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AGRICULTURAL GREENHOUSE SOLAR-ASSISTED CLIMATIZATION SYSTEMS DESIGN AND OPTIMIZATION, FOR THE SEMI-ARID REGION OF NORTHERN MEXICO

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Abstract

An agricultural greenhouse is thermally analyzed using the simulation program TRNSYS 17. The thermal loads resulting from the heating and cooling are calculated to maintain the greenhouse temperature within the range of crop development. Construction materials, geographical location and the optimal development characteristics of the Saladette tomato and its different growing stages are also reported. The thermal performance inside and outside the greenhouse with and without air conditioning is also described. The heating and cooling loads are shown for an idealized air conditioning system considering the number of heat exchangers, temperatures required by the crop and the hot/cold water temperature available in the system. The results of a thermal analysis for a three day in June is described in detail. The temperatures inside and outside of the greenhouse, including the thermal load for the most critical day of the year are shown. Simulation results show that 4,231,966 GJ and 39,324,140 GJ are being demanded for heating and cooling respectively along a typical meteorological year. A case of study is presented in order to analyze the greenhouse in which energetic requirement is partially provided using solar energy. The simulation shows that in order to achieve a solar fraction of 72% for heating and 30% for absorption cooling, 300 solar collectors are needed.

Keywords*: Agricultural greenhouse, Solar heating and cooling, Trnsys simulation, Solar heat for industrial processes.*

1. Introduction

In Mexico tomato production in greenhouses with controlled environments is taking great importance. The use of highly automated greenhouses allows to control the necessary variables for tomato growing and thus significantly increase the volume of annual production in continuous operation (Kolokotsa et al., 2010). The main variables for a greenhouse are temperature, humidity, CO2 and the plagues (Attar et al., 2013), (Chargui and Sammouda, 2014), (Kamel and Fung, 2014). It is necessary to have a closed greenhouse in order to control the variables as proposed by Vadiee and Martin (2013 a). However, in extreme climates with low relative humidity, cold but sunny winters and hot summers, it is possible to get temperature variations up to 25 °C in a day. For a greenhouse under these conditions and continuous operation throughout a year, requires a high power supply so huge that become unaffordable for commercial operation. Currently, for a greenhouse optimum design it is necessary to calculate the heat transfer rates to and from the envelope, required to maintain the optimum temperature for the crop. Quantification of a greenhouse energy demand is a challenging task, due to the continuous variation of atmospheric variables. Therefore it is also uncertain to

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develop a reliable economic analysis that allows to determine whether the obtained production profit justifies the initial investment and operating costs (Souliotis et al., 2009). Nowadays, there is specialized software such as TRNSYS that analyze different design scenarios, in order to compare the thermal performance of different configurations, sizes and types of technology used, delivering results with less than 6% of uncertainty (Almeida et al., 2014) (Attar and Farhat, 2015). TRNSYS has been used to model and analyze greenhouses, in places like Zimbabwe (Mashonjowa et al., 2013), Nepal (Seona et al., 2012) and Australia (Lu Aye et al., 2010), nevertheless studies for the northern part of Mexico has not yet been developed.

No papers were found for the energy performance and the economic analysis of greenhouses. Developed in this paper, is the analysis of the interaction of an agricultural greenhouse with the climatic conditions of the semi-arid region of northern Mexico, specifically in the proximity of 28° N latitude. An air conditioning system is proposed, based on the circulation of hot/cold water through heat exchangers located inside the greenhouse. The aim of this paper is to demonstrate that the amount of energy, and thus the air conditioning equipment required for a greenhouse throughout a year are enormous on its original architecture, resulting in low profitability. It is therefore proposed, a detailed analysis of technical alternatives to reduce the thermal loads of a greenhouse. Thermal insulation and shading are mainly considered to reduce as much as possible the investment needed for air conditioning operation. These will lead to an optimal design of the air conditioning system, including construction materials, shading system and a combination of heating and cooling equipment assisted with solar energy, that together aim to reduce the project cost and thus maximize production profit.

1.1. Crop Information

1.1.1. Tomato Variety

The greenhouse used as a case of study produces organic Saladette tomato in a variety called “Moctezuma and Cuauhtémoc” (Figure 1).

