Article

Energy Gain in Passive Solar Greenhouses Due to CO₂ Enrichment

Anastasia Martzopoulou 1, Dimitris Vafiadis 2 and Vassilios P. Fragos 3,*

1 School of Architecture, Aristotle University of Thessaloniki, 54124 Thessaloniki, Greece; amartzopoulou@arch.auth.gr
2 Ministry of Rural Development and Food, Regional Center of Plant protection and Quality Control Thessaloniki, PO Box 60436, 57001 Thermi, Greece; drdimi@gmail.com
3 School of Agriculture, Aristotle University of Thessaloniki, 54124 Thessaloniki, Greece
* Correspondence: fragos@agro.auth.gr; Tel.: +30-231-0-99-1764

Received: 10 February 2020; Accepted: 4 March 2020; Published: 7 March 2020

Abstract: The production cost of greenhouse cultivation depends mainly upon significant amounts of energy consumption in order to keep the optimum environmental condition for plant growth. The expenditure on energy, either for heating or cooling, ranges between 30% to 60% of the total production costs, and any attempt to save energy will result in a positive effect on the potentiality of production accordingly, affecting the greenhouse product prices. Research has shown that CO₂ enrichment in greenhouses significantly increases the yield of most indoor cultivation of plants of the C3 category. For these plants, when the CO₂ concentration increases by three times above that of the atmosphere (380 ppm), the optimum plant growth temperature shifts higher by 5 °C to 10 °C reaching up to 30 °C to 32 °C. Therefore, huge amounts of solar energy can be captured inside the greenhouses, as the ventilation can be decreased. Alongside this, the use of a simple passive solar system consisting of plastic sleeves filled with water is considered to be an improved way to increase the energy inside greenhouses. In this work, three experimental trials were conducted to examine the benefit of the solar energy captured inside a greenhouse during CO₂ enrichment at high temperatures. Finally, a modeling approach based on the heat loss equation was developed in order to establish the energy saving inside the greenhouses under the circumstances mentioned.

Keywords: energy saving; greenhouse; passive solar heating system; CO₂ enrichment

1. Introduction

The cost of heating and cooling are the major sources of production expenditure in order for the optimum indoor climatic conditions to prevail for both better quality and higher yield. During the main cultivation periods of spring and autumn, the day and night temperatures inside a greenhouse are frequently not kept at the optimum levels and are characterized by a wide variation; this indicates the necessity of daytime cooling and overnight heating. The cost of energy consumed ranges from around 50% of the total production costs, and this percentage may rise to 80% during cold periods of the year; this fact is shown in the prices of the product, which in many cases are a great deal higher in winter than in summer. Therefore, any effort to save energy has a positive effect on the potentiality of production and in the prices of greenhouse products.

CO₂ concentration is one of the main factors which affects plant growth. The ambient CO₂ level is about 380 ppm by volume. For the majority of greenhouse crops, photosynthesis increases as CO₂ levels increase from 380 ppm to 1000 ppm. On the other hand, any actively growing crop, in a greenhouse with no ventilation, can reduce the CO₂ concentration in the air during the day to as low
as 200 ppm. Therefore, ventilation is needed to permit the outside air to enter the greenhouse to enable the level of CO₂ to be kept at least around the same as that of the atmosphere.

Another more intensive way to increase the CO₂ level inside greenhouses is by introducing CO₂ enrichment directly into the plants. Some experiments have shown that CO₂ enrichment increases the yields by 12% to 25% for different crops such as cucumber, sweet pepper, green bean and tomato [1–3]. Other studies present even higher yields for specific crops along with the CO₂; for example, tomato crops had a production increase ranging from 30% to 70% [4–8]. Similar behavior is presented by pepper and aubergine cultivation [8–10], and also other works referring to cucumber cultivation showed a production increase of between 25% and 50% [8,11–13]. For floriculture plants, the benefit of CO₂ enrichment is reflected mainly in the quality amelioration [14–17].

