Int. Agrophys., 2011, 25, 257-264

INTERNATIONAL
Agrophysics
www.international-agrophysics.org

Experimental performance of a hybrid solar energy saving system in greenhouses

G.K. Ntinas, P.G. Kougias, and Ch. Nikita-Martzopoulou*

Laboratory of Agricultural Structures and Equipment, Faculty of Agriculture, Aristotle University of Thessaloniki, 54124 Thessaloniki, Greece

Received October 13, 2010; accepted December 28, 2010

A b s t r a c t. The present study investigates the possibility of energy saving during the spring period in a conventionally heated greenhouse, using an innovating hybrid solar energy saving system. The greenhouse was divided in two equal parts (experimental and control), where tomato plants were cultivated hydroponically. The control part of the greenhouse covered the heating requirements exclusively by a conventional heating system. The experimental part used the conventional heating system only when the hybrid solar energy saving system could not maintain the greenhouse air temperature above 16°C. The hybrid solar energy saving system was consisted of a transparent cylindrical polyethylene sleeve filled with water and two perforated polyethylene tubes resting on the top of it. Through these tubes, air was pumped in order to inflate them and to be mixed with the greenhouse air. The use of hybrid solar energy saving system led to an energy saving portion capable of decreasing the greenhouse energy cost. Energy saving between the two parts of the greenhouse was recorded to be 36% from March to May. It has been also calculated that the oil consumption was significantly decreased in the experimental part and for the whole experimental period was 149.08 l, while in the control part reached 233.03 l. The application of this system contributed to smoother variation of the greenhouse air temperature and the rockwool slabs temperature, leading up to a better plant growth.

K e y w o r d s: greenhouse, solar sleeves, energy saving, microclimate, tomato

INTRODUCTION

During the last decades, a remarkable raise of greenhouse crop production has been observed in Greece and also in the wider Mediterranean region. The main reasons for this constant increase were the escalating tendency and effort to modernize rural crop production.

The direct consequence of this trend was an increase in energy consumption used to satisfy the greenhouse needs. Energy consumption for greenhouse heating and cooling reached approximately 1.5% of Europe total energy budget (Santamouris *et al*., 1994b). Studies on greenhouse heating strategies have shown that the heating cost exceeds 30% of the overall operational cost, even if a greenhouse faces the South (Santamouris *et al*., 1994a).

The rise of greenhouse energy cost results in reducing the construction rate of new greenhouses. To overcome this problem, several heating technologies have been applied to greenhouses depending to their location, size and climatic conditions (Sethi and Sharma, 2008). It is also reported by various authors (Sethi and Sharma, 2007; Omid and Shafaei, 2005; Singh and Tiwari, 2000) that a well-designed and precisely controlled greenhouse can induce a significant increase in the internal air temperature varying from 2.5 to 15°C and also maintain better conditions for plant growth.

In the Mediterranean area the greenhouse conventional heating systems use oil or natural gas. These systems are consisted either of an air heater or of ground pipes located close to the plant rows (Bartzanas *et al*., 2005). It has been proven that a low position of the heating pipes has significant advantages, since it minimises heat loss by radiation to the transparent covering and maximises radiation to the plant canopy, and also creates a good movement of the heated air through the canopy, while it is capable to obtain a better horizontal and vertical temperature distribution in the greenhouse (Popovski, 1988).

Despite all the advantages that heating provides to the increase of the off-season production, many growers prefer not to establish a heating system due to the high investment and running cost. Therefore, the increasing interest in reducing the greenhouse energy cost and the necessity for energy saving, led to extensive efforts in exploitation of renewable energy sources, such as geothermal energy, biomass and solar energy (Kondili and Kaldellis, 2006; Lund *et al.*, 2005; Nikita-Martzopoulou, 1988).

*Corresponding author's e-mail: gntinas@agro.auth.gr

It is stated that passive solar heating systems, such as the simple passive solar plastic sleeves filled with water, next to the plant rows, can lead to a reduced consumption of conventional fuels. A water-filled plastic sleeve operates by absorbing the incident solar radiation, which results in an increase of the water temperature contained in the plastic sleeves. Consequently, the water acts as a heat deposit. During the night, or at any time that the greenhouse air temperature is lower than that of the water in the sleeves, the stored heat is released in the internal environment of the greenhouse by natural convection and radiation. It has been proved that using the particular heating system in a greenhouse, the internal air temperature was up to 3-5°C (Zabeltitz, 1994) higher compared to control greenhouse and 3-4°C (Mavrogianopoulos and Kyritsis, 1993) higher than outside air temperature. Sethi and Sharma (2008) reported that a 2-6°C increase in the inside air temperature can be achieved at various locations ranging from 32° to 52.5° N for 72 to 500 m^2 greenhouse areas.

