5	32.19	30.51
October	3.54	554,502.6	38.62	36.61
November	1.74	272,552.1	18.98	19.99
December	1.32	206,763.7	14.40	13.65
January	1.62	253,755.4	17.68	16.75
February	1.75	274,118.5	19.09	18.10

EnergyPlus was employed for the feasibility study. In an initial parametric study of greenhouse sizes (1, 2, and 3 acres), a greenhouse was used to determine if the available waste heat was sufficient to cover annual heating loads (McMorrow, Wang et al. 2015). Springing off of the McMorrow, Wang model, a more complex model was created and mechanical systems simulated in EnergyPlus.

Geometry

Modern greenhouses are made of a variety of materials, each with a range of advantages and disadvantages. In addition, there are a variety of forms a greenhouse can take, including an A-frame shape to a Quonset style. In an A-frame greenhouse, there are four components in its construction to consider: the roof, gable, wall, and curtain wall (Nelson 2012). For the purposes of this engineering study, it was assumed that the greenhouse would be A-frame. It was also assumed that the greenhouse, would have a series of pitches, or gables, forming 15 bays. These gables are located at the top of the 20 foot wall, are 30 feet wide and 10 feet tall. Figure 1 shows the geometry of the A-frame bays.

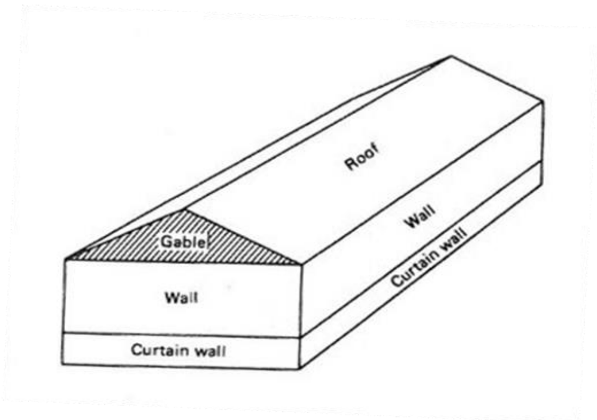

Figure 1: Typical A-frame greenhouse geometry

The 3-acre, 15 bay greenhouse was modled in SketchUp using the OpenStudio plug in. The occupied space was divided into five thermal zones; four parimeter and one large central zone. The unconditioned bays were considered a sixth zone. Figure 2 shows how the SketchUp geometry and zone division.

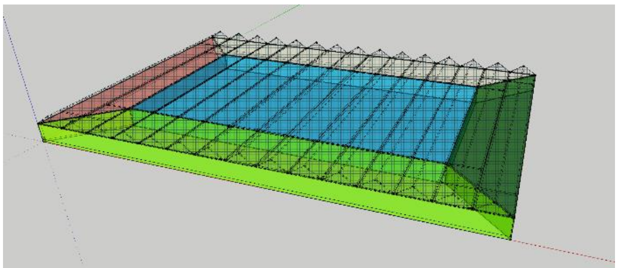

Figure 2: Geometry of the 3-acre greenhouse model in Sketchup

In order to simmulate realistic air mixing, opperable windows were created on all surfaces between zones and an airflow network was created in EnergyPlus.

Mechanical Systems

An ideal air load model was used to estimate the heating energy consumption and as a consistent starting point for mechanical system implementation. All construction modifications, material updates, and airflow networks, were made prior to mechanical system design. Once the basic model was completed, mechanical systems were added. Two models with variable air volume systems and one model with water to air heat pumps were created. Model 1 had a VAV system with electrical components. This model was used as an example of standard practice with which to compare innovative systems which utilize waste heat. Model 2 had a VAV system with hot water heating coil and reheat coils. This model represented a greenhouse with VAV in which the waste heat water was utilized. The third system, Model 3, was designed with five water to air heat pumps. In Model 2 and 3, the waste heat water was modelled as a gas fired boiler.

Water to air heat pumps were selected as the best option for several reasons. Most importantly, the heat pump system can efficiently transfer heat to the air. This is due to the high coefficient of performance. Additionally, the heat pumps offer flexibility and the potential for water stored during the day to be used at night. Even if the temperature of the water drops significantly in storage, the heat pumps can raise the temperature of the air without the use of backup electric coils. This would be practical for actual application. A simplified diagram of the waste heat system is shown in figure 3.

