Solar Heat Supply Optimization for the Climate Control of Agricultural Greenhouses

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Abstract. The use of agricultural greenhouses in Mexico has increased considerably in recent years. These greenhouses, however, are built with foreign designs and with no analysis of the energy exchange between the greenhouse and the local environment. The objective of this work was to simulate the proper sizing and operation of a solar thermal system meant to provide heating for agricultural greenhouses. The system consists of a field of solar collectors, two thermal storage tanks, and an auxiliary furnace. We present a thermal-economic analysis of the heating duty required by greenhouses in the city of Chihuahua, Chihuahua, Mexico, for growing tomatoes. This is achieved through simulation in TRNSYS, using the weather conditions and solar energy available in the region. We modeled a greenhouse that uses liquefied petroleum gas (LPG) and compared it with an identical greenhouse fitted with solar energy, both of them using hot air as a heating medium.

Keywords: TRNSYS, Dynamic Simulation, Agricultural greenhouses, Solar process heat.

INTRODUCTION

A greenhouse is any closed structure covered by transparent material, inside of which an artificial microclimate can be created in order to grow plants in optimal conditions outside of their usual growing season (Sheti, 2009; Teitel *et al*., 2009; Bartazanas *et al*., 2009). This kind of agriculture requires high energy consumption due to heating, ventilation, and air conditioning (HVAC) costs (Chinese *et al*., 2005). An energy source is needed in order to keep the microenvironment within the comfort range of the particular plant to be grown. The use of agricultural greenhouses in Mexico has grown rapidly in recent years. These structures, however, have been built using foreign designs and with no analysis of the heat exchange between the greenhouses and the local environment. Insufficient or nonexistent knowledge about the energy consumption behavior and the maximum energy demand of these systems is always a source of anxiety for the owners. The fossil fuels they currently use as an energy source are a limited and imported resource, which makes their price uncertain and gives these fuels a great influence over the profitability of the business (Huacuz, 2004). This is why solar thermal energy is a source of heating power worth evaluating for use in this industry. The HVAC energy requirements of a greenhouse are not easy to estimate, since they stem from the energetic interaction of the building and the surrounding environment. The weather varies continuously following daily and seasonal cycles, and is different for different geographic locations. If solar energy for heating is added to the problem, then both the HVAC requirements of the greenhouse *and* the supply of heating energy are variable. This makes it necessary to use calculation methods based on numerical simulation, considering not only all the physical variables of the system but also the cyclic variation of environmental conditions.

OBJETIVE

The objective of this work was to develop a computational simulator to estimate the heating energy required by agricultural greenhouses. This simulator also enables the technically correct and economically optimal dimensioning of the solar-energy-assisted heating system capable of meeting the demands of the greenhouse.

METHODOLOGY

The TRNSYS Simulation Software

This simulation platform makes it possible to simulate the behavior of non-stable thermal systems. One of its main advantages is that it enables the simulation of weather conditions from any geographic region for which average monthly information is available on temperature, relative humidity, and solar radiation. The information used in this work for the weather conditions of the city of Chihuahua, Mexico, was taken from Martín-Domínguez and Hernández-Álvarez, 2002. TRNSYS makes it possible to simulate the energetic processes and climatic conditions as a function of time, using integration periods as short as five minutes and covering as much as a continuous year of operation of the simulated system.

System modeling

The modeled greenhouse had the geometry shown in Figure 1. The total floor surface area considered was 200 m^2, and the structure is built with cellular polycarbonate as the surrounding material. The crop used for the analysis is tomato (Table 1). TRNSYS enables the simulation of the interactions of the greenhouse with its surroundings, continually determining the magnitude and direction of the existing mass and energy flows. TRNSYS integrates the instantaneous variables over time, and this obtains total consumptions throughout the desired periods of time.

System components

The simulated system is composed of a greenhouse, several flat solar collectors, two insulated water tanks for energy storage, an auxiliary LPG-powered heater, an air-water heat exchanger, and several pumps and fans. The system's connectivity is shown in Figure 1. The model includes the control systems needed to maintain the desired greenhouse conditions, through turning equipment on/off and regulating HVAC flows. Continuous operating times of one year are simulated, and energy consumption is integrated to determine yearly values.