The main advantage of using water as a thermal heat storage medium is the low cost but on the other hand the major problem of using ground sleeves inside the greenhouse is that approximately 20-25% of the valuable ground surface becomes unavailable for cultivation. In some cases the amount of the unavailable space can reach 35% (Grafiadellis, 1999), which is a limiting factor for other agricultural handlings in the greenhouse.

The main objective of this study was to evaluate the energy saving in a conventionally heated greenhouse where an innovating hybrid solar energy saving system (HSESS) was installed. The HSESS was composed of a polyethylene sleeve filled with water and two peripheral polyethylene tubes filled with air. These two peripheral tubes were functioning as a gutter above the sleeve where the rockwool slabs were placed. The innovation of this system lies to the fact that the problem of lesser ground space was overcome, keeping the path rows free. Also, HSESS keeps the advantages of the polyethylene ground sleeves *eg* low cost and energy saving. The energy consumption of the experimental part of the greenhouse was compared to that of the control part which was heated only by the conventional heating system. Furthermore in this study, the decrease of the conventional fuel consumption, with a respective decrease in crop production cost, was calculated. Finally, the variation of the greenhouse air temperature and the rockwool slabs temperature was also investigated in order to examine the influence of this system on the precocity and plant growth of tomato cultivation.

MATERIALS AND METHODS

A north-south orientation modified tunnel greenhouse of the Center of Agricultural Structures Control located in the Farm of Faculty of Agriculture at Thermi (40°32' N and 22°59' E), Thessaloniki, Greece, was used for the study. The research was conducted during spring period, from March to May, 2007. The greenhouse was covered with UV stabilized polyethylene (PE). The ridge and side height of the greenhouse was 3.6 and 2.1 m, respectively.

For the purposes of the experiment, the greenhouse was divided at length in 2 separate parts of 10 x 7 m each, with cover area of 164.6 m^2. The two resulting greenhouse parts were separated by a corridor of 2 x 7 m. The greenhouse soil was covered with a double-side plastic polyethylene sheet (black downwards-white upwards) in order to prevent weed growth and to increase reflection of the incident solar radiation.

In both parts tomato (Hybrid Optima F1) was cultivated hydroponically. This variety presents good precocity and high tolerance to plant diseases and nematodes. The planting population used was 210 plants, 105 per part (15 000 plantations per ha), distributed in five rows. The hydroponic cultivating system was set up to provide the same amount of nutritious elements in both parts. To avoid infections and diseases, there was no recycling of the nutrient solution. The nutrient solution was provided to the plants by a drip system, which was automatically controlled by an electronic controller (Rainbird Image 2). During the experiment, pH and electrical conductivity (EC) of the nutrient solution were measured, using a portable pH/mV/°C Meter (HANNA Instruments HI8424) and a portable Multi-Range Conductivity/TDS Meter (HANNA Instruments HI8733).

Each part of the greenhouse had two openings for natural ventilation, one at the west side and one at the east roof. The maximum opening of these windows was 1 m and they were set to function at a temperature set point of 23°C.

The conventional heating system was installed at both parts of the greenhouse (experimental and control). The control part of the greenhouse was heated exclusively by the conventional heating system as shown in Fig. 1. The conventional heating system was consisted of the following components:

- a boiler, heated the circulating water which was the thermal medium;
- an insulated metal pipe system, connected to the boiler and transferring the thermal medium (water) inside the greenhouse;
- two electrovalves, adapted on the metal pipes, to control the water flow;
- a network of black polypropylene (PP-R) heating pipes (25 mm diameter) for the circulation of water around the plant rows. These pipes were placed close to each gutter holding the growing substrate including three supply and return lines for each plant row;
- a control board was set up in the intermediary corridor;
- two time counters were installed on the control board, one for each part of the greenhouse, in order to measure the boiler operation time. The control board was also connected with two temperature sensors that recorded the

