TRNSYS SIMULATION AND OPTIMIZATION OF A SOLAR-THERMAL COLLECTION AND STORAGE SYSTEM FOR THE HEATING OF AGRICULTURAL GREENHOUSES

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Abstract

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 the following variables: size and design of the greenhouse, construction materials, crop, 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 of the greenhouse within the established limits. The simulator was developed using TRNSYS (Transient Energy Systems Simulation Tool). For a given set of parametric values, the program analyzes a year of operation and simulates the operation of the system at 10-minute intervals. Energy expenditures are summed throughout the year of operation, producing yearly totals that can be compared with the results from different 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 maximize the operation profits.

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

Introduction

In the semi-desertic plateau of northern Mexico, ambient temperature varies significantly between day and night due to the fact that low ambient humidity causes heavy radiative heat losses to the atmosphere. Searing summers are followed by freezing winters, all of which makes the use of greenhouses essential. There is no other way to control the conditions needed to grow the food supply required by the growing local population.

Climate control represents the primary energy expenditure of greenhouse operation. Temperature and humidity must be kept within narrow margins, in order for the crops to develop properly throughout the year and reach the production volumes that make the whole enterprise profitable. Until now, heating based on fossil fuels was the only option available to the local growers. Many family-owned agricultural businesses have failed in the last few years due to increases in fuel prices and farmers' inability to anticipate the profitability of particular greenhouse designs, crops, and regions.

An agricultural greenhouse is a closed structure covered with materials transparent to visible light, inside of which a controlled artificial micro-climate allows yearlong agricultural production under optimal conditions (Sheti, 2009; Teitel *et al*., 2009; Bartazanas *et al*., 2009). This kind of production system requires a large supply of energy in order to maintain internal temperature and humidity within the comfort range of the selected crop (Chinese *et al*., 2005; Meijaard, 1989).

The type and amounts of energy required, as well as the associated costs, are functions of the greenhouses' size, geometry, and construction materials as well as the kind of cultivated crop, the geographic location of the greenhouse (local climatology), the costs of fuel, electricity, and water, and even the type of climate control used in the operation of the facility.

The use of fossil fuels as an energy source has become less desirable due to increasing price and decreasing availability. These factors impact the economic profitability of industrial systems based on fossil fuel consumption (Huacuz, 2004), which add to the negative environmental impact associated with their use. Because of these problems, the possibility of using solar thermal energy for heating is presented as a desirable alternative subject to evaluation.

The reliable prediction of energy consumption in greenhouse operations is a requirement not just for the design or selection of the climate control equipment, but also for the economic evaluation of the project.

Greenhouse energy requirements are not easy to calculate, because they originate from the interaction of the building and the environment. Environmental conditions vary greatly by geographic location, and differently by the hour, day, and season. Furthermore, if solar energy is used as an energy supply, both the greenhouse energy requirements and the energy source availability will be continuously varying with time.

The transient behavior of the problem requires the unavoidable use of numerical simulation in order to estimate the greenhouse-environment interactions and the resulting energy flows required for its controlled operation.

The mathematical model should include all the physical variables of the greenhouse and the simulation of the varying environmental conditions.

Objective

The objective of this paper is to present a computational simulator developed for the estimation of the heating energy requirements of agricultural greenhouses. The example case presented corresponds to a greenhouse located in the semi-arid desertic region of Chihuahua City, which has the typical climatic conditions of northern of Mexico.

The presented case corresponds to a greenhouse with 200 m^2 of floor surface, constructed with polycarbonate covering. It has the size and geometry shown in Figure 1, and the crop is tomato.

The heating energy supply is provided by a field of solar panels, two insulated thermal tanks, and an auxiliary LPG heater that maintains the water temperature of the second thermal tank (TT2) at a selected minimum, as shown in Figure 2.

The implementation of the simulation model in TRNSYS 16 is shown in Figure 3. We present a parametric analysis of the system, as well as the economic analysis of a 10-year projected lifespan. This information makes possible the selection of the optimal design for the given environmental conditions.

Methodology

Simulation platform

The software platform used to develop this work was TRNSYS (Transient Energy Systems Simulation Tool), version 16. This platform enables the simulation of complex thermal systems in transient conditions. It is possible to simulate the climatic conditions of any geographic location for which at least basic monthly average data exist for air temperature, relative humidity, and solar irradiation (Martín-Domínguez and Hernández-Álvarez, 2002).

System modeling

A greenhouse with the size and geometry shown in Figure 1 was modeled. The selected covering material was cellular polycarbonate, and the selected crop was tomato.