Fig. 1: Saladette tomato inside the greenhouse of this case of study

1.1.2. Requirements for temperature, humidity and CO_2

The requirements of temperature, relative humidity and CO_2 concentration of Saladette tomato are found in the following table.

Tab. 1: Required environmental specifications for the crop (Castellanos, 2004)(León, 2006).

Requirement	Values
Temperature for all production stages (°C)	15 – 30
Humidity (%)	70 – 85
CO_2 concentration (ppm)	700 - 800

1.2. Greenhouse information

1.2.1. Geographical location

The greenhouse analyzed in this work is located within the Agroindustrial Park Naica, Saucillo Municipality, Chih., Mexico. Its geographical coordinates are 28.062543 N, 105.534867 W.

1.2.2. Design and type of technology

The greenhouse is a multi-chapel type (greenhouse technology developed in Canada), designed for medium and highly automated operations. It has 9 chapels spread over a surface area of 1.6 hectares and an approximate volume of 100,000 m^3. The double-walled polyethylene cover is supported by metallic structures represented by dots in Figure 2.

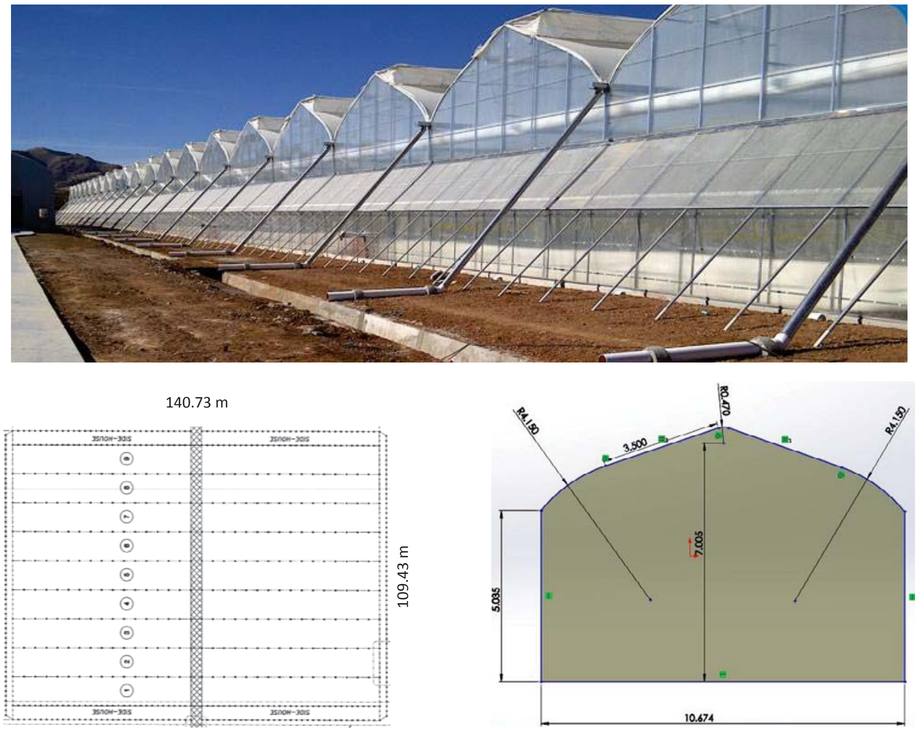

Fig. 2: Multi-chapel Greenhouse type

1.2.3. Current Climate Control

Currently the greenhouse has no air conditioning system. Instead, it has a double walled cover, and a natural ventilation induced by a vent system with a mechanized aperture, located at the top of the structure.

2. Proposed air conditioning system

The greenhouse air conditioning system proposed and its main components are shown in Figure 3. The system use a heat exchanger (water-air) network distributed in the greenhouse to cool or heat the air inside, without introducing external air that contaminates and dilute the CO^2 concentration. The heating system is mainly composed by a field of solar thermal collectors, a storage tank and an auxiliary heating system based on LPG. It also has a refrigeration equipment to produce cold water during summer.