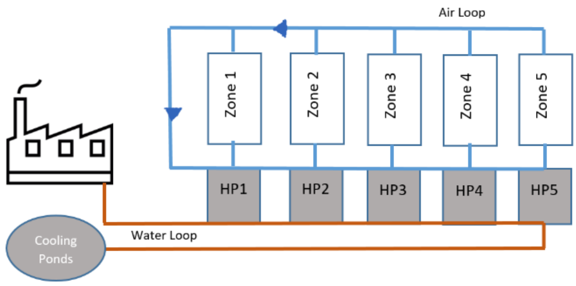

Figure 3: Skematic system diagram for water to air heat pump using waste heat

In the simulation, the waste heat source (gas-fired boiler) provided 46°C (114.8°F) water to the VAV and water to air heat pumps in Models 2 and 3 respectivly. Nominal heating coefficient of performance (COP) for the water to air heat pump is 4.2. A year-long energy simulation was conducted for Cody, Wyoming with TMY (Typical Meteorological Year) weather data. Temperature setpoint were 70.0°F (21.1°C) at night and 80.0°F (26.7°C) during the day.

Results

Simulation results support initial calculations suggesting that available waste heat will provide a large percent of the required heating. Furthermore, results indicate that heating energy consumption in the 3-acre greenhouse could be reduced by 67% through the utilization of waste heat and water to air heat pumps.

The demand for waste heat varies throughout a typical day based on the outdoor temperature and temperature set points for the greenhouse space. Figure 4 shows the heating demand for the greenhouse space in comparison with available waste heat from industry for a typical winter day. In this graph the heating demand represents joules of heat energy transferred from the waste heat water to the space. The hourly heating demand is well below the available waste heat at any point during the day.

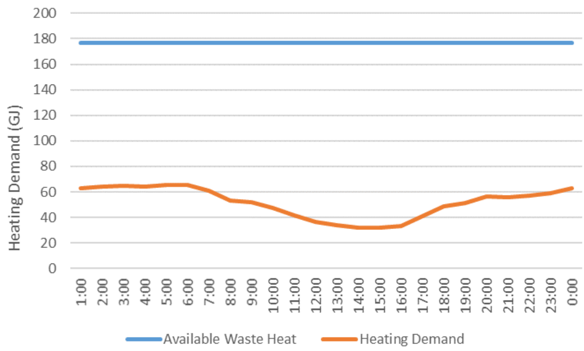

Figure 4: Comparison of hourly heating demand and available waste heat in a typical winter day (Jan. 3rd.)

A comparison of the total annual energy consumption of the three systems shows a large energy improvement of both waste heat systems over the electric VAV system. Figure 5 shows the annual heating electrical consumption for the three models. Additionally, the heat pumps system was found to be more efficient then the VAV system with waste heat source. This was because the VAV system required the fans and pumps to work much harder. The heat pump system used approximately 1200 GJ of electricity per year for fans and pumps while the VAV system used over 8000 GJ. Including all electric components such as compressors, reheat coils, fans and pumps, electricity consumption was 13780 GJ for the electric VAV system, 9057 GJ for the VAV system with waste heat utilization and 5983 GJ for the heat pump, waste heat system.

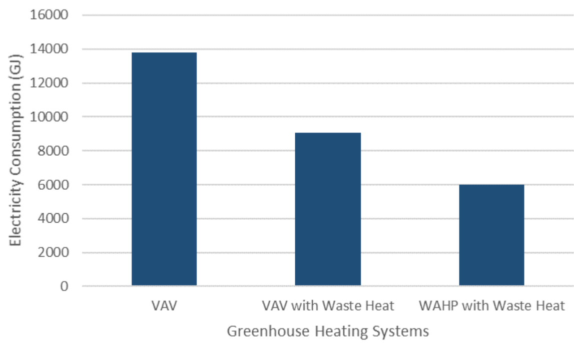

Figure 5: Annual Electricity used for Heating

Comparison of Electric VAV and Heat Pump Systems

A 67% reduction in electrical consumption from the electric VAV system (System 1) to the WAHP system coupled with waste heat source (System 3) was calculated by comparing the total electrical energy required to maintain the heating set points for both systems over the course of a year. This comparison could be made because all components of both systems were specified as electrical. The total electrical energy for the water to air heat pump system includes power for pumps, fans and supplementary electric heating coils. The quantity of energy provided by the waste heat (gas fired boiler) is not included in the total energy consumption calculation because it is considered free heat. Figure 6 shows the hourly electrical heating energy consumption of the electric variable air volume system and the water to air heat pump system. It is clear from this figure that there is a significant reduction in both electrical heating energy and energy consumption variability with the heat pump system.

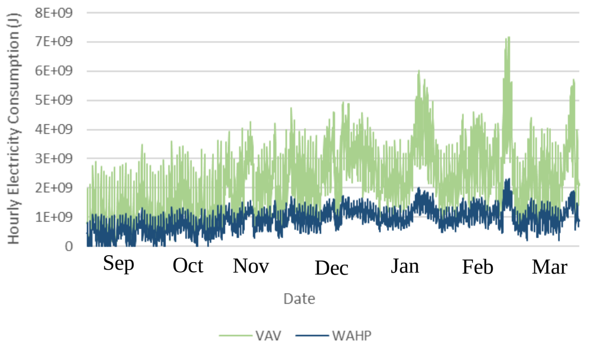

Figure 6: Comparison of Hourly Electric Consumption for electric VAV system and Water to Air Heat Pump system for Winter Months.