All the crops mentioned above, as with most of those cultivated in greenhouses, belong to the category of C₃ plants which grow under optimum day temperatures ranging from 16 °C to 25 °C, and at night from 14 °C to 18 °C [18]; this emphasizes the necessity of daytime cooling and overnight heating be taken into consideration and the awareness that the most favorable periods for the cultivation of greenhouse crops are the spring and autumn. Experiments have shown that when the CO₂ concentration is increased to about a threefold level rather than the usual 380 ppm, the optimum temperature for the growth of most of the C₃ plants shifts higher by 5 °C to 10 °C, reaching 30 °C to 32 °C [19–21]. This phenomenon enables the movement of the starting point of ventilation to a higher temperature with a simultaneous application of CO₂, increasing the hours of feasible enrichment during the day and also the days over a year. In this way, the duration of ventilation is reduced, resulting in the maintenance of high temperatures inside greenhouses due to the higher collection of solar energy.

Additionally, efficient ways to increase the temperature inside a greenhouse are the use of passive solar heating systems. Taking into account that most greenhouses are heated with fossil fuels, passive solar systems are considered great options in the concept of energy transition and the importance of changing the dominance of fossil fuels [22]. The most widespread passive solar heating system used in greenhouses is composed of transparent, water-filled polythene sleeves [23]. The main advantage of this system is its low cost and easy placing. Scientific research, conducted mainly in Mediterranean countries for many years, has revealed that the air temperature inside greenhouses with this system was higher by 6 °C compared to those of greenhouses without it, and up to 8 °C above the outside temperature [24–35]. In any case, solar water heating systems may significantly reduce the auxiliary heating and its respective operation cost [36].

In recent years research has focused on energy-saving methods in many sectors. The use of solar energy to replace conventional fuels, protect the environment and reduce production costs in the agricultural sector is of great interest. However, to date, and according to international literature, no research has been conducted on the contribution of CO₂ enrichment to greenhouse energy saving. This is the first time such an approach has been attempted. Notably, this research examines the possibility of a better exploitation of solar energy, due to a longer period of collection inside the greenhouse during CO₂ enrichment, taking into consideration, firstly only the thermal capacity of the greenhouse itself and also, during a second stage, the thermal capacity of a passive solar heating system composed of plastic sleeves filled with water.

2. Materials and Methods

2.1. Greenhouse and Passive Solar System Description—Instrumentation

This research work was carried out in a N–S orientated, modified double arch-type greenhouse at the Centre of Agricultural Structures Control, located on the Farm of AUTH (40°32′ N latitude and 22°59′ E longitude), in Thermi, Thessaloniki, Greece. The greenhouse was divided into two identical plots, namely experimental and control, separated by a fully ventilated gap of 2.0 m. Each plot had a total area of 140.0 m² (10.0 m × 14.0 m), and the gap was 2.0 m × 14.0 m (Figure 1). The side and ridge
heights of the greenhouse plots were 2.1 m and 3.6 m, respectively. UV stabilized polyethylene (PE) was chosen for the greenhouse cover, and at the doors inside the greenhouse, polyethylene curtains were placed to avoid heat losses and CO$_2$ leaks. Both plots had two openings for natural ventilation, one facing the west and the other on the east side.

The passive solar system was composed of transparent, water-filled cylindrical polyethylene sleeves of 150 μ thickness (Figure 1). Each sleeve was 8.0 m long, with a perimeter of 1.20 m (ϕ 38.2). A total of 8 sleeves were used between the rows of plants and were placed on a black plastic film that covered the greenhouse soil in order to prevent weed growth and to increase absorption of the incident solar radiation. Each sleeve was filled with a total of 916 L of water, and in order to avoid algae species growth, CuSO$_4$·5H$_2$O in a quantity of 0.016 g/L water was dissolved in the water. During the day, the water was heated up from the solar radiation that entered the greenhouse, and therefore thermal energy was stored in the system. When the indoor air temperature fell below the water temperature, then the stored heat was released by conduction, convection and radiation [37].