TRNSYS calculates the energy flows that occur between a building and the surrounding environment. The climatic conditions for the selected geographic conditions are generated at intervals as short as 10 minutes. Mass and energy balances and heat transfer calculations are performed on the components of the simulated system, and new values of the thermodynamic properties are obtained for each time step. The simulation includes the control systems required to maintain the desired greenhouse interior conditions. They operate by turning the equipment on/off, and by regulating heating/cooling flows. Simulations for one year of continuous operation are performed, and instantaneous energy and mass flows are integrated over time to obtain the annual consumptions.

The simulated system consist of the greenhouse building, a field of solar collectors, two thermal tanks connected in series, an auxiliary LPG heater serving TT2, and a water-air heat exchanger that heats the air that goes into the greenhouse. Also included are the water pumps and the air fan, as shown in Figure 2.

TRNSYS implementation

Figure 3 shows the TRNSYS implementation of the simulation, in which each icon represents the mathematical model of an element in the system.

Work fluids

Water is used as a working fluid for heat collection and storage, as well as to heat the air flow that goes into the greenhouse. This is shown in Figure 2.

The first flow circuit carries water from the lower, colder part of TT1 to the solar collector field. This loop works only when the control system detects that there is enough solar energy reaching the collectors.

The second flow circuit carries water from the cold bottom of TT2 to the auxiliary heater. If temperature is below the selected set point, heat is supplied to maintain the minimum temperature. If TT2 water temperature is above the set point, because of the energy added to water on the solar collectors’ field, the auxiliary heater remains turned off, and the third loop operates with the existent water temperature.

The third flow circuit takes hot water from TT2 to the heat exchanger, and returns it to the cold part of TT1. This water loop provides heat to the air flow that goes into the greenhouse.

There are two additional flow circuits. The first one is for ventilation; it brings atmospheric air into the greenhouse at the existing ambient conditions. The second one is for cooling, and introduces previously cooled atmospheric air into the greenhouse. At any moment, the control system decides if the ventilation flow can contribute to the heating or cooling of the greenhouse (at no additional cost). If not, heating or cooling flows are used. It should be noted that ventilation and cooling systems are not discussed in this paper; only the heating system is described and analyzed.

The purpose of the greenhouse is to maintain the air temperature within a certain range that permits optimum crop growth, called comfort range, which is different for each crop. Table 1 contains the values for the case of tomato. Comfort ranges can have an amplitude of 6 to10°C, depending on the crop. In this work, two different control modes were analyzed. In Narrow Band Control (NBC), the greenhouse internal temperature is forced to remain very close to the mean temperature of the comfort range. In a second mode called Broad

Band Control (BBC), temperature is allowed to oscillate anywhere within the limits of the comfort range. In this second mode, temperature remains close to the upper limit during the summer and close to the lower limit during winter. The economic consequences of these control modes are shown in Figures 4 to 6.

Parametric analysis

The simulator described here enables the study of several design and operational parameters of agricultural greenhouses, but in this paper only the effect of the following are discussed: number of solar collectors used, thermal energy storage volume, second thermal tank (TT2) minimum water temperature limit (which triggers the heat supply in the auxiliary heater), and the greenhouse temperature control mode used (NBC or BBC).

Crop climatic requirements

The simulator can accommodate every crop for which comfort data is available. Only tomato is discussed in this paper. The comfort data was obtained from the literature (IDEA, 2008) and is shown in Table 1.

Greenhouse building material

The building material considered in this work was cellular polycarbonate, for which a global heat transfer coefficient of $U = 3.5$ W/m^2 ºC is recommended and the optical properties are given in Table 2.

Solar collector capital cost

The use of solar collectors reduces the use of LPG, but introduces a capital cost to the Project. The cost considered in this work was $300 USD per collector.

Cost of thermal storage

The use of two thermal tanks was considered in all the cases analyzed in this work, since they introduce a capacitance effect useful even in the case of no solar collection, reducing the required size of the gas heater. The storage volume mentioned in Figures 4 to 9 corresponds to the first tank (TT1). The second tank (TT2) has half the volume of TT1. The considered cost was $4,455 MXN per m^3.

Auxiliary heater cost

The cost of the auxiliary water heater required for this system size was $42,450 MXN.

Fuel cost

The cost of the LPG required in the auxiliary heater, as well as its heating value, are shown in Table 3.

Results obtained

Once the simulator was implemented and tested, multiple runs were performed varying the parameters mentioned above. A broad view of the physical behavior was obtained, and the corresponding economics calculated.
One-year-long operation periods were simulated in each run. We considered the climatic conditions of Chihuahua City, which correspond to the typical semi-desertic climate of northern Mexico.
Heating and fan energy consumptions were calculated for each case. (an air flow pressure drop of 1” water column was considered).