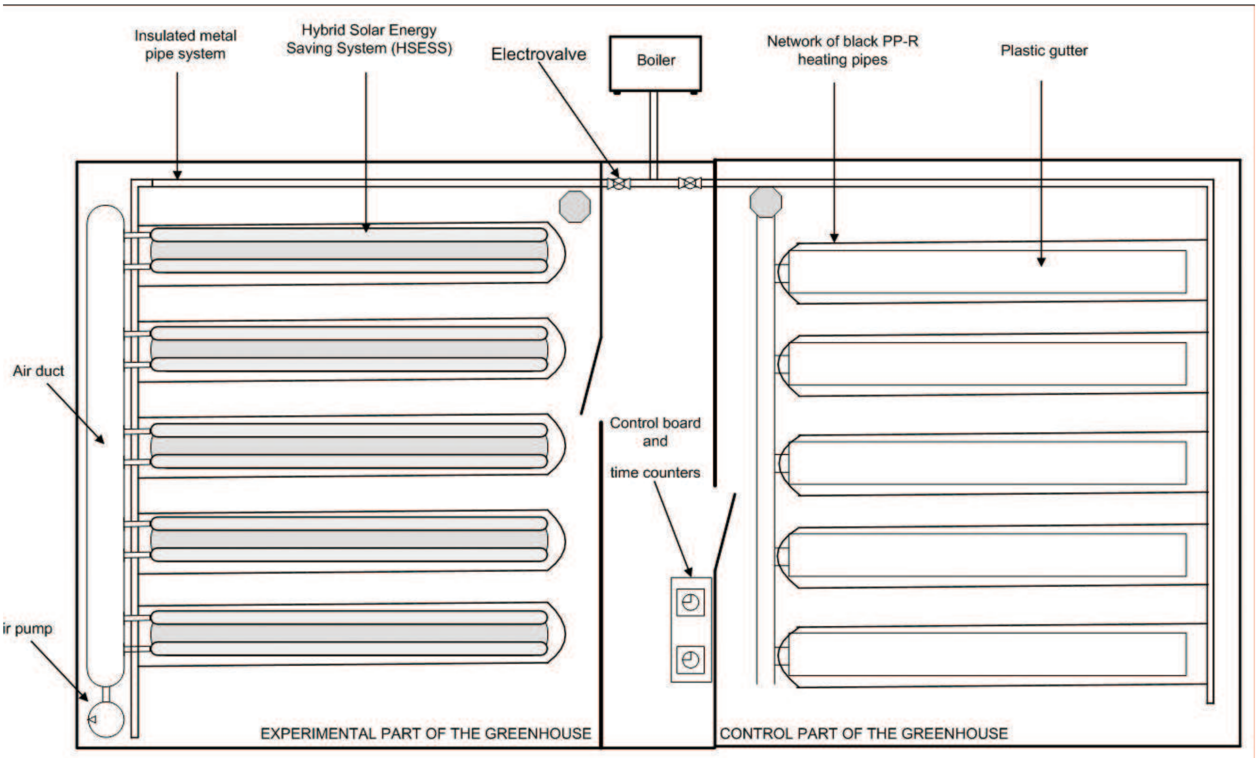

Fig. 1. Conventional heating system and the HSESS.

greenhouse air temperature. The critical temperature point at which the conventional heating system started operating was 16°C.

The HSESS was installed in the experimental part of the greenhouse (Fig. 1). This innovating system (Fig. 2) was composed of:

– a transparent cylindrical PE sleeve, 7 m long with a perimeter of 1.52 m and
– two tubes, made of PE, laid on the top of the sleeve, inflated by an air pump of the greenhouse.

The tubes were 6.8 m long, with a perimeter of 0.2 m. Along the air tubes, small ventilation holes were made so that part of the circulating air was coming out to the rockwool slabs. The air pump system was capable to fill the total volume of the air tubes. These air tubes were also acting as side walls to create a gutter for the drainage of the excess nutrient solution. In between the peripheral tubes and on top of the sleeves a thin layer of gravel was placed in order to facilitate drainage of the excess nutrient solution to avoid algae growth. Rockwool slabs were placed on top of the gravel layer.