The instruments used in the experiments (Figure 1) were:

- Twelve temperature sensors (PT-100 type), 4 for the air, 4 for the soil and 4 for the water, inside the greenhouses.

Figure 1. Greenhouse ground plan.
• An inside CO\textsubscript{2} sensor (double beam infrared CO\textsubscript{2} analyzer).
• An inside pyranometer (class A).
• Two inside humidity–temperature sensors (HOBO H8).
• An outside weather station equipped with a wind gauge, a wind indicator, a thermometer, a pyranometer and a humidity meter.

The inside values of the temperature sensors were measured every 10 s of the pyranometer every 5 s and of the CO\textsubscript{2} sensor every second. The measurements were stored using a computer-based data acquisition system (Data logger CR-10). Both greenhouses were equipped with fully computerized irrigation and fertilization systems.

2.2. The System and Application of CO\textsubscript{2} Enrichment—Ventilation of Greenhouses

The CO\textsubscript{2} enrichment took place only in the experimental greenhouse using a pipeline between the plant rows (Figure 1). This pipeline was composed of one main 10.0 m long pipe and 8 CO\textsubscript{2} distribution pipes each 8.0 m long. All pipes were made of black polyethylene with the same \( \phi \)16 mm diameter; this pipeline was suspended at a height of 0.5 m from the soil, and the distribution pipes had holes every half meter, facing downwards. The CO\textsubscript{2} was coming from a 35 kg capacity bottle located in the space between the two greenhouse plots. A CO\textsubscript{2} and acetylene compressed gas cylinder regulator of 200 bars helped the regular flow of the gas, as it had been compressed in liquid form.

At sunrise and before solar radiation reached the CO\textsubscript{2} compensation point, which is, in fact, the CO\textsubscript{2} concentration when the photosynthetic rate equals the respiratory rate (net photosynthesis equals zero), a short ventilation was carried out to remove the accumulated night humidity. The CO\textsubscript{2} compensation point was reached during early morning and late evenings, and for most C3 plants was 10 W.m\(^{-2}\) PAR, which was the photosynthetically active radiation [38]. The pyranometer measured the total horizontal solar radiation in W.m\(^{-2}\), and PAR was 42.9\% of it [23]; therefore, to determine the CO\textsubscript{2} compensation point, the total solar radiation measured by the pyranometer was multiplied by 0.429. After closing the windows of the two greenhouses, CO\textsubscript{2} enrichment in the experimental greenhouse was realized as long as the temperature was kept at desired levels. The aim was to maintain the CO\textsubscript{2} concentration at a level of 1000 ppm (about a threefold level higher than the usual concentration of 380 ppm).

The ventilation was controlled automatically, and the starting point was set at 23 °C for the control greenhouse and at 30 °C for the experimental one. The ventilation was turned off when the temperature of the control greenhouse fell below 20 °C, and that of the experimental greenhouse dropped to 25 °C; this was followed by a new cycle of enrichment. Exceptionally, when the temperature conditions permitted only morning and afternoon enrichments, the starting point of the last one was at 27 °C since the oncoming sunset did not permit the temperature to rise above 30 °C to 32 °C after the windows were closed. For this reason, the CO\textsubscript{2} enrichment ceased when solar radiation intensity arrived at the CO\textsubscript{2} compensation point. Also, when the relative humidity, very rarely overcame the desired level of 75–80\%, a short period of ventilation, before sunset, assisted the decrease in greenhouse air humidity.