Base energy requirement

Figure 4 shows the energy consumption of a system without solar collectors. All heating energy is supplied by the auxiliary gas heater.

Effect of the control mode

The effect of the control mode used is shown in Figures 4, 5 and 6. It can be observed that the use of the NBC increases the energy consumption by 30% to 40%, compared with the use of BBC. Results shown in Figures 7 to 9 were obtained using the BBC, which proved to be cheaper.

Effect of thermal storage volume

Five different TT1 volumes were analyzed, as shown on Figures 7, 8 and 9. Results show that, for the greenhouse size here modeled, the storage volume of 6 m^3 proved to be best.

Effect of water temperature on TT2

The temperature available for heating the air supply has a remarkable effect on the energy consumption and economics of the system.
For the case of no solar energy usage, the lowest energy consumption is obtained if the TT2 temperature is maintained at about 90°C, as shown in Figure 4. The hotter the water, the lower the flow required for the air heating process, and consequently the lower the electric energy required in the pump.
If solar energy is collected in flat plate collectors, however, the collection temperature is always much lower than 90°C. Therefore, a much lower temperature must be used in the TT2 if the energy provided by the solar collectors is to be used in substitution of the energy provided by the LPG. This can be observed in Figures 5 and 6: a TT2 water temperature between 45°C and 55°C provides the lowest energy consumption.
Because of this realization, the results shown in Figures 7 to 9 were obtained considering a TT2 water temperature set point of 50°C.

Effect of the number of solar collectors used

The number of solar collectors used has, obviously, a direct effect on the reduction of LPG usage, as can be observed in Figure 7. It is shown that a system with a 6 m^3 TT1 can reduce up to 90% of gas use if enough solar collectors are used. It is also interesting to note that, given the mismatch between solar availability (by day only, and greater in the summer) and heating requirement (by night only, and greater in winter), even with 100 collectors one can only reach a 90% reduction in fuel use.

Financial analysis

For the economic analysis of the project, we considered that annual energy consumption remains constant during the 10-year working life of the system. The initial capital costs include only the auxiliary heater, thermal tanks and solar collectors. LPG costs in Mexico have had an annual increase of 9% during the last several years. Electricity has increased 5% annually, and inflation has also been 5% in the last years. This information was used to calculate the net present value of all the different simulated designs.

The lowest projected cost results from 6 m^3 of thermal storage and 20 solar collectors, as shown in Figure 8. Figure 9 shows the savings or losses incurred by using different number of solar collectors, compared against the base case (with no solar energy usage). This figure shows that savings of about $100,000 MXN on the present value of the project are obtained with 20 solar collectors, but the savings can turn into losses if a larger number of collectors is selected.

Conclusions

The estimation of the energy consumption required to maintain greenhouses within the thermal comfort conditions of their crops requires the use of detailed dynamic simulation, capable of modeling the climatic variations during extended periods of time.

TRNSYS can analyze the effect of the main thermal design parameters on the energy consumption of a system, and facilitate the economic analysis to determine the project profitability as a function of energy and equipment costs.

The possibility of obtaining economic benefits by using solar energy as a heating source in agricultural greenhouses appears to be very sensitive to the correct dimensioning of the system. An improper selection of the number or size of the required equipment may cause not only the cancelation of the possible profit, but also the introduction of heavy economic losses, with costs even higher that those incurred without the use of the solar energy.

The design tool here discussed is now in the final developing stage, and it is expected that it will be very useful in the physical and economic design of greenhouses. With this tool and the knowledge of crop production volumes and their market value, it should be possible to determine whether a given greenhouse design will be a profitable business for the investors.

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Table 1 *Greenhouse climatic comfort values for tomato.*

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

Table 2 *Optical properties of polycarbonate covering (IDAE, 2008)*

	Absortivity α	**Transmissivity** τ	**Reflectivity** ρ
Solar 300-2,500 nm	0.08	0.78	0.14
Visible 380-760 nm	0.08	0.77	0.14
Infrared 2,500-40,000 nm	0.93	0.02	0.5