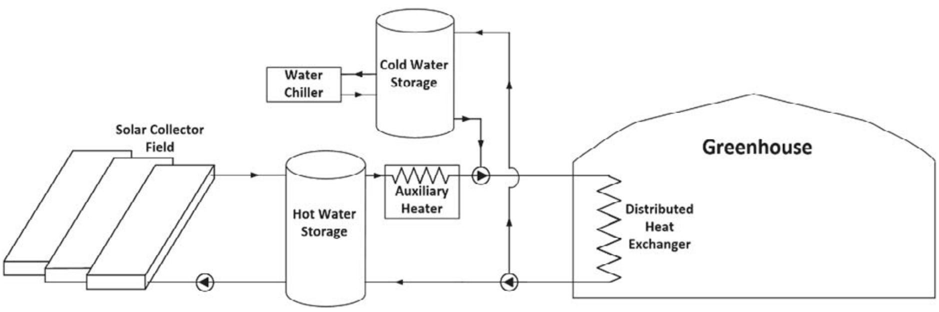

Fig. 3: Greenhouse air conditioning system proposed.

3. Simulation

3.1. Simulation tools

The software packages required for the proposed analysis, were among others, SketchUp Pro, Simulation Studio, TRNBuild, TRNEdit, Meteonorm, Berkeley Lab Window 7.2, MS Excel and TRNSYS 17. The greenhouse geometry was first modeled, then the materials physical properties of the envelope and the translucent cover were incorporated, after that, the thermo-mechanical components were simulated. In Figure 4, the type of greenhouse technology and its implementation in the SketchUp Pro software is displayed.

Fig. 4: Greenhouse technology type and SketchUp schematization.

The main components of the air conditioning system and its interaction is shown schematically by means of TRNSYS 17 Icons as shown in Figure 5.

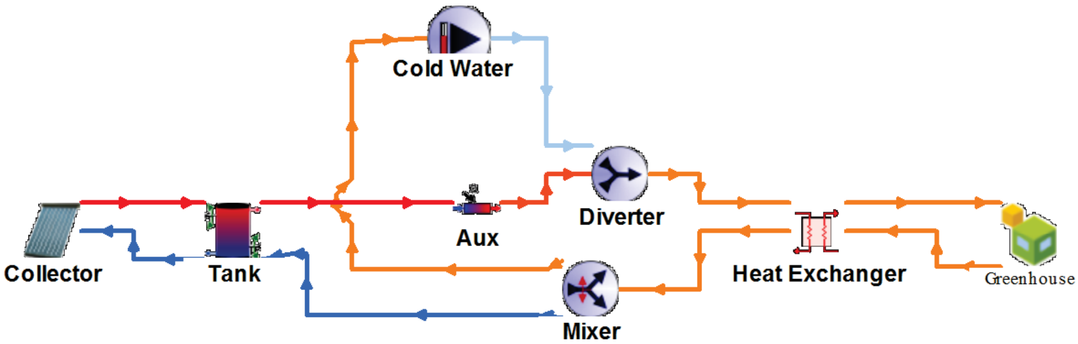

Fig. 5: TRNSYS system setup.

3.2. Simulation remarks

System operation was simulated throughout a typical year, in a 15 minute (step) based calculation. Parametric variation was performed using the climatic information (TMY) of the city of Delicias, Chihuahua. Instantaneous flow rates were integrated over periods of a day and a year to get the daily and annual cumulative.

4. Results

4.1. Thermal Performance

In Figure 6 the environment temperature behavior is shown for a typical meteorological year (TMY) in the specified greenhouse location. The temperature range recommended for a good development of a tomato crop at all stages is also displayed.