System behavior

Water is used as working fluid for the capture and storage of solar thermal energy, and to heat the current of atmospheric air that provides heating for the greenhouse, as shown in Figure 1. The first flow circuit takes cold water from the bottom of the stratified thermal tank to the field of flat solar collectors. This circuit works when the control system detects that the temperature difference between the entrance and exit of the collectors is more than 10°C. The second circuit takes water from the cold part of the second thermal tank to the LPG heater, and if necessary supplies the energy needed to keep the water at the predetermined minimum temperature. If the water in the second thermal tank reaches temperatures higher than the setpoint due to heat input from the collector field, the auxiliary heater remains off and the heating circuit operates with the heat stored in the second thermal tank.

The third flow circuit takes water from the second thermal tank to the heat exchanger and back to the cold part of the first tank. The purpose of this flow is to heat the air current that will provide heating for the greenhouse. Two control schemes were considered in order to maintain the internal greenhouse temperature within the comfort zone of the crop. The first is Narrow Band Control (NBC), which tries to maintain the internal temperature constant at the optimal comfort level (22°C). The second scheme is Broad Band Control (BBC), which keeps the greenhouse temperature within the maximum and minimum values tolerated by the crop.

Simulation model in TRNSYS

Figure 2 shows the simulation model of the described system, as implemented in TRNSYS. Each icon shown in the figure represents a mathematical model with a specified function (called Types), which can be a physical device (like a pump or a thermal tank) or a theoretical device (like a weather data generator or a data storage unit). Each Type has input and output variables, through which it connects to other Types, and parameters that define its specific characteristics (area, volume, power, etc.).

Table 1. Ideal conditions for growing tomato

Crop	Optimal Temperature °C	Minimum Temperature °C	Humidity %
Tomato	22	18	60

Parametric Analysis

The simulator described in this work makes it possible to study the effect of several additional parameters that affect the design, construction, and operation of agricultural greenhouses. This work, however, shows only the effect of varying the following parameters: number of collectors, thermal storage volume, water temperature in the second thermal tank, and greenhouse temperature control scheme (Table 1).

Financial Analysis

We performed a financial analysis, taking all cash flows to their net present value. The initial capital investment includes the cost of collectors, the auxiliary furnace, and the storage tanks (Table 2). The yearly operating cost of the system consists of the cost of LPG for the auxiliary heater and electricity for the fans. We considered a useful life of 10 years, an annual LPG cost increase of 9%, an annual electricity cost increase of 5%, and an inflation of 5%. These values are the average cost increases in Mexico over the last 10 years. The total cost of the inversion was calculated by summing the net present value of the capital investment and all the yearly operating costs. The total costs of the designs were compared to determine the most optimal of them. The fuel used in this study was LPG, which has a combustion heat value of 43 MJ/kg and a cost of 0.84 US $/kg.

Table 2. Capital cost of equipment

Device	Cost US $	Description
Auxiliary heater	3,601	Each
Collectors	354	Each
Thermal storage tank	378	m^3

RESULTS

Basic energy requirement (with no solar power)

Figure 3 shows the energy use of the heater during a year of operation with no input of solar energy.

Effect of the control scheme

Figures 3, 4, and 5 show the results of using the NBC and BBC control schemes. The figures show how keeping the greenhouse temperature as close as possible to the optimal growth temperature (NBC) represents a cost increase of between 20% and 30% over the cost of BBC.

Effect of the number of collectors

The number of collectors used has a direct effect on the use of LPG, as shown in Figure 6. With a 6 m^3 main thermal tank, fuel savings of up to 90% with sufficient collectors.

Effect of the thermal storage volume

Five different storage volumes were analyzed for the first thermal tank: 3, 6, 12, 18, and 24 m^3. Figure 6 shows that the optimal storage volume for this case study is 6 m^3. Greater volumes than this carry a negligible increase in energy savings. Figures 7 and 8 show that, for the simulated greenhouse, 6 m^3 is also the economically optimal size.