Table 3 *Auxiliary heater fuel characteristics*

Fuel	**Heating Value MJ / kg**	**Fuel Cost MXN $ / kg**
Gas LP	43.25	9.90

Figure 1 *Greenhouse schematic design (dimensions in meters)*

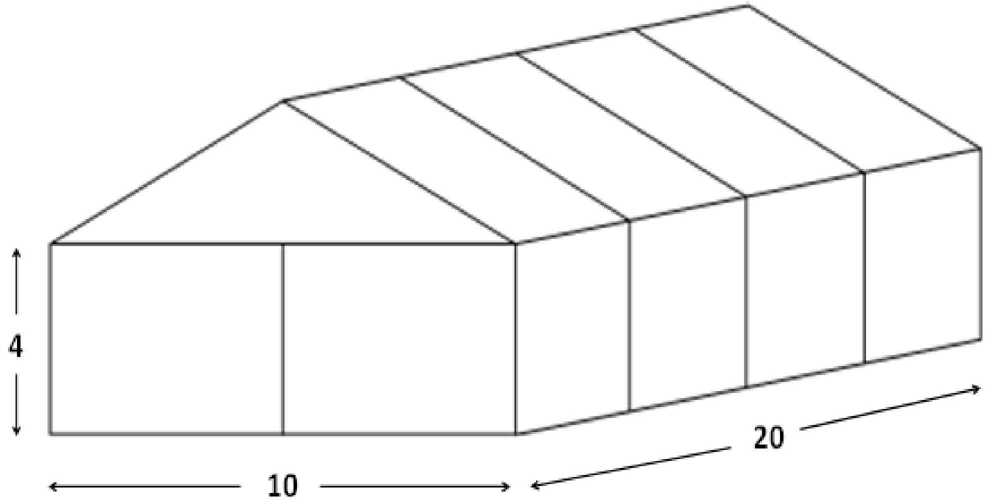


Figure 2 *Simulated system*

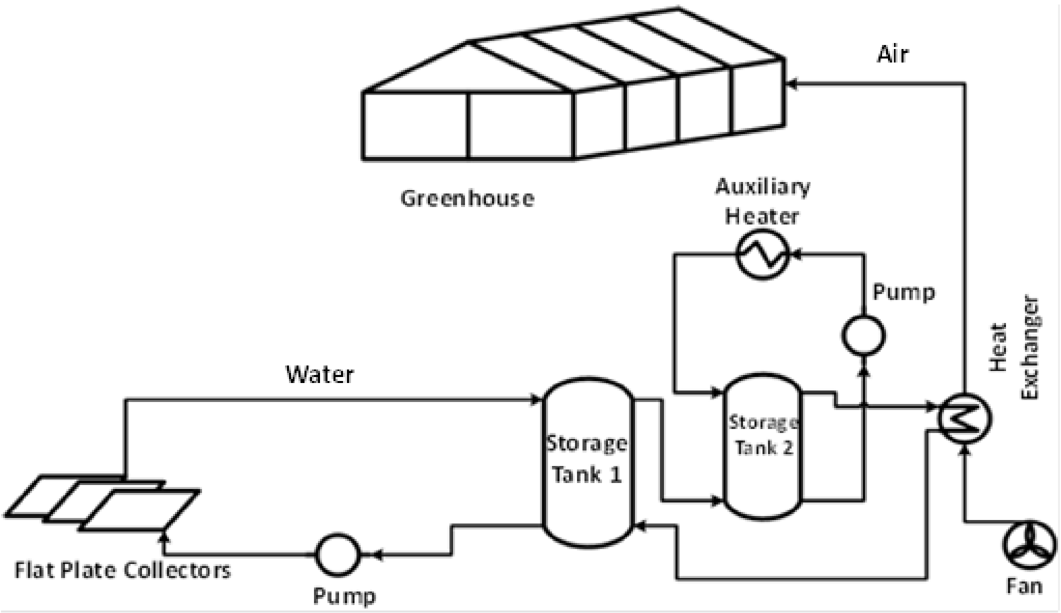


