Parametric analysis of a solar heating system for agricultural greenhouses with dynamic simulation in TRNSYS

Ignacio R. Martín-Domínguez[1], M. Teresa Alarcón-Herrera,
José A. Burciaga-Santos, Plinio E. Castro-López
[1] Advanced Materials Research Center (CIMAV)
Department of Renewable Energy and Environmental Protection
Miguel de Cervantes 120. Complejo Industrial Chihuahua. 31109 Chihuahua, Chih. México.
+52 (614) 439-1148 ignacio.martin@cimav.edu.mx

Abstract

The use of greenhouses is essential to control the conditions needed to grow the food supply. Climate control represents the greatest energy expenditure when operating a greenhouse. Temperature and humidity must be kept within narrow margins so the crops can properly develop throughout the year and reach a profitable production volume. Many family-owned agricultural businesses have failed because of increasing fuel prices and the farmers' inability to anticipate the profitability of particular greenhouse designs, crops, and regions.

This work presents a computational simulator created to estimate the behavior of a greenhouse fitted with a solar-thermal collection system and an auxiliary propane-butane (LPG) heating system. The simulator enables parametric studies on size and design of the greenhouse, construction materials, crop type, geographic location (climate) of the site, type and number of solar collectors, thermal storage volume, and type of temperature control. The simulator calculates the energy consumption in the auxiliary heater needed to keep the temperature and humidity of the greenhouse within the established limits. The simulator was developed using TRNSYS (Transient Energy Systems Simulation Tool). Energy expenditures are calculated every 10 minutes and summed throughout a year of operation, producing yearly totals that can be compared with results from different designs (parametric combinations). We present an economic analysis that considers a project life of 10 years, the cost of the solar collection system, thermal storage, and auxiliary heater, as well as the cost of LPG and inflation. Our analysis shows how to reach an optimal design of the heating system that will minimize fuel costs.

Key words
Greenhouses, Solar process heat, Simulation, Operation costs, TRNSYS

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, 2005). 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.

Objective

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 appropriate 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 dynamic (unsteady) behavior of thermal systems. One of its main advantages is that it enables the simulation of weather conditions of 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 was built with cellular polycarbonate as the covering 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.

Table 1. Ideal conditions for growing tomato

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

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 below. By turning equipment on/off and regulating HVAC flows, the model includes the control systems needed to maintain the desired greenhouse conditions. Continuous operating times for one year are simulated, and energy consumption is integrated to determine yearly values.

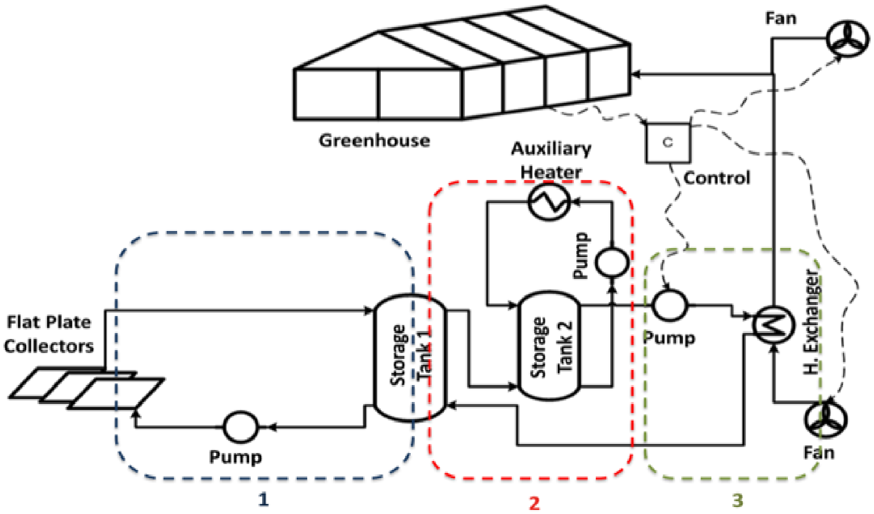

Figure 1. Simulated system

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 (tank 1) 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 for tomato). 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, efficiency curve, etc.). The simulation evaluates mass and energy balances on each component of the thermal system, with time steps as small as 5 minutes, and the energy consumption is summarized through one year of system operation. The climatic conditions are simulated every 10 minutes for the geographic location selected, and the resulting instantaneous greenhouse behavior is obtained along the year.