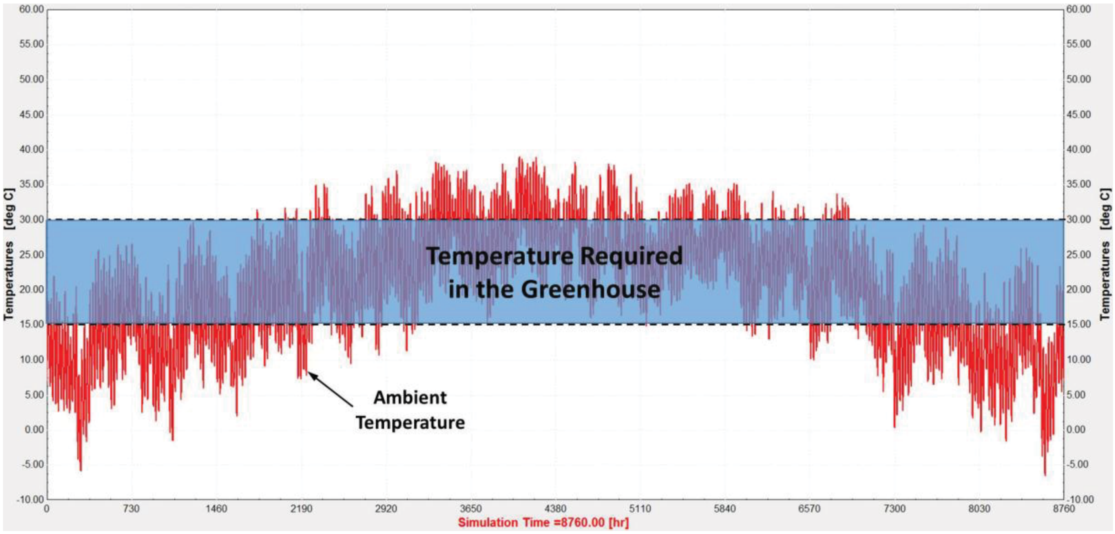

Fig. 6: Environment temperature and range required inside the greenhouse.

The air temperature performance inside the greenhouse is shown in figure 7, when operating closed and without air conditioning. The temperature range required for the crop development is also shown. In this case the greenhouse is performing closed in order to maintain relative humidity and CO2 concentration under control, however, the temperature remains within the comfort zone for only a few weeks a year.

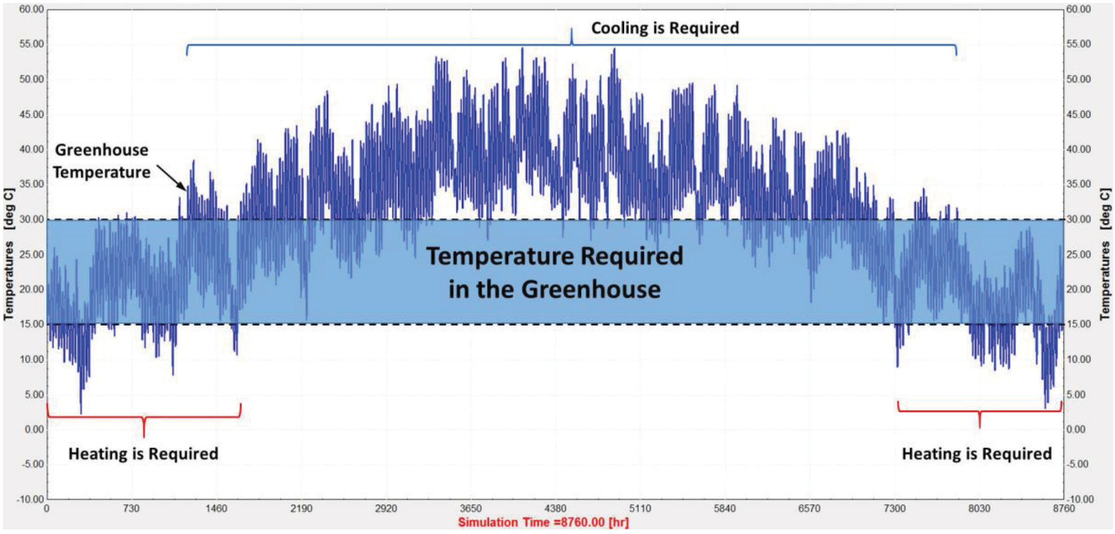

Fig. 7: Air temperature behavior inside the greenhouse without air conditioning, and the crop thermal comfort zone.

The time periods when heating or cooling is required are shown in figure 7. It is noted that for this climate conditions, cooling requirements during the summer season are significantly higher than those of heating in winter, due to the natural greenhouse effect. It can be observed that without air conditioning, the vast majority of time throughout the year, the air temperature inside the greenhouse is above the comfort zone, reaching lethal to plants temperature values, this makes not only impossible to harvest in summer, but necessary to replace dead plants at the end of the hot season.

4.2. Theoretical thermal loads for Heating and Cooling

To achieve a perfectly controlled climate within the greenhouse, it is required to supply heating and cooling to counteract the external thermal loads, at the same rate as they occur. In the simulation this is achieved assuming that there is an unlimited hot or cold water supply, and energy is transferred to or from the air instantly. This indoor ideal temperature control is obtained and the instant energy consumption is determined. The greenhouse thermal simulation for the previously described is shown in Figure 8. The graph shows that for the coldest day, heat must be supplied at a rate of 1,370 kW to the greenhouse and for the warmest day heat needs to be extracted at a rate of 2,490 kW from the greenhouse.