Effect of the storage temperature in the second thermal tank

The water temperature in the second thermal tank has an important effect on the system's energy usage. For a system with no solar collectors (Figure 3), the lowest total fuel consumption is reached with a temperature of 90°C. When collectors are used, on the contrary, the storage temperature must be lowered to match the temperature reached by the collector field. Figures 4 and 5 show that the ideal temperature is between 45 and 55°C. The results in Figures 6, 7, and 8 considered a minimum operating temperature of 50°C for Tank 2.

Financial Analysis

Figures 7 and 8 present the results of the financial analysis. As shown in Figure 7, the project cost of a system with no solar collectors increases proportionally with the size of the thermal tanks. When solar collectors are being used, however, the cost first drops with greater storage volume and then rises. The minimum cost is reached at 6 m^3, so this volume was used throughout the simulation. The configuration with the lowest total cost was found to be a main storage tank of 6 m^3 and 15 solar collectors. Figure 8 compares the savings that this configuration achieves with respect to the case with no solar collectors. The maximum expected saving is approximately US $8,484. It should be noted that configurations other than the optimal not only reduce the potential savings, but can easily turn into substantial losses.

CONCLUSIONS

Due to the variability of climate throughout the day and year, dynamic simulation is a crucial tool for the estimation of the energy flows required to keep a greenhouse at a crop's ideal growth temperature. TRNSYS simulation shows the effect of the main design parameters on energy consumption, and facilitates the financial analysis that determines the profitability of a project. A poorly executed sizing of the system's main components can result not only in a decrease in the expected savings, but also in net losses over the cost of operating with no solar power at all.