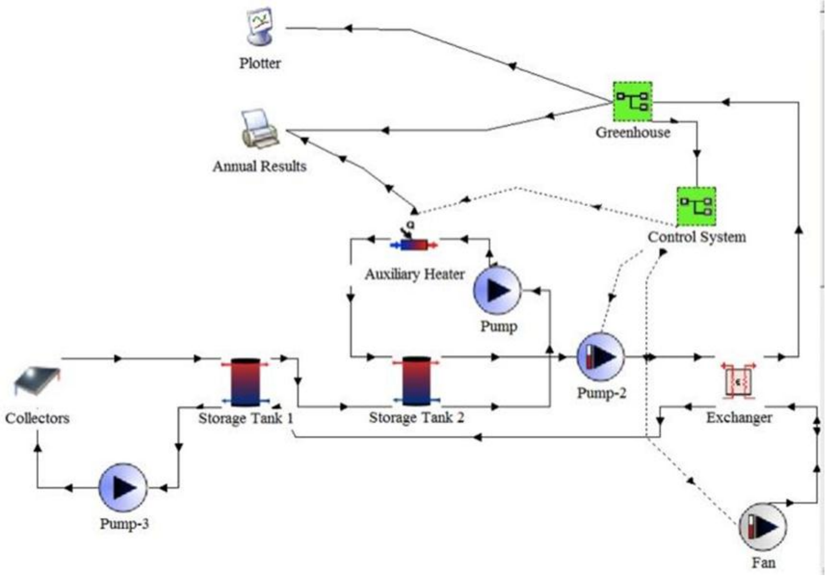

Figure 2. Simulator developed in TRNSYS

Parametric Analysis

The simulator described in this work makes it possible to study the effects 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 2).

Table 2. Parameters varied in this work

Parameter	Range	Units
Number of solar collectors used	0 - 100	Collectors
Thermal Tanks capacity	3 - 24	m^3
Temperature in thermal tank 2	30 - 90	ºC
Greenhouse temperature control schema	Narrow and Broad Band	-

Financial Analysis

We performed a financial analysis, taking all cash flows to their net present value. The initial capital investment includes the cost of solar collectors, the auxiliary heater, and the storage tanks (Table 3). The yearly operating cost of the system consists of the accumulated cost of LPG for the auxiliary heater and electricity for the fans.

Table 3**. Capital cost of equipment**

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

We considered that the greenhouse will incur the same yearly energy usage (thermal and electric power) during its entire life. The yearly cost of these energy expenditures, however, will change over the time since LPG gas and electricity continuously increase their prices. For that reason the yearly energy costs were calculated for the life span of the greenhouse, and then taken to their present value. The economic parameters considered are listed in Table 4 (these values are the average cost increases in Mexico over the last 10 years).

Table 4**. Economic parameters used**

Parameter	Value	Units
Greenhouse service life	10	Years
LPG gas yearly price increment	9	%
Electric power yearly price increment	5	%
Inflation rate in México	5	%

The total project cost of a greenhouse design was calculated by adding the initial capital investment and the net present value of all the yearly operating costs. The total costs of the designs were compared to determine the optimal. The fuel considered in this study was LPG, which has a combustion heat value of 43 MJ/kg and a current cost of 0.84 US $/kg.

Results

Basic energy requirement (with no solar power)

Figure 3 shows the energy use of the greenhouse (LPG only) during a year of operation with no input of solar energy. It can be seen that the BBC scheme results in a lower energy usage, and maintaining the 2nd thermal tank at the highest considered temperature also reduces the energy usage. The use of the smallest thermal storage volume results in the minimum energy use.

This result shows that if no solar energy is to be used, the best option is to store energy at the highest possible temperature in 3 m^3 storage tanks, for the case presented.