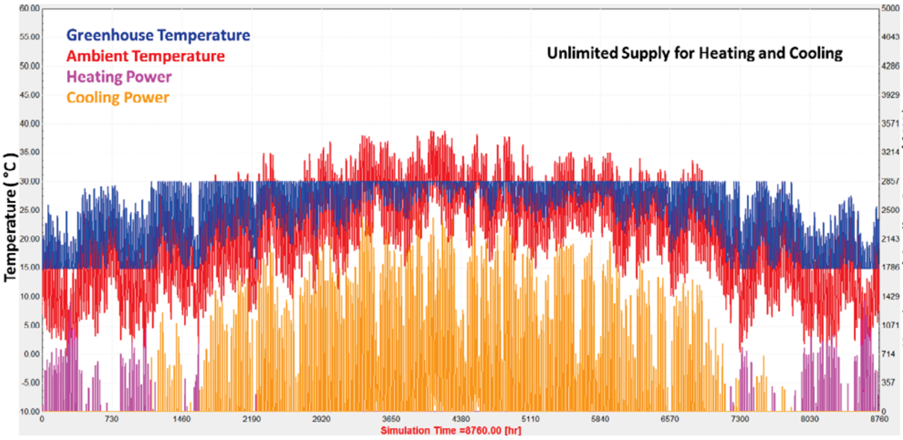

Fig. 8: Greenhouse inside and outside temperatures and the heating/cooling power.

However, by introducing the physical performance of the required equipment, the type and number of devices used for air conditioning are obtained, additionally an estimate of the cost is also obtained. Physical and economic data of real devices, available in the local market were used in this work to obtain an initial estimate of the economic impact of the greenhouse air conditioning.

4.3. Heat transfer equipment

To maintain the previously mentioned comfort zone inside the greenhouse, the effect on the use of different number of heat exchangers was analyzed. Figure 9 shows the behavior of the air temperature within the greenhouse based on the number of heat exchangers used for air conditioning. Commercially available fan and coil heat exchangers of an overall heat transfer coefficient of 400 W / ° C were simulated. The greenhouse performance using 0, 85, 145 and 180 exchangers is shown.

It is noted that in order to control the indoor temperature in winter using 85 heat exchangers is easily achieved, however cooling in summer requires more equipment. It is also noted that even when using 145 heat exchangers, there are periods at temperatures above the desired maximum level. Increasing the number to 185 it improves only marginally. This illustrates that the problem is no longer technical but economical and it is compulsory to determine how far it is appropriate to add equipment for an overall economic feasibility.