ACKNOWLEDGEMENTS

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FIGURES

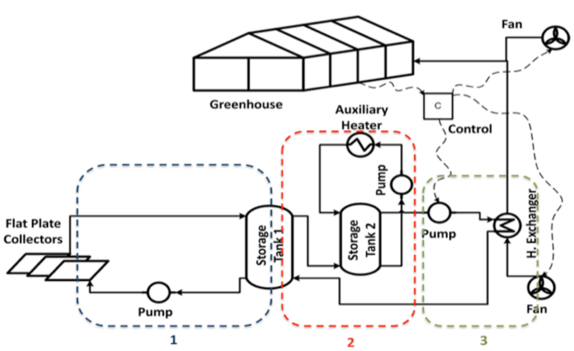

Figure 1. Simulated system

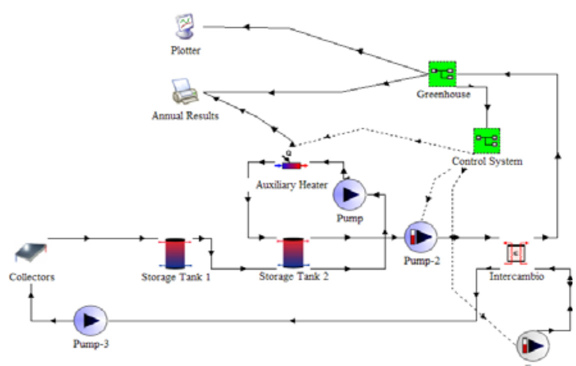

Figure 2. Simulator developed in TRNSYS

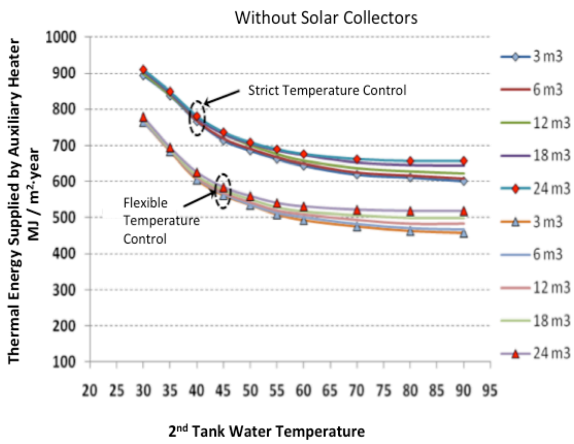

Figure 3. LPG consumption

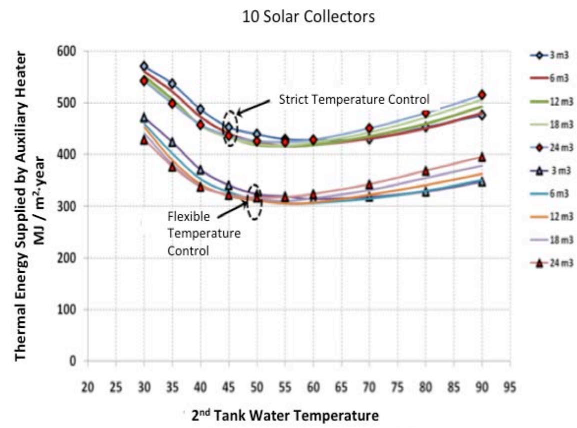

Figure 4. Energy usage with 10 collectors

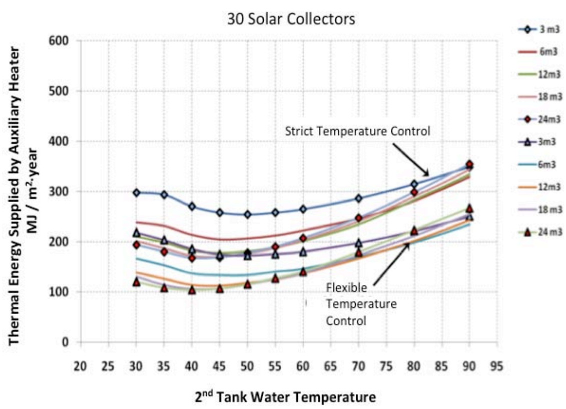

Figure 5. Energy usage with 30 collectors

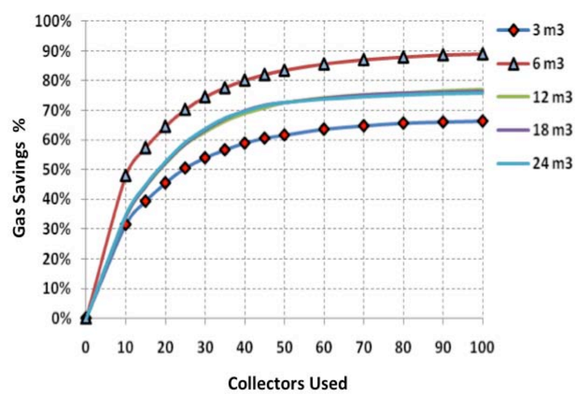

Figure 6. Fuel savings.

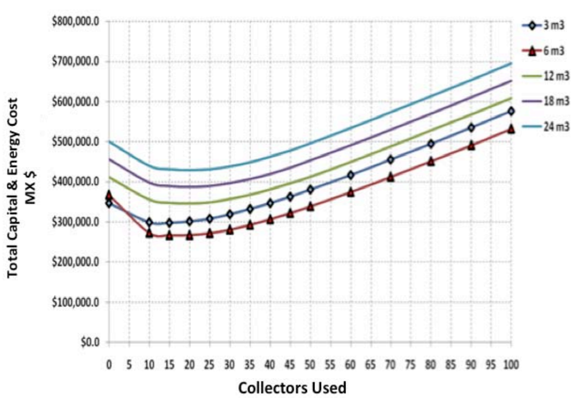

Figure 7. Net present value of the project (MX$)

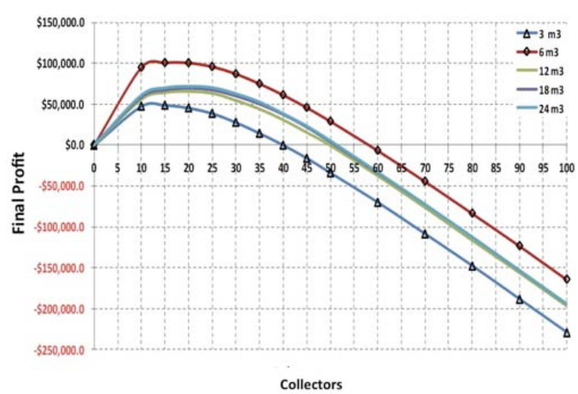

Figure 8. Final profit of the project (MX$)