Each sleeve was filled with a total of 1 287 l of water. In order to avoid any formation of algae in the water, 15 g $CuSO_4$ $5H_2O$ per sleeve were added. Each sleeve has been placed on a black polyethylene sheet which absorbed the

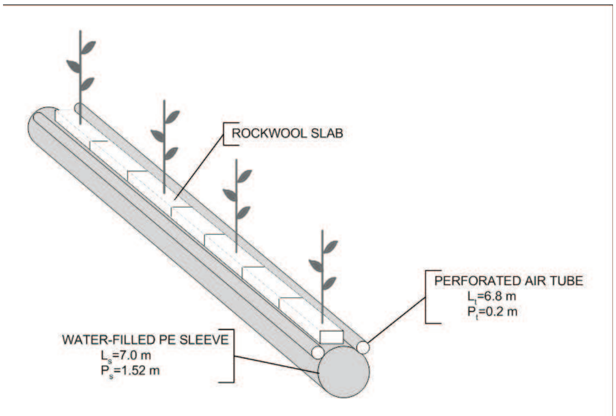

Fig. 2. The hybrid solar energy saving system and its characteristics (where L_s, P_s are the sleeve length and perimeter respectively and L_t, P_t are the tubes length and perimeter, respectively).

incident solar radiation. A total of five such sleeves were used, above which, five rows of hydroponically cultivated tomato plants were placed (Fig. 2).

As mentioned before, the thermal needs in the experimental part of the greenhouse were met mainly by the HSESS and supplementary by the conventional heating system.

The climatic variables, which characterize the greenhouse microclimate, were measured every 5 min. The rockwool slabs temperature was measured by twelve temperature sensors PT-100 type, six in the experimental part of the greenhouse and six in the control one. The water temperature in the sleeves was also measured by a PT-100 type temperature sensor, at the center of the sleeve. The greenhouse air temperature and humidity were measured by four temperature-humidity sensors of HOBO H8 type, two in each section, placed above the cultivation, one at a height of one meter and the other at two meters distance from the ground. A calibrated pyranometer (class A), measured the solar radiation intensity inside the greenhouse. Figure 3 depicts the location of the sensors in each part of the greenhouse. An external meteorological station at the Center of Agricultural Structures Control, consisting of an anemometer, a wind vane, a thermometer, a pyranometer and a hygrometer, was used to measure the external climatic conditions. The recording and management of all climatic data were stored using a computer based data acquisition system (Data logger CR-10). In addition, two time counters recorded the total boiler operation time for the two parts of the greenhouse. The conventional heating system was set to operate at a temperature of 16.0°C (temperature set point). Two PT-100 type temperature sensors, one in each part, were connected with the time counters. The data from the PT-100 type sensors and the pyranometer could be monitored in real time, while the HOBO H8 type sensors recorded automatically and data were retrieved at a later stage. The analysis of the above data led to the estimation of energy saving.

Particular attention has been given to the calibration of the measurement instruments. Systematic controls and constant verifications of measurements have been performed. According to the manufacturers, the temperature sensors (PT-100 type) may present a deviation of ± 2%, the temperature-humidity sensors (HOBO H8 type) can present a variation of ± 5%, while the pyranometer may present a variation of ± 0.5%. The results showed that these variations did not have a significant effect on the results of the experiment.

Furthermore, in order to examine the influence of HSESS on the plant growth, plant height and stem perimeter were measured every 10 days. The crop precocity was investigated by recording the formation time period of the first flower and fruit.

RESULTS AND DISCUSSION

The design of heating, ventilating and cooling systems in greenhouses is based on the energy balance of these structures. The undesirable heat losses from a greenhouse occur mainly by long-wave radiation, conduction and convection and also by infiltration. In order to calculate the greenhouse heating requirements, the minimum desired internal air temperature for any cultivation *eg* 16°C for tomato must be taken into account. The external temperature is considered to be the lowest value of the mean minimum temperatures recorded for the months that the experiment lasted.

The regional mean minimum monthly temperature for March, April and May are 4.7, 6.1, and 13°C respectively. The mean minimum temperature of March (4.7°C) is the value used to calculate the heating requirements.