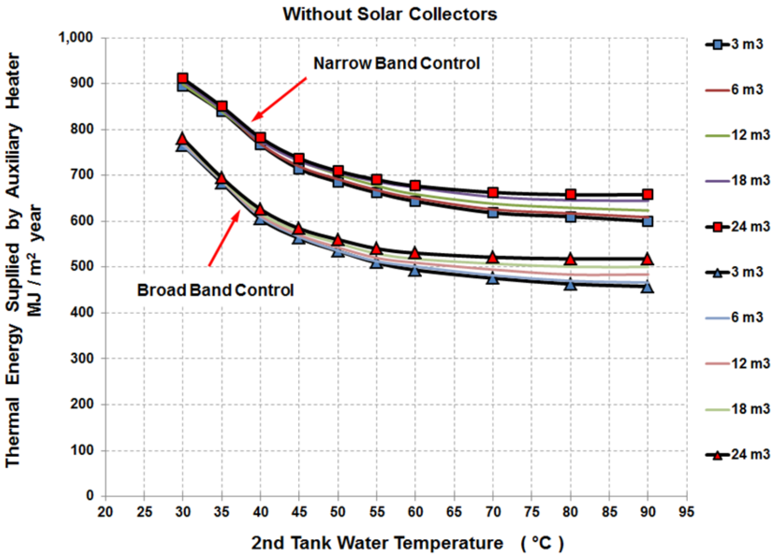

Figure 3. LPG consumption

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.

Effect of the control scheme

It is known that each agricultural crop has a preferred environmental temperature range to live and produce. Maintaining the temperature continuously inside this range in a greenhouse is the principal purpose of the facility, since the crop production will be maximized. In this work we analyzed two temperature control schemes, in the Narrow Band Control (NBC) scheme, the greenhouse temperature was kept within 2ºC of the optimal temperature, year long. In the Broad Band Control (BBC), temperature was kept within the preferred temperature range of the crop.

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.