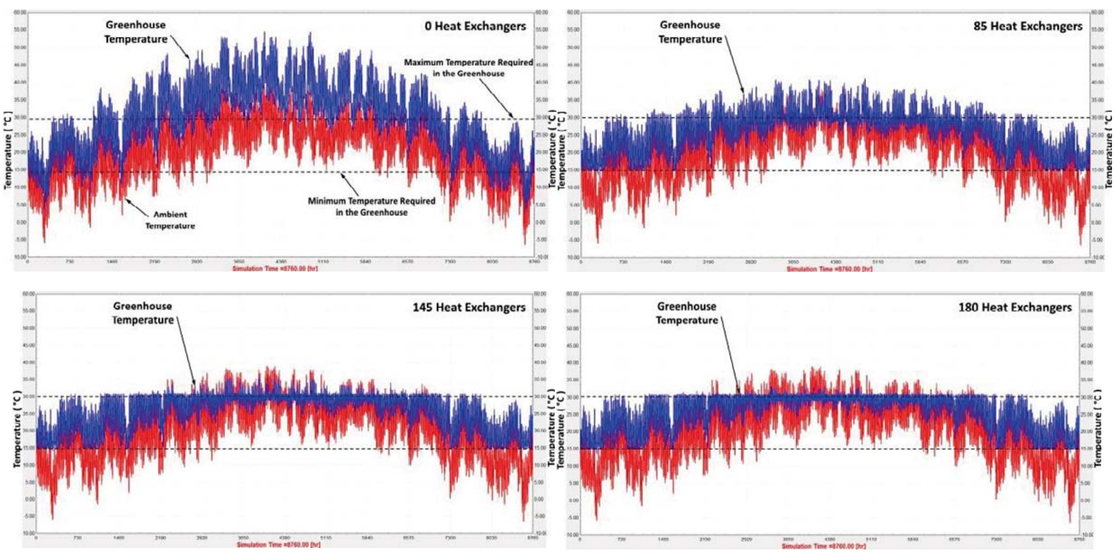

Fig. 9: Thermal performance in the greenhouse using 85, 145 and 180 heat exchangers.

From the technical point of view in the previous graphs, it can be concluded that the required number of heat exchangers for the air conditioning of the greenhouse should be 180 in order to ensure that the internal temperature will partially not exceed the maximum level in the year.

4.4. Actual thermal heating and cooling loads

To analyze the greenhouse thermal loads using the locally available heat transfer equipment, considerations shown in Table 2 were made.

Tab. 2: Considerations for the analysis of thermal heating and cooling loads.

Parameter	Value
Heat exchangers amount	180
Available hot water temperature (°C)	60
Minimum allowed temperature inside the greenhouse (°C)	15
Available cold water temperature (°C)	2
Maximum allowed temperature inside the greenhouse (°C)	30

Based on the limitations imposed in the table above, simulation shows that to maintain the greenhouse interior temperature within the comfort zone it is necessary to insert and remove the heat rate amount shown in Figure 10. The heating and cooling power values are of around 3,700 kW and 1,800 kW respectively.

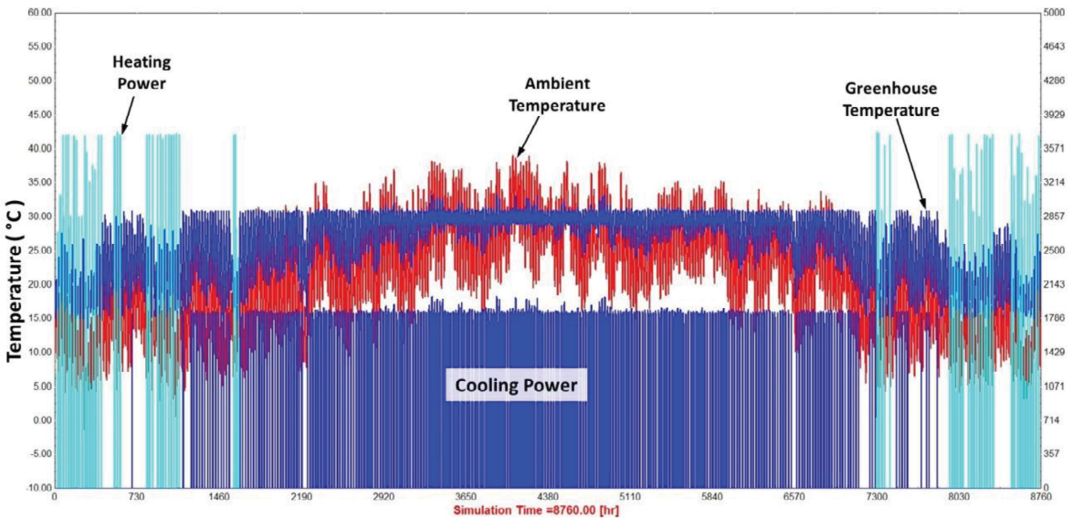

Fig. 10: Necessary heat transfer rate.

4.5. Greenhouse daily thermal performance

To analyze in detail the thermal performance outside and inside the greenhouse without air conditioning, simulation results on June 19th, 20th and 21st are shown in Figure 11. This figure shows that the temperature inside the greenhouse is above the maximum allowed temperature. Even the exterior temperature is generally above that temperature.