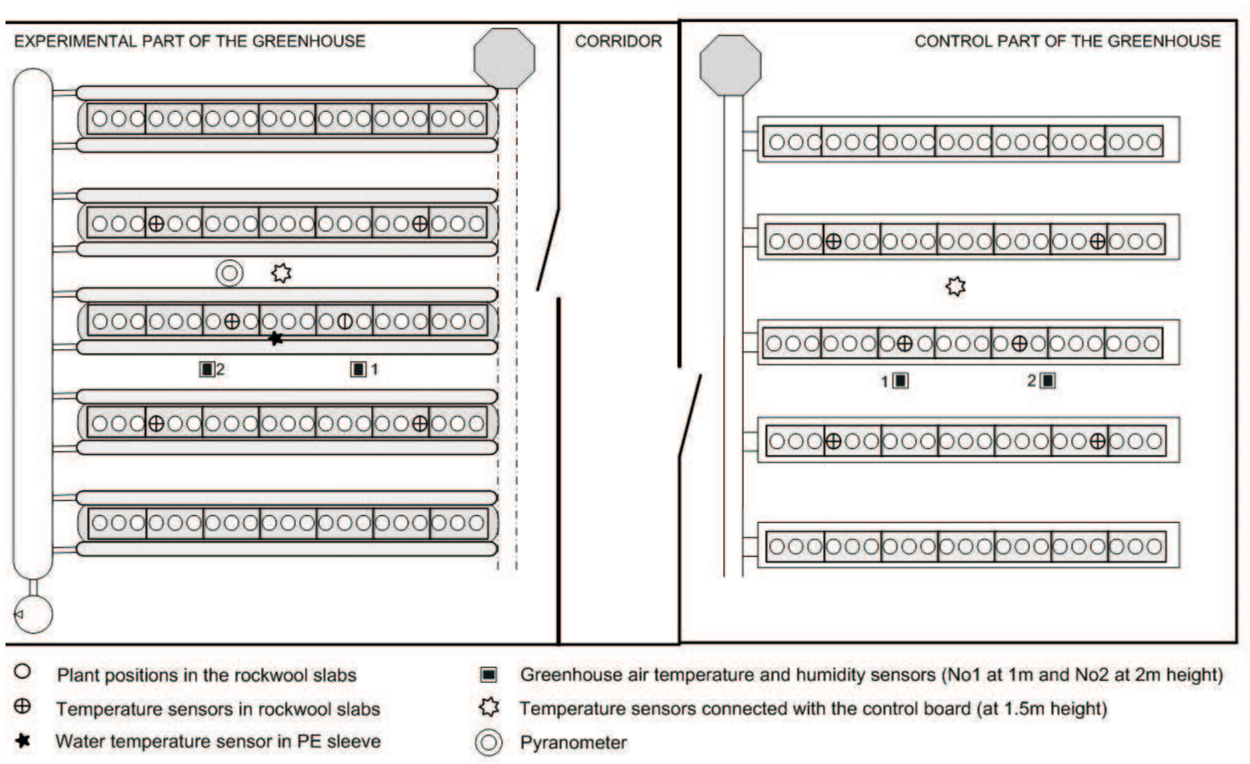

Fig. 3. Location of the sensors in each part of the greenhouse.

The total heating requirements of a greenhouse can be determined by the equation:

$$Q = UA(T_i - T_o), \quad (1)$$

where: Q is the heat flow rate (W), U is the overall heat transfer coefficient (W m^{-2} °C^{-1}), A is the greenhouse covering surface area (m^2), T_i is the desired inside air temperature (°C) and T_o is the outside air temperature (°C).

The value of the overall heat consumption coefficient of greenhouse single polyethylene cover is 6.8 W m^{-2} °C^{-1} (Hanan, 1998) and consequently, the heating requirements of the greenhouse were calculated as follows:

$$Q = UA(T_i - T_o) = 6.8\ 1\ 4.6\,(16 - 4.7) = 12.64\ \text{kW}. \quad (2)$$

According to technical characteristics of a boiler, its thermal efficiency is up to 90%, so an amount of at least 10% losses is taken into consideration. In order to meet the heating requirements of each part of the greenhouse, the boiler used in the research had a power output equal to 14 kW.

The total operation time of the boiler for the control greenhouse, from March 1 until May 31, was 226.46 h (Table 1). The hour-meter recorded 144.88 h of boiler operation in the experimental part of the greenhouse, in which HSESS was installed. The research carried out during the spring period hence the heating requirements were progressively decreasing.

It is obvious that the total boiler operation time in the experimental part of the greenhouse was significantly lower than the corresponding operation time of the control part for each month. For the whole experimental period the time difference of boiler operation between the two parts was 81.58 h. This led to an energy saving percentage capable of decreasing the greenhouse energy cost. This energy saving amount was calculated at 29.7, 40.4, and 86.9% during the months of March, April and May respectively. For the total experimental period, the energy saving amount was calculated at 36%.