Figure 3 *TRNSYS simulation model*

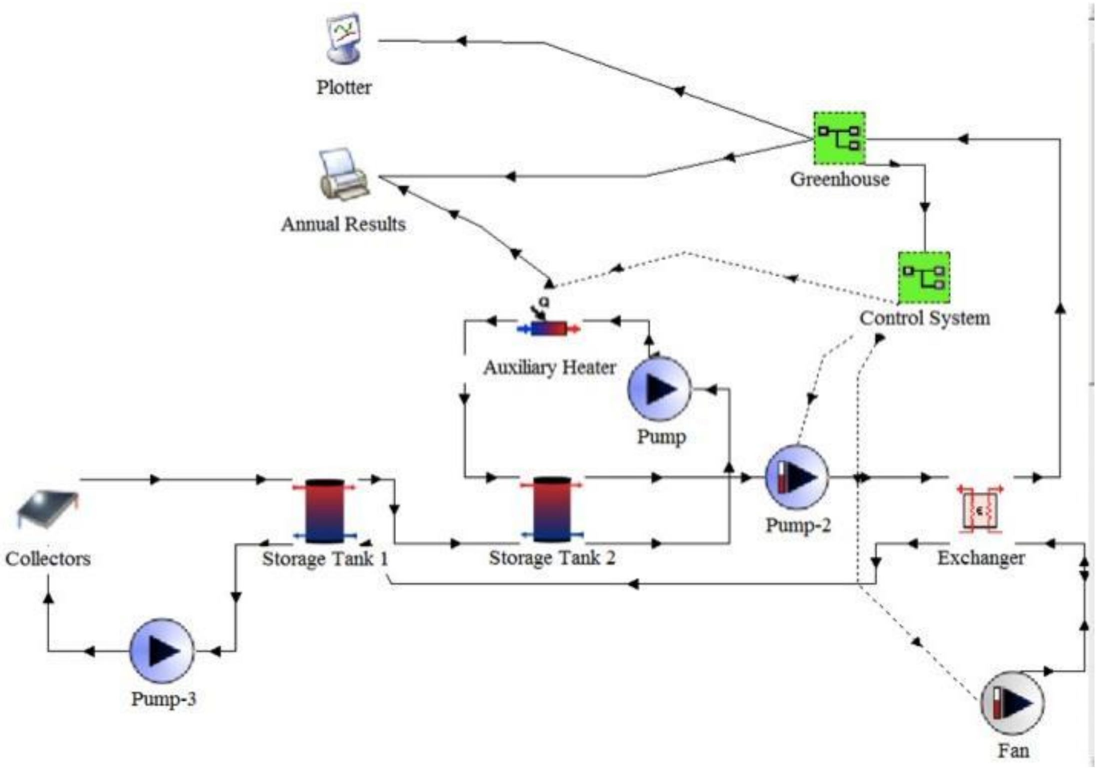


Figure 4 *Thermal energy supplied by the auxiliary heater, with no solar collectors*

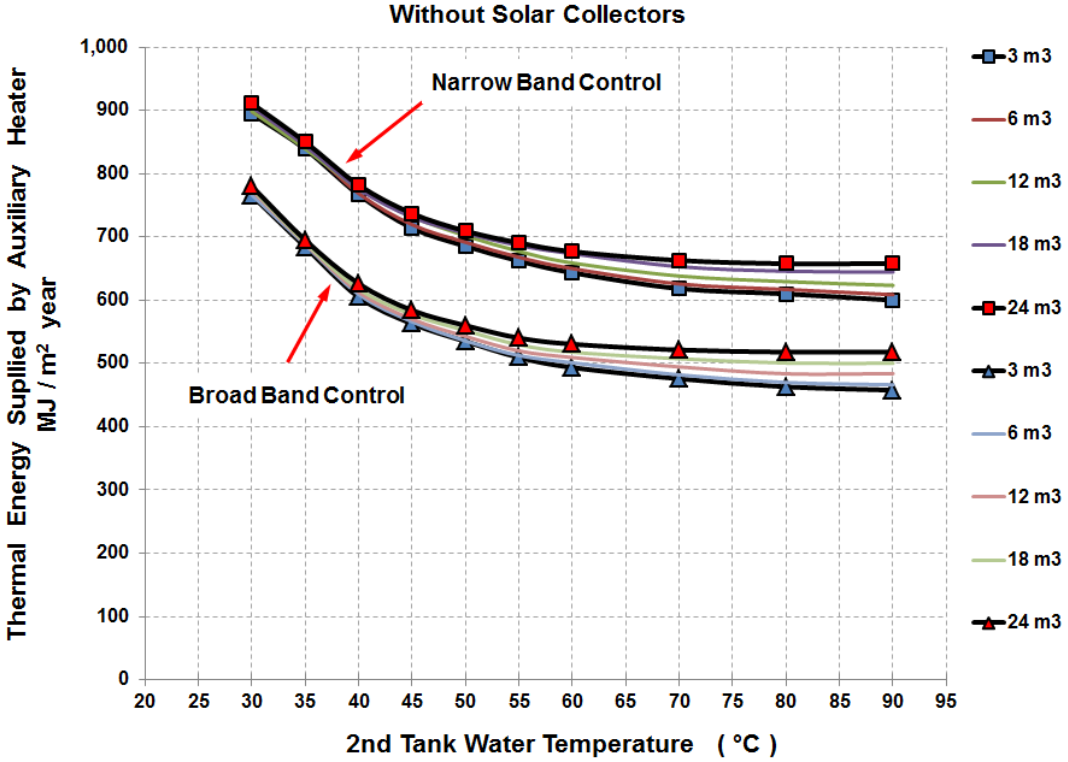


Figure 5 *Thermal energy supplied by the auxiliary heater, with 10 collectors operating*