Annually, the electric VAV system consumes 13,780.02 GJ of heating energy while the WAHP system only consumes 5982.99 GJ. Figure 7 shows the hourly electrical consumption of the WAHP system vs. the electrical VAV system over the course of a typical winter day.

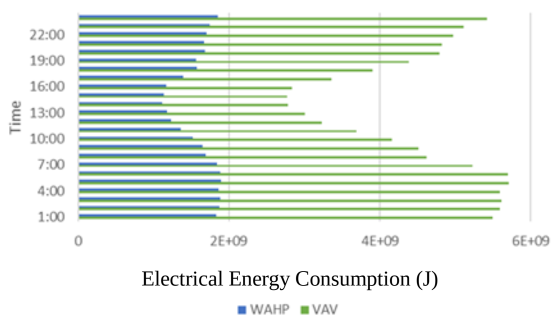

Figure 7: WAHP vs. VAV Hourly Electrical Consumption for Jan. 3rd.

A closer look at the simulation results show that the heat pump model is able to maintain temperature set points. Figure 8 shows the outdoor temperature as compared to the interior zone temperature as regulated by the VAV and WAHP waste heat system. The line representing VAV zone temperature overlaps with the line for WAHP zone air temperature.

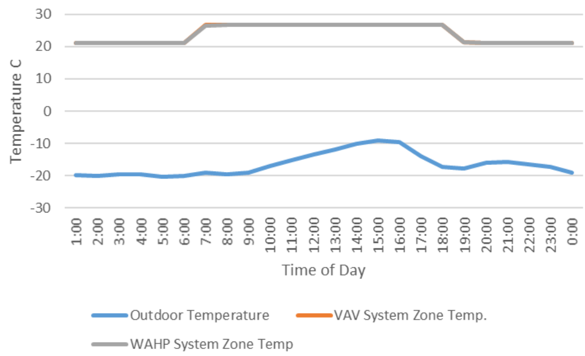

Figure 8: Outdoor Vs. Controlled Indoor Air Temperature for VAV and WAHP Systems on a typical winter day

Based on these results, the waste heat source provides more than enough heat to maintain the greenhouse temperature, but there are still challenges associated with transfer of the heat from the water to the interior space. This model utilized a water to air heat pump with a COP of 4.2 and was able to achieve an electricity reduction of 67% over a VAV system with electrical heating components.

Limitations

There are several limitations to this study what will be the focus of future simulations. First the interaction between crops and greenhouse controlled environment were not an integral part of this study. Further more, control operation for the mechanical systems of the greenhouse should be optimized and other types of mechanical systems should be considered in future study. Most importatanly, experimental data is needed to validate the results of simmulations. In the event that this project is complete, the results from the simmlation can be compared and the accuracy determined.

Conclusion

The results show a significant potential for greenhouses to save energy through waste heat utilization. The 67 % reduction in annual heating energy, as show in figure 9, could make greenhouse feasible in many more locations and cold climate urban areas.

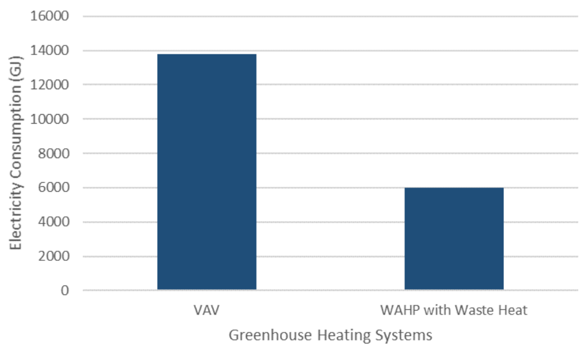

Figure 9: Annual Electricity Consumption for heating of electric VAV vs. WAHP, Waste Heat System

Advances like waste heat utilization in greenhouse technology are crucial for several reasons. As our environment continues to change, food security in urban and rural areas particularly in cold or harsh climates becomes a growing concern. The demand for food is expected to double in the next fifty years. As this demand grows the amount of land available for agriculture decreases. Greenhouses offer greater yield per area, decreased water consumption and protection from pests and disease. However, greenhouses are only feasible if we can decrease the amount of energy necessary for operation. Waste heat is one possible solution. This feasibility study demonstrates the great potential of this technology and opens the door for a more main stream form of greenhouse energy modelling.

Acknowledgement

This research was support by Laura Jane Musser Foundation.

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