As already mentioned, in order to meet the heating requirements for each part of the greenhouse, the heat was produced by the boiler with a power output of 14 kW. According to the manufactures, a boiler with such an output consumes 1.17 kg oil h^{-1} or ~ 1.029 l oil h^{-1} (specific mass of oil, 0.88 kg l^{-1}). From the boiler total operation time that has been stated above, the total oil consumption can be calculated by multiplying the boiler total operation time with the oil consumption for the specific boiler, according to its technical specifications. Table 1 shows the monthly and the total oil consumption for heating the experimental and the control part of the greenhouse. The total amount of oil used to cover the heating needs for the experimental part was 149.08 l and the corresponding amount for the control one reached 233.03 l. The difference in oil consumption for the whole experimental period was 83.95 l. This result has a great financial and energy saving value considering that the average daily oil saving was 0.91 l.

Since the experiment was spread over three months as previously described, in order to display the daily temperature conditions, a typical 24 h period was selected for the diagrammatic representation of the results. As shown in Fig. 4, for the first eight hours of the day air temperature in the experimental part of the greenhouse was about 1°C higher than that of the control one. For the same time it was observed that the air temperature in the control part was below the critical point of 16°C for longer period resulting in further energy consumption in order to cover its thermal needs.

As previously mentioned, the hybrid solar energy saving system absorbs part of the solar radiation entering the greenhouse during the day and consequently, excess transmitted solar heat is passively stored in the water contained in the PE sleeves. Thus, the maximum air temperature in the experimental part reached 29.50°C, while in the control one reached 32.76°C. In the afternoon external air temperature began to drop at 17:00 h. From Fig. 4 it can be observed that the air temperature value was rapidly decreased in the control compartment. Instead, in the experimental part the

T a b l e 1. Total operation time of the boiler and oil consumption for heating the experimental and the control part of the greenhouse, from 1st March until 31st May

Month	Experimental part of the greenhouse		Control part of the greenhouse		Time difference (h)	Oil consumption difference (l)
	Total boiler operation time (h)	Oil consumption[a] (l)	Total boiler operation time (h)	Oil consumption[a] (l)		
March	89.03	91.61	126.70	130.37	37.67	38.76
April	54.86	56.45	92.19	94.86	37.33	38.41
May	0.99	1.02	7.57	7.79	6.58	6.77
Total	144.88	149.08	226.46	233.03	81.58	83.95

[a] Oil consumption was estimated by multiplying the total boiler operation time with the oil consumption for the specific boiler, according to its technical specifications.

air temperature decrease was smoother due to the presence of the HSESS. This can be explained by the fact that, stored heat in the water contained in the PE sleeves is transmitted by natural convection and radiation to the greenhouse environment when the air temperature inside the greenhouse is lower than that of the water. Also, the circulating air is reaching warmer to the plant level due to the common contact surface of the perforated tubes with the PE sleeve. As a result, the greenhouse air temperature was maintained at higher level values overnight.

Optimum root zone temperature is beneficial for plant growth and increases crop yields. Figure 5 shows the temperature variations of the rockwool slabs in both parts of the greenhouse, the external air temperature and the water temperature in the PE sleeves on April 1. From this figure it is noted that, during the night, the minimum substrate temperature, and therefore the root temperature, in the experimental part was 18.60°C, while in the control one was 16.97°C. During the day the maximum substrate temperature in the experimental compartment was 25.07°C, while in the control one reached 29.15°C. In the experimental part the substrate temperature variation was 6.47°C and the corresponding variation of the control one was 12.18°C.

This difference occurred due to the placement of the rockwool slabs above the PE sleeves and indicates that the root zone temperature variation was closer to optimum.

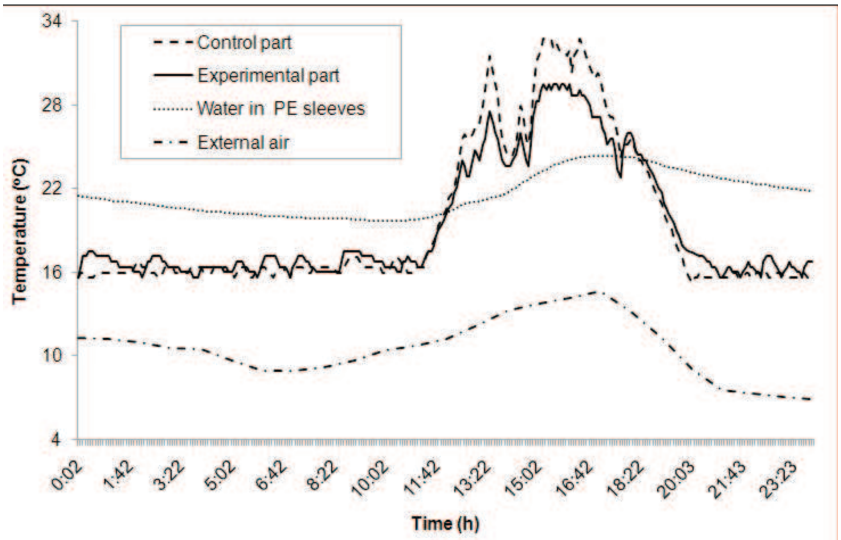

Fig. 4. Variation of the greenhouse parts air temperature, water temperature in plastic sleeves and external air temperature on April 1.