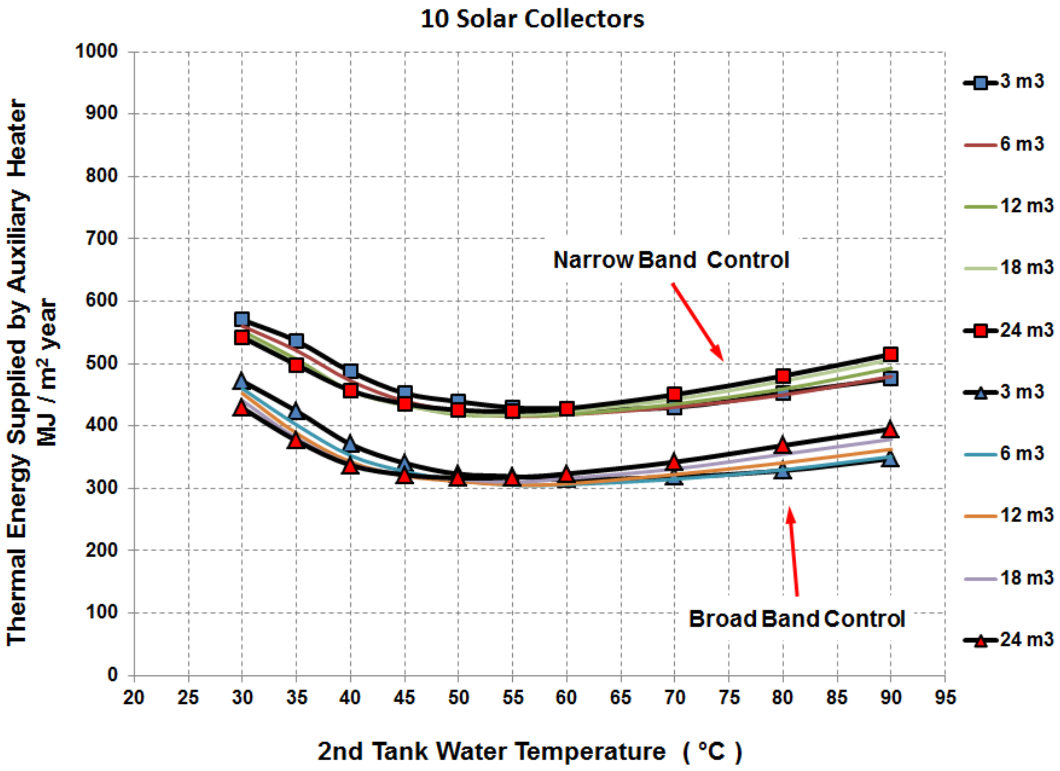


Figure 6 *Thermal energy supplied by the auxiliary heater, with 30 collectors operating*