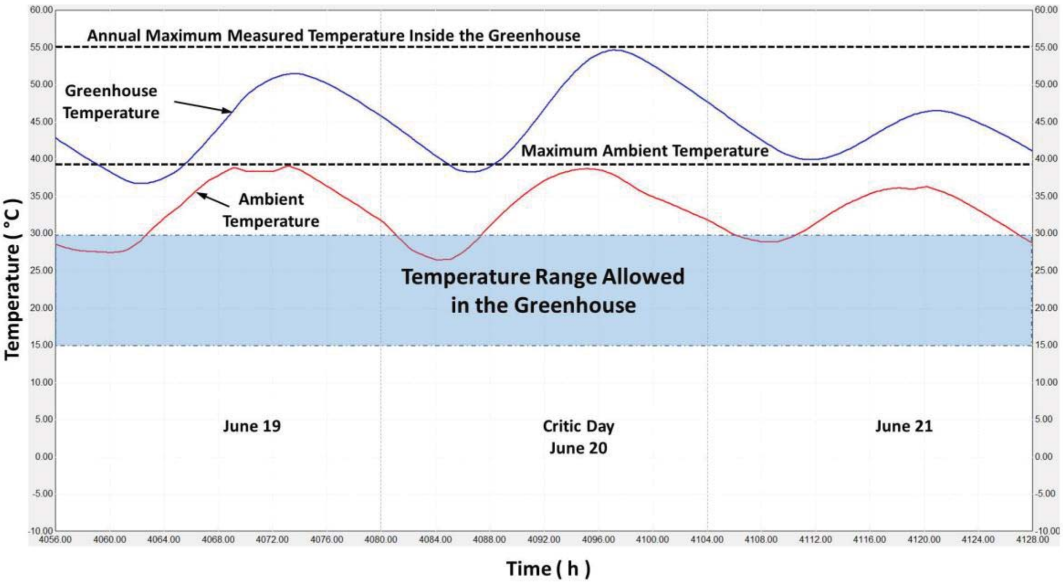

Fig. 11: Temperatures reached inside and outside the greenhouse on June 19th, 20th and 21st.

Figure 12 presents the thermal performance inside and outside the greenhouse when the air conditioning system is used. The power required for the three day cooling is also displayed, additionally the energy required on June 20th is included. The simulation showed that the highest cooling demand of the year is on that day.

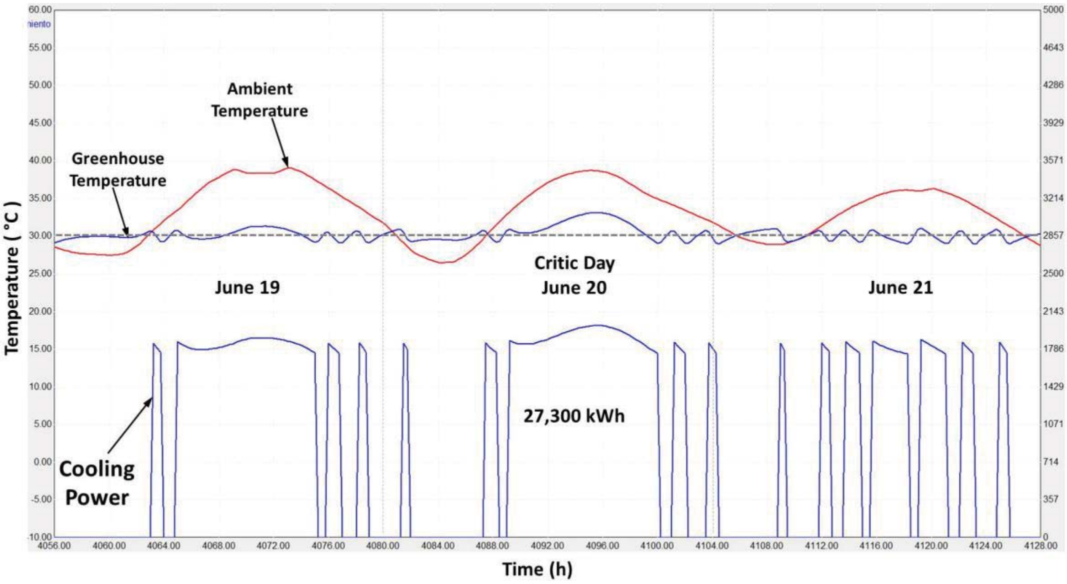

Fig. 12: Thermal performance inside and outside the greenhouse using air conditioning on June 19th, 20th and 21st.

Figure 13 shows the thermal performance inside and outside the greenhouse using air conditioning along with the power and energy inputs to achieve this. However, the necessary energy to extract heat from the greenhouse is 27,300 kWh and it can be supplied by a device with an output of 325 tons of refrigeration.