2.3. Experimental Methods

Three experimental stages were considered to examine the benefit of the solar energy captured inside a greenhouse due to the CO\textsubscript{2} enrichment at high temperatures. The first stage was carried out during the spring of the first year, where the effect of the contribution of CO\textsubscript{2} enrichment on the energy balance of the experimental greenhouse was studied. In this stage, no passive solar system was incorporated, and only the greenhouse thermal capacity was taken into consideration. The duration of this experimental stage was 42 days, and the second experimental stage lasted 39 days during the autumn following the installation of the above mentioned passive solar system. In this experimental stage, the thermal capacity of the passive solar system was considered, and the third experimental stage was a replica of the second one and was carried out in the next spring with a duration of 28 days.
The selected crops during the experiments were pepper, tomato and cucumber. A total of 900 plants were used, 300 in each experiment. In the two experiments during the spring period of two successive years, the pepper and tomato plants in the first year and pepper and cucumber plants in the second were combined. In the experiment, during the autumn period, a combination of pepper and cucumber plants was used and the arrangement of the plants is shown in Figure 1.

2.4. Modeling the Energy Saving

The mathematical expression of the energy saving with the CO\(_2\) enrichment at high temperatures, resulting in fossil fuel saving, is made by the following methodology.

The temperatures of the air and soil in the two greenhouse plots were recorded and presented graphically every half an hour, each night. Calculating the heat loss of each greenhouse plot during the night, the difference in energy storage between them is possible to be estimated. The greenhouse heat loss is given as follows:

\[ q = \frac{A_c}{A_g} \cdot U \cdot (T_i - T_o) \]  
(1)

where

- \( q \) = rate of heat flow, W \( \cdot \) m\(^{-2} \)
- \( A_c \) = polyethylene surface area, m\(^2\)
- \( A_g \) = ground surface area, m\(^2\)
- \( U \) = overall heat transfer coefficient, W \( \cdot \) m\(^{-2} \) \( \cdot \) °C\(^{-1}\)
- \( T_i \) = inside air temperature, °C
- \( T_o \) = outside air temperature, °C

According to the structural components of the control and experimental greenhouses, the surface of the cover material \( (A_c) \) and the ground surface \( (A_g) \) of each greenhouse amount to 289.08 m\(^2\) and 140 m\(^2\) respectively. The value of the total heat transfer coefficient is equal to 6.8 W \( \cdot \) m\(^{-2} \) \( \cdot \) °C\(^{-1}\), [23].

With the application of Equation (1) considering the air temperature recorded during the night, in the two plots, the energy diagrams were produced. The difference in the amount of energy between the control and experimental greenhouses for its minutes, which is presented as the dark brown area, is given in the following equation:

\[ \Delta E = E_{exp} - E_{ctr} = \int_{it}^{d} q_{exp} \, dt - \int_{it}^{d} q_{ctr} \, dt \]  
(2)

where

- \( \Delta E \) = energy difference, W \( \cdot \) min \( \cdot \) m\(^{-2}\)
- \( E_{exp} \) = the surface enclosed by the heat flow curve \( q_{exp} \) (experimental region,)
- \( E_{ctr} \) = the surface enclosed by the heat flow curve \( q_{ctr} \) (control region,)
- \( it \) = night-time/day, min

The integral (2) was calculated using the MATLAB program, of MathWorks Corporation.

3. Results and Discussion

3.1. First Experimental Stage, During the Spring—No Passive Solar System

The recording of temperatures started at the beginning of April and terminated in the middle of May, when the air temperature inside the greenhouse rose above 16 °C during the night for three successive nights. Normally, at the beginning of this period, artificial heating is applied to the commercial greenhouses in order to maintain the air temperature to at least above 12 °C; therefore, this study gave the opportunity to ascertain the effects of the artificial heating that was reduced during the spring cultivation period. To examine the effect of CO\(_2\) enrichment at high temperatures on energy
saving, the air and soil temperatures of the two greenhouses were recorded each night. The duration of the enrichment ranged from 3 to 10 h during the day, while the difference in the ventilation period ranged from 3 to 8 h per day.