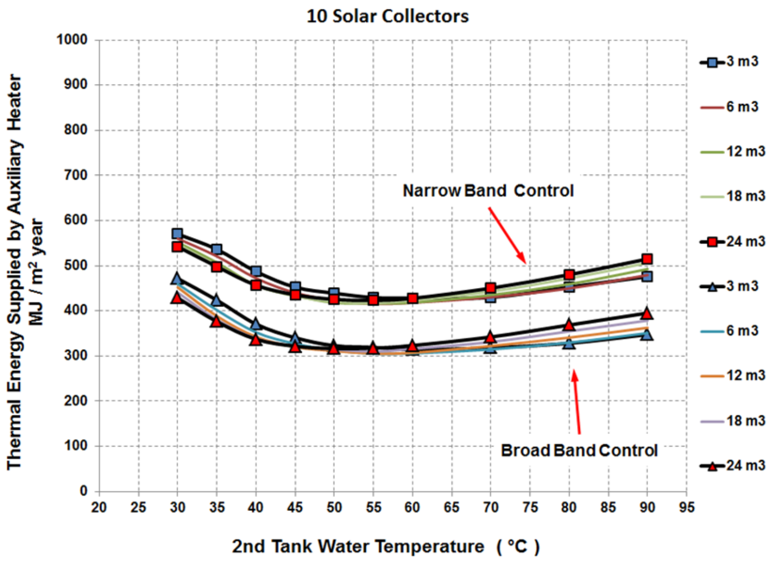

Figure 4. Energy usage with 10 collectors

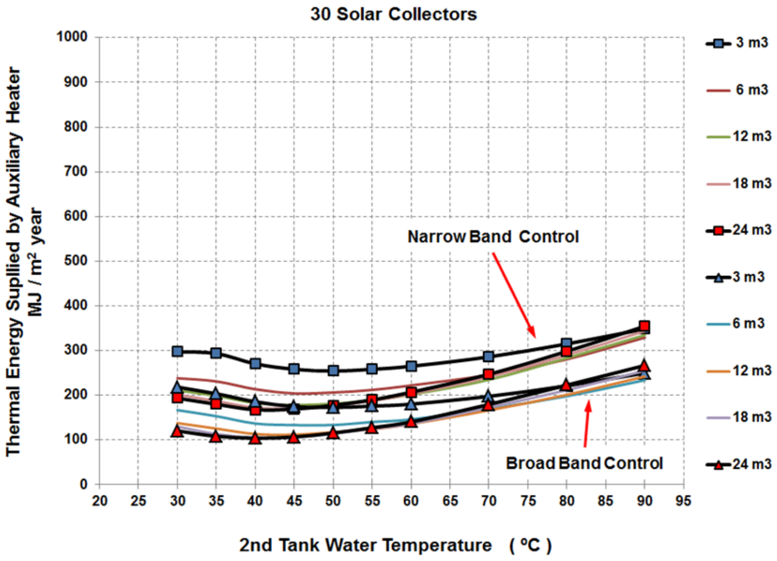

Figure 5. Energy usage with 30 collectors

Effect of the number of collectors

The number of collectors 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%, can be reached with sufficient collectors. As it can be observed, a complete fuel usage reduction can't be reached. This mainly occurs because the heating energy use and solar energy availability are out of phase. Heating is mainly required during the winter nights, forcing the use of an auxiliary heater.

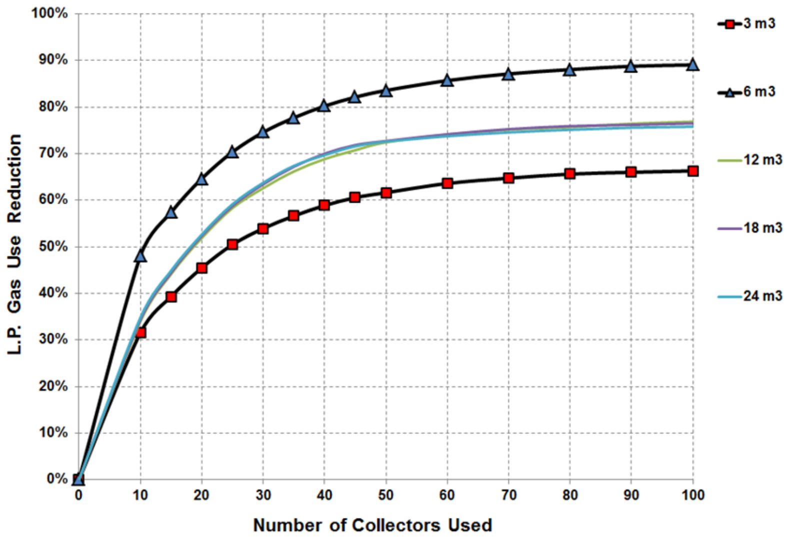

Figure 6. Fuel savings.

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 study case 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.

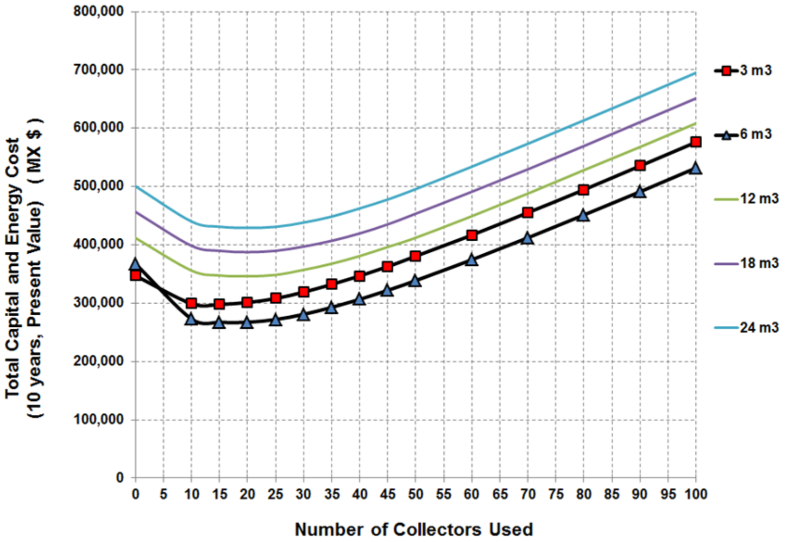

Figure 7. Net present value of the project (MX$)

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 savings are 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.