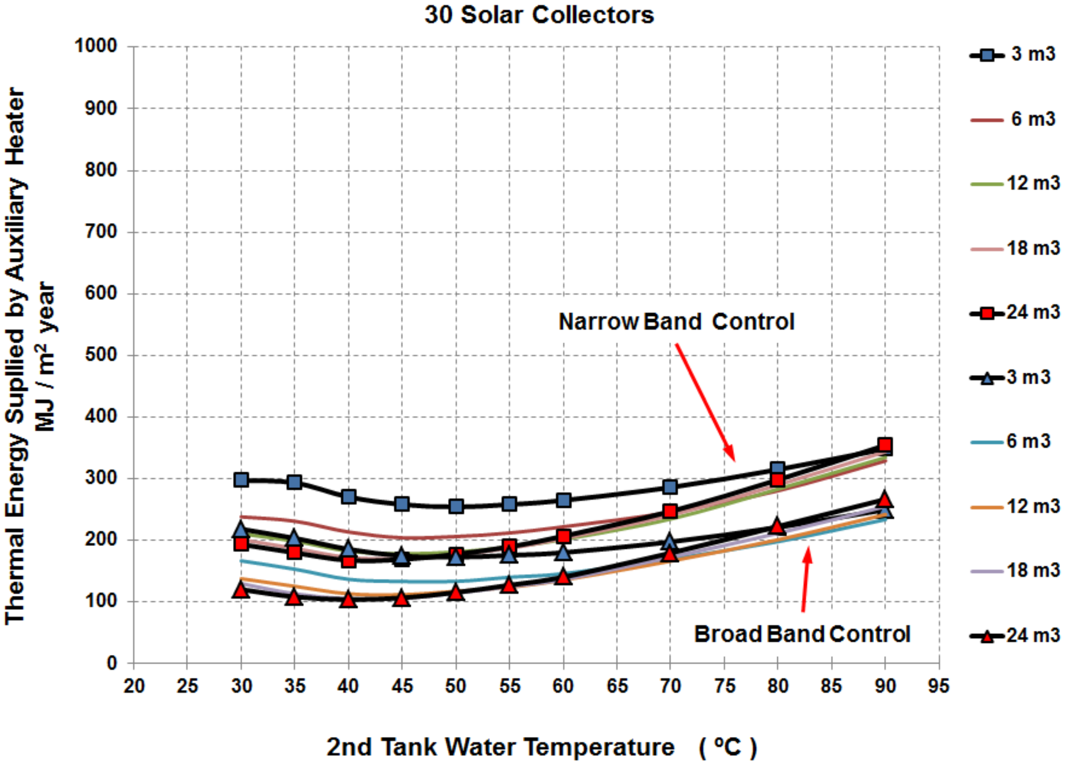


Figure 7 ***Gas consumption reduction***

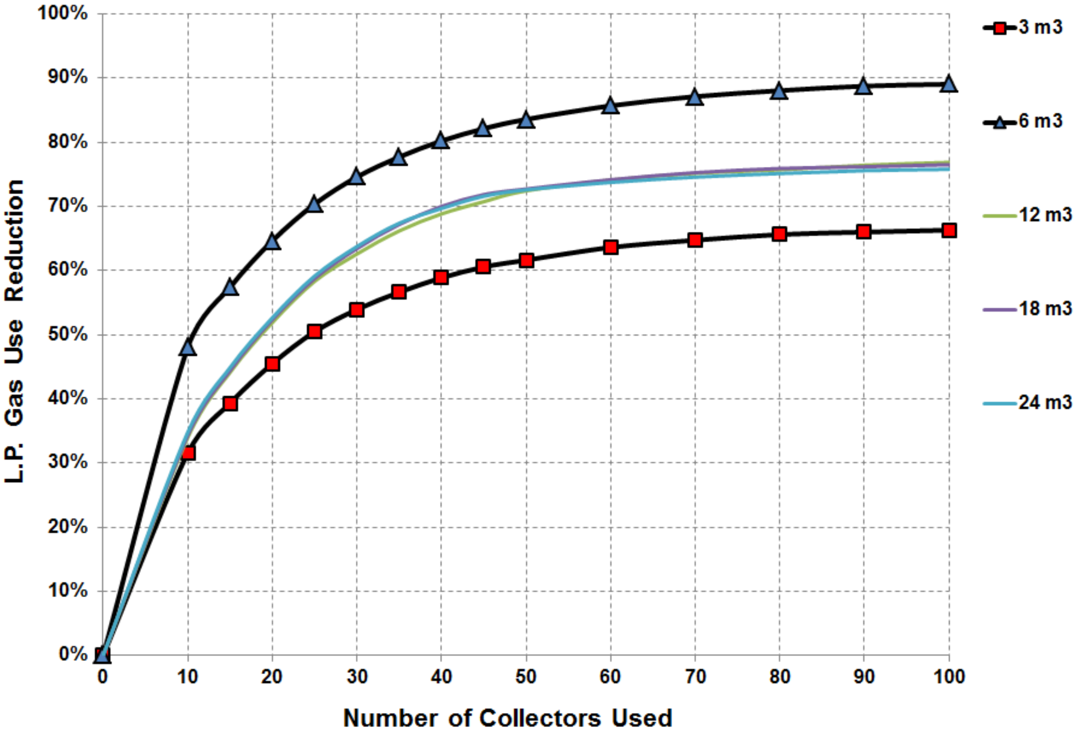


Figure 8 *Total capital and energy costs, present value, 10 years operation*