The results collected from all the nights during the experimental trial allow the conclusion to be drawn that the air temperature of the experimental greenhouse was up to 1.6 °C higher than that of the control greenhouse. The soil temperature of the experimental greenhouse was, also, correspondingly higher by 2.6 °C.

Figure 2 presents the air, soil and ambient temperatures of the two greenhouse plots during the night between April 17 and 18. The air temperature of the control greenhouse dropped to 16.3 °C at 22:15, while that of the experimental greenhouse was one hour later, at 23:35. The temperature of the control greenhouse fell below 10.9 °C at 06:15 a.m., while that of the experimental greenhouse was found to be 11.8 °C at the same time just before sunrise. Figure 2 shows that at 20:15, near sunset the ambient temperature was 11.0 °C, the air temperature of the experimental greenhouse was 19.9 °C and that of the control greenhouse was 18.5 °C.

During the 42 nights of this experimental trial and taking into consideration that 16 °C was the optimum night temperature and thus the temperature for the beginning of artificial heating, it was found that there was no need for artificial heating in the experimental greenhouse for 8 nights. During the remaining period, the necessary heating of the experimental plot started 0.5 to 4 h later than that of the control greenhouse, resulting in corresponding energy savings.

Applying Equations (1) and (2), the energy diagram in Figure 3 shows the energy gained in the experimental greenhouse. The solution of Equation (2) for a night-time (it) 600 min/night presents the difference in energy gain between the two greenhouse plots and this is represented by the dark brown area (Figure 3). From the above findings, it was concluded that under the existing conditions, the energy captured in the experimental greenhouse was 0.83 kWh·m\(^{-2}\), whereas that of the control greenhouse was 0.67 kWh·m\(^{-2}\); therefore, the experimental greenhouse captured 0.67 kWh·m\(^{-2}\) or 23.8% more energy than the control greenhouse. For the whole greenhouse area (140.0 m\(^2\)), during the night, the above difference is 22.4 kWh/night, or 1.93 kgoe (kg oil equivalent)/night [39].
Throughout the whole period of this experimental trial, the total energy in the experimental greenhouse, ranged from 6.9 kWh/night to 25.1 kWh/night, higher than that of the control greenhouse, with a mean value of 16 kWh/night (1.38 kgoe/night). For a greenhouse of 1.0 ha the energy difference between the two greenhouses is 1142.9 kWh/night or 98.3 kg oil equivalent/night. For the 42 nights, this energy difference is 48.0 MWh·ha$^{-1}$ or 4.13 toe (tonnes oil equivalent) per hectare.

3.2. Second Experimental Stage, During the Autumn

The passive solar system was installed in the two greenhouse plots and was used during autumn. In this period, cultivation is usually over in commercial greenhouses due to the necessity of artificial heating. Accordingly, the experimental trials of this stage aimed to discover whether an elongation of the cultivation period would be possible with a considerable reduction of supplementary artificial heat, which begins when the air temperature falls below 16 °C during the night before sunrise.

The ventilation of the experimental greenhouse started when the air temperature reached 30 °C and in the control greenhouse at 23 °C. In this way, the passive solar system of the experimental greenhouse collected more solar energy on the condition that CO$_2$ enrichment was kept at high levels.

The duration of this stage was 39 days, and the experimental procedure and measurements of three representative nights of this experimental period appear below. The first night was in the second half of October (23 to 24), the second in the first half of November (5 to 6), and the third in the second half of November (19 to 20).

The CO$_2$ enrichment of the experimental greenhouse was feasible only in the morning and afternoon on October 23 for 3 h and 30 min due to prevailing high temperatures; thus, the windows of the experimental greenhouse remained closed for 3 h 15 min longer than those of the control greenhouse. The windows of the experimental greenhouse remained closed for a longer time on November 5 compared to the length of time on October 23. In fact, the windows of the experimental greenhouse remained closed for 7 h and 30 min longer than those in the control greenhouse; this resulted in a greater difference in air temperature between the greenhouse plots during the night of November 5 to 6 compared to that of the night of October 23 to 24.