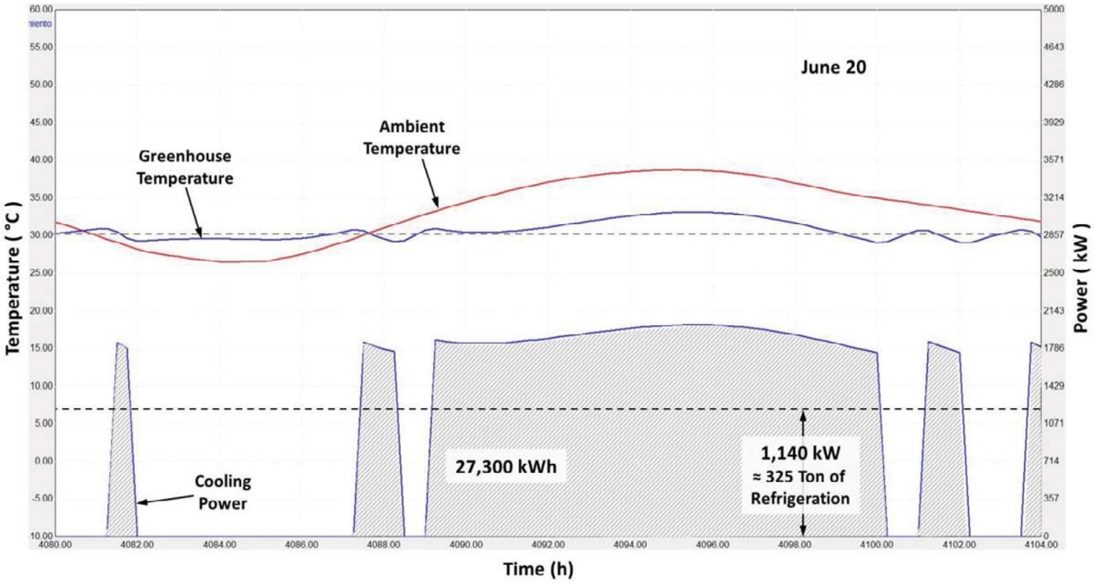

Fig. 13: Power, energy and thermal performance of the air conditioned greenhouse on June 20th.

4.6. General results

The simulation results allows to observe that the energy required for the greenhouse heating and cooling to keep the temperature within the optimum thermal zone for the crop development throughout the year is 4,231,966 and 39,324,140 GJ GJ respectively.

Once the number of heat exchangers is determined and the temperature considerations are set, the power calculated for heating and cooling results in 3,700 kW and 1,800 kW respectively.

This huge energy consumption can be supplied by several sources such as oil, LP gas, natural gas, electricity, biomass, and solar (Vadiee and Martin, 2013 b), (Vadiee and Martin, 2014).

The following case of study allows to analyze the system performance when part of the energy is met by a solar source. The simulation results show that in order to achieve a solar fraction of 72% for heating and 30% for absorption cooling, the equipment required is shown in Table 3.

Tab. 3: Required equipment to supply a specific solar fraction.

Equipment	Amount	Unit Price ($USD)	Total Price ($USD)
Evacuated tube solar collector (heat pipe)	300	500	150,000
Thermal storage @ 60 L/m^2	75 m^3	5,000 / 25 m^3	15,000
heat exchanger overall heat transfer coefficient (400 W/°C)	180	2,433	437,940
Auxiliary heater (1,000 kW)	1	53,552	53,552
Absorption refrigeration system (1,140 kW)	1	325,000	325,000

5. Conclusions

Energy requirements have been studied in order to maintain the greenhouse air temperature in an optimal range for the crop development, as well as the heat exchange equipment required for the air conditioning throughout the year.

It was found that the thermal loads for both heating and cooling are very high, thus making the technology implementation unfeasible either for conventional or solar energy supply in the crop production throughout a year.

Consequently, all of the above encourage to propose a detailed analysis of the technical alternatives applied to reduce the thermal loads in the greenhouse, mainly by means of the analysis of thermal insulation and shading and thereby predicting lower operation costs by heating and cooling.

After an energy efficiency analysis it is possible to propose the use of solar energy for the heating and the cooling of the greenhouse.

6. Acknowledgements

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