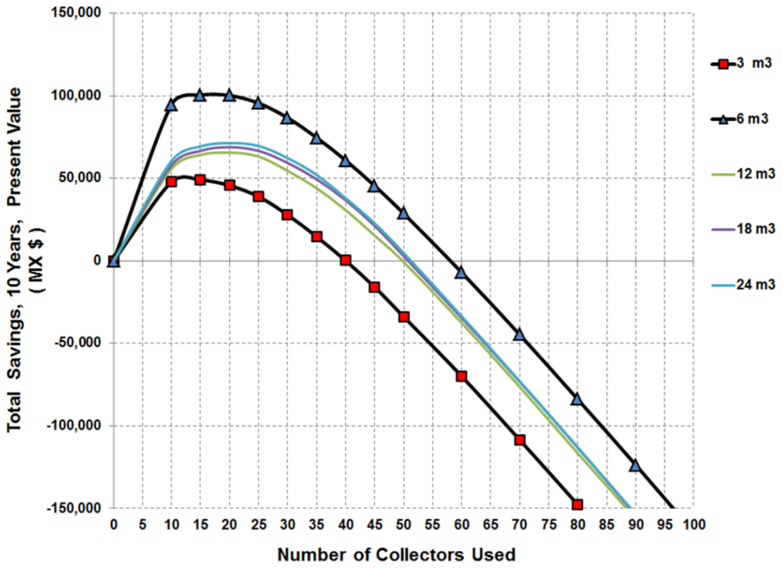

Figure 8. Final profit of the project (MX$)

Conclusions

Due to the variability of climate throughout the day and throughout the year, dynamic simulation is a crucial tool for the estimation of 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 selection 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

The present work was performed as part of a research project CHIH-2009-C01-117363, supported with funds from the Fondo Mixto CONACyT – Gobierno del Estado de Chihuahua, México.

The authors wish to thank Mr. Daniel A. Martín-Alarcón, of the Massachusetts Institute of Technology, for the proofreading and translation

References

Bartazanas, T.; Tchamitchian, M. y Kittas, C. (2005). Influence of heating method on greenhouses microclimate and energy consumption. Biosystems Engineering. 91:487-499

Chinese, D.; Meneghetti, A. y Nardin, G. (2005). Waste to energy based greenhouse heating: exploring viability conditions trough optimization models. Renewable Energy. 30:1573-1586

Huacuz J.M. (2005). The road to green power in Mexico-reflections on the prospects for the large scale and sustainable implementation of renewable energy. Energy Policy. 33:2087-2099

Martín-Domínguez, I.R. y Hernández-Álvarez, R. (2002). Datos climáticos de cuatro ciudades del estado de Chihuahua, para la simulación de uso de energía en edificaciones utilizando el paquete TRNSYS. Artículo ERE 01-49. Memorias de la 26 Semana Nacional de Energía Solar ANES. 181-185. Noviembre 11-15. Chetumal, Q.R. México.

Sethi, V.P. (2009). On the selection of shape and orientation of a greenhouse: Thermal modeling and experimental validation. Solar Energy. 83:21–38.

Teitel, M.; Barak, M. y Antler, A.; 2009; Effect of cyclic heating and thermal screen on nocturnal heat loss and microclimate of a greenhouse. Biosystems Engineering. 102:162-170

acsee2012

The Asian Conference on Sustainability, Energy and the Environment 2012

May 3-6, 2012

Organized by the International Academic Forum

Held at the Ramada Osaka

3-16-19 Toyosaki, Kita-Ku,

Osaka, City Osaka Prefecture, Japan 631-0072

Official Receipt of Registration Payment

Ignacio R Martin-Dominguez (0407) has paid the registration fee of 50000 JPY

Certificate of Tfttjpo Dibjs

This is to confirm that Ignacio R Martin-Dominguez (0407) participated in the Asian Conference on Sustainability, Energy and the Environment as a session chair, and has presented the paper,

Parametric Analysis of A Solar Heating System for Agricultural Greenhouses, with Dynamic Simulation in TRNSYS

contributing to the academic success of the event.

Please contact me for any further details

Joseph Haldane

Executive Director

IAFOR Japan