The CO$_2$ enrichment in the experimental greenhouse on the night of November 19 to 20 of November was feasible for 3 h and 50 min and continued for 20 min longer than that of the night, October 23 to 24.
Temperature recordings of air, water sleeves and soil in the two greenhouse plots were taken in order to examine whether CO$_2$ enrichment resulted in the amelioration of the passive solar system efficiency. Figures 4–6 present the abovementioned recordings for the three nights.

The ambient temperature drop was normal during the first two nights selected from October 23 to 24 and November 5 to 6, as for most of the nights in this period. There was a normal temperature drop during these nights. However, some nights presented severe ambient temperature variations, such as those appearing on the night of November 19 to 20 (Figure 6). These variations had a respective influence on the indoor temperatures of the two greenhouses, with more intense variations appearing in the control greenhouse. The latter was especially clear after 02:40 when the ambient temperature started to decrease at a more intense rate. The softer air temperature variations in the experimental greenhouse were beneficial for the plants since this helps them to adapt normally to the temperature conditions. Similar findings were valid for the temperature of water sleeves and soil.

Within the whole experimental period of this stage, the air temperature difference between the two greenhouses ranged from 0.3 °C to 2.2 °C, while the soil temperature difference ranged from 1.1 °C to 3.9 °C.

Figure 4 shows that at 18:20, towards sunset, on the evening of October 23, the ambient air temperature was 4.8 °C, the air temperature of the experimental greenhouse was 11.8 °C and that of the control greenhouse was 10.9 °C. The temperatures in the two plots, just before sunrise on October 24 was 5.9 °C and 5.6 °C, respectively. The water and soil evening temperatures of the experimental greenhouse was 24.4 °C and 12.9 °C, and the morning temperatures 12.7 °C and 11.1 °C, correspondingly. With an ambient temperature of 14.2 °C at 18:30 towards sunset on the evening of November 5, the air temperature of experimental greenhouse was 21.9 °C and that of the control greenhouse was 19.3 °C. The respective temperatures in the two plots just before the sunrise on November 6 were 5.9 °C and 5.6 °C. The water and soil evening temperatures of the experimental greenhouse were 14.4 °C and 12.9 °C and the morning temperatures 12.7 °C and 11.1 °C, correspondingly (Figure 5).

Finally, around sunset on the evening of November 19, the ambient temperature at 18:00 was 12.5 °C, the air temperature inside the experimental greenhouse was 15.3 °C and that of the control greenhouse was 14.2 °C. The respective temperatures in the two plots before the sunrise on November 20 was 7.4 °C and 6.6 °C. The water and soil evening temperatures in the experimental greenhouse was 17.4 °C and 16.4 °C, and the morning temperatures were 15.7 °C and 14.7 °C, correspondingly (Figure 6).

The ambient temperature drop was normal during the first two nights selected from October 23 to 24 and November 5 to 6, as for most of the nights in this period. There was a normal temperature drop...
variation inside the two greenhouses, although the temperature at 01:50 a.m. on October 24 was below zero, falling to −0.4 °C (Figures 4 and 5). However, some nights presented severe ambient temperature variations, such as those appearing on the night of November 19 to 20 (Figure 6). These variations had a respective influence on the indoor temperatures of the two greenhouses, with more intense variations appearing in the control greenhouse. The latter was especially clear after 02:40 when the ambient temperature started to decrease at a more intense rate. The softer air temperature variations in the experimental greenhouse were beneficial for the plants since this helps them to adapt normally to the temperature conditions. Similar findings were valid for the temperature of water sleeves and soil.

Finally, around sunset on the evening of November 19, the ambient temperature at 18:00 was 12.5 °C, the air temperature inside the experimental greenhouse was 15.