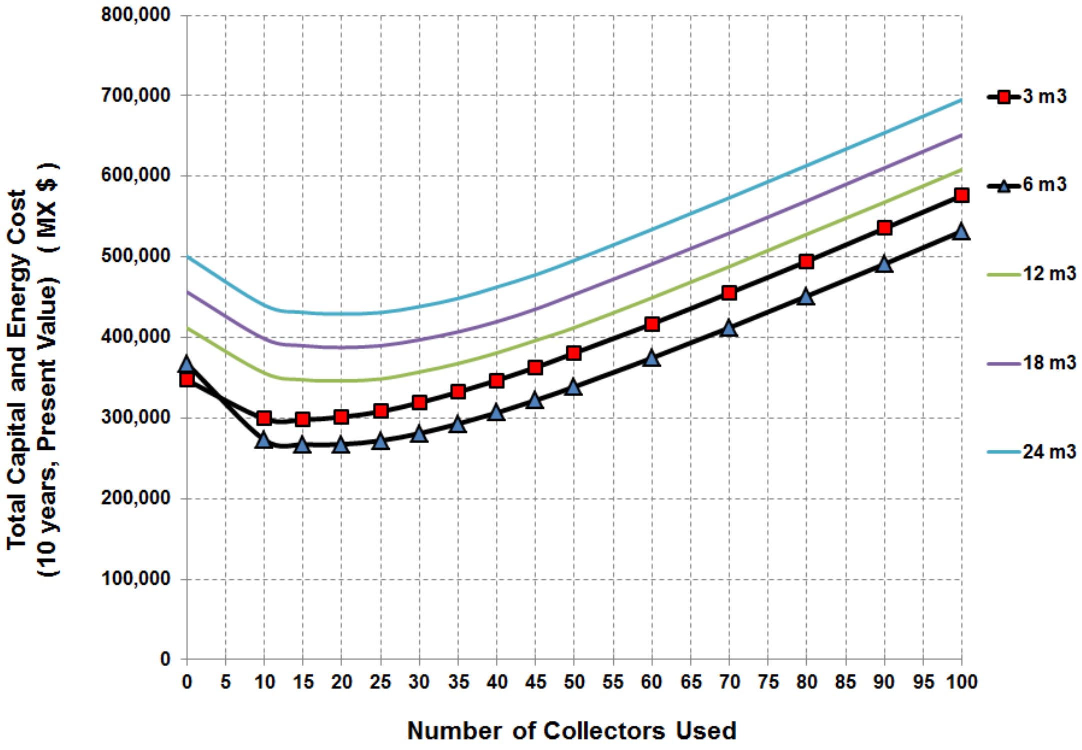
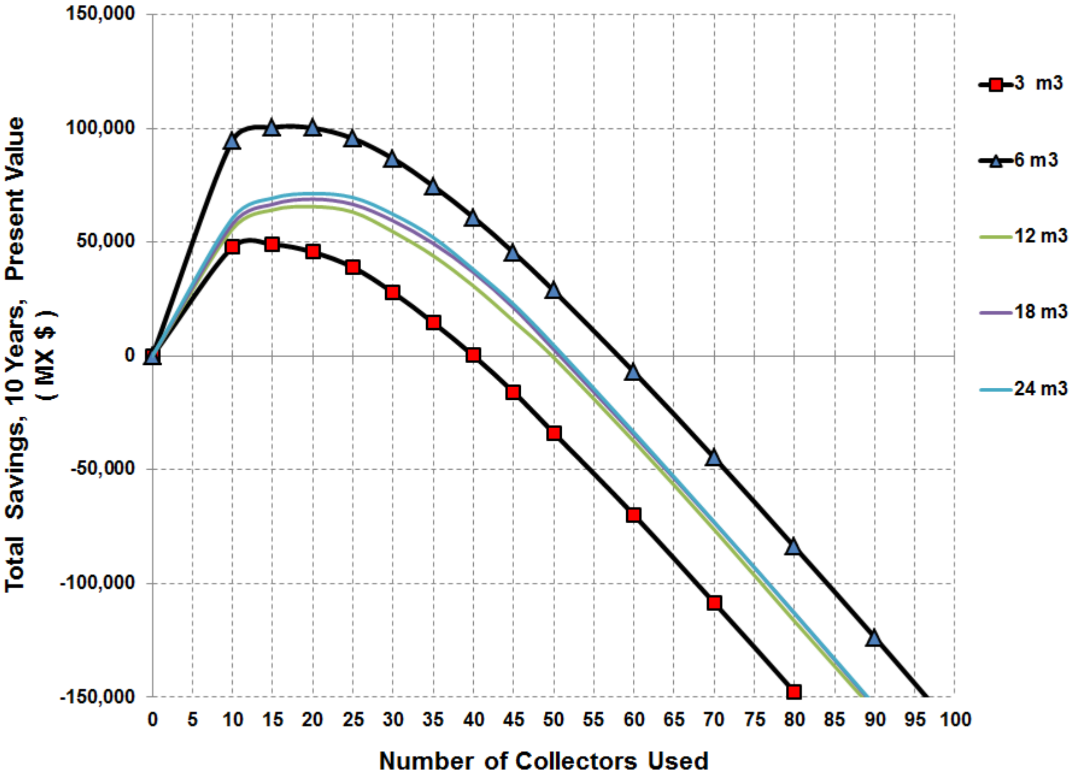


Figure 9 *Net savings compared to no solar energy use, present value 10 years operation*



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