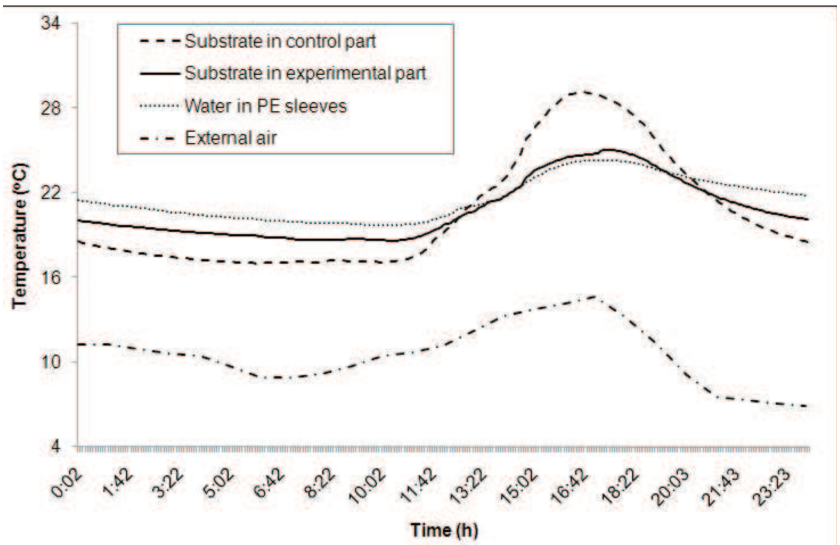

Fig. 5. Variation of the greenhouse parts substrate temperature, water temperature in PE sleeves and external air temperature on April 1.

In order to study the influence of the HSESS to the crop, all the other factors affecting plant growth remained the same. The nutrient solution supply was simultaneous in both compartments and in equal quantities and intervals. Moreover, cultivation practises were the same for all plants. During the research plant height and stem perimeter were measured. The crop precocity was studied by recording the formation time period of the first flower and fruit. To avoid errors, the plants of the external lines of each crop were excluded from the measurements, since the microclimate is more stable and homogeneous in the central area of a crop than in the periphery (Fig. 1).

The PE sleeves, due to their innovating structure resulted in the recirculation of the internal air and thereby more homogeneous microclimate conditions were achieved. Optimum temperature and recirculation of the greenhouse air are critical factors for the growth of stems and leaves of the plants.

The analysis of the recorded measurements indicated that the tomato crop in the experimental part of the greenhouse presented earlier plant growth. At the end of the research, the tomato plants demonstrated an average height of 197.67 cm in the experimental part, and 172.67 cm in the control one. The difference of the height was rated at 12.65%. As far as the stem perimeter measurement concerns, there was a slight diversification of approximately 2.37% at a height of 10 cm on the stem, i.e. the average stem perimeter was 7.03 cm in the experimental compartment and 6.86 cm in the control one.

The flowering and fruiting start period was calculated from the date of the seed germination in the substrate. The tomato plants in both experimental and control parts of the greenhouse revealed the first flower from 01/04 to 07/04. The first flower appeared after 48 days on average after the seed germination in the experimental part, and after 49 days on average in the control part. Therefore, there was no significant variation in terms of first flowering. The first tomato fruit formation in the experimental part was observed from 07/04 to 14/04, while in the control one from 07/04 to 15/04. The fruiting in the experimental part started after 55 days on average, compared to the fruiting in the control one where the first fruit appeared after 56 days on average. So, there was no important difference concerning to the time period of the first fruit formation between the two compartments.

Therefore, for hydroponic tomato cultivation, although the plant growth recorded statistically significant difference between the two studied parts of the greenhouse, no statistically significant difference was observed during the stage of first flower and fruit formation.

The presented results indicate the HSESS importance not only as an energy saving technology but also as a significant contributor to the farmer's income. The only parameter that should be taken into account, for the evaluation of the HSESS economic feasibility, is the installation cost due to the fact that this system does not have a significant functional cost. The installation cost is considerably low compared with the amount of oil saving, in order to cover the thermal needs of the greenhouse. The difference in average oil consumption per one ha of greenhouse was calculated to be 130.00 l day^{-1}. Hence, during the experimental period the total oil saving would be 11 192.86 l, highlighting the use of HSESS as a profitable solution to the producer. The economic efficiency of this system is directly related to the amount of the energy saving achieved and thus it may be either higher or lower.

CONCLUSIONS

1. The experimental part of the greenhouse, where the hybrid solar energy saving system was installed, demonstrated up to 36% energy saving for the total research period.
2. The use of hybrid solar energy saving system results in a considerable reduction of oil consumption. During this experiment the oil reduction was calculated to be 83.95 l for the total experimental period. The daily fuel saving amount was on average 0.91 l. Additionally, in a greenhouse that sizes 1 ha, the oil consumption would be decreased by 11 192.86 l that is on average 130.00 l day^{-1}.
3. The hybrid solar energy saving system contributed in a smoother air temperature variation and also in the rockwool slab temperature.
4. Furthermore, the smoother temperature variation resulted in more favourable plant growth conditions. Between the two studied compartments of the greenhouse there was statistically significant difference in growth, rated at 12.65% in plant height and 2.37% in stem perimeter. No statistically significant difference was observed for the period until the first flower and the period until the first fruit formation.
5. Among the several existing solar systems for greenhouse heating, the investigated hybrid solar energy saving system appears to be of a great interest, because of its simplicity, the combined use (hydroponic and energy saving application) and the high efficiency on solar energy exploitation. Also this system overcomes the specific difficulties that other systems present *eg* lesser ground space.

ACKNOWLEDGMENTS

The Authors would like to acknowledge the 'Geothermiki S.A.' for co-financing this project and for the technical assistance.

REFERENCES

Bartzanas T., Tchamitchian M., and Kittas C., 2005. Influence of the heating method on greenhouse microclimate and energy consumption. Biosys. Eng., 91(4), 487-499.

Grafiadellis M. and Traka-Mavrona E., 1999. Heating greenhouses with solar energy-new trends and developments. In: Protected Cultivation in the Mediterranean Region (Ed. R., Choukr-Allah). CIHEAM Press, Paris, France.

Hanan J.J., 1998. Greenhouses Advanced Technology for Protected Horticulture. CRC Press, Boca Raton, FL, USA.

Kondili E. and Kaldellis J.K., 2006. Optimal design of geothermal-solar greenhouses for the minimisation of fossil fuel consumption. Appl. Thermal Eng., 26(8-9), 905-915.

Lund J.W., Freeston D.H., and Boyd T.L., 2005. Direct application of geothermal energy: worldwide review. Geothermics, 34(6), 691-727.

Mavrogianopoulos G. and Kyritsis S., 1993. Analysis and performance of a greenhouse with water filled passive solar sleeves. Agric. Forest Meteorol., 65, 47-61.

Nikita-Martzopoulou C., 1988. Comparison of geothermal heating systems in greenhouses with tomato crop. Int. Agrophysics, 4, 233-241.

Omid M. and Shafaei A., 2005. Temperature and relative humidity changes inside greenhouse. Int. Agrophysics, 19, 153-158.

Popovski K., 1988. Factors influencing greenhouse heating and geothermal heating systems. Geothermics, 17(1), 173-189.

Santamouris M., Argiriou A., and Vallindras M., 1994a. Design and operation of a low energy consumption passive solar agricultural greenhouse. Solar Energy, 52(5), 371-378.

Santamouris M., Balaras C.A., Dascalaki E., and Vallindras M., 1994b. Passive solar agricultural greenhouses: a world-wide classification and evaluation of technologies and systems used for heating purposes. Solar Energy, 53(5), 411-426.

Sethi V.P. and Sharma S.K., 2007. Thermal modelling of a greenhouse integrated to an aquifer coupled cavity flow heat exchanger system. Solar Energy, 81(6), 723-741.

Sethi V.P. and Sharma S.K., 2008. Survey and evaluation of heating technologies for worldwide agricultural greenhouse applications. Solar Energy, 82(9), 832-859.

Singh R.D. and Tiwari G.N., 2000. Thermal heating of controlled environment greenhouse: a transient analysis. Energy Conversion Manag., 41(5), 505-522.

Zabeltitz Von C., 1994. Effective use of renewable energies for greenhouse heating. Renewable Energy, 5(1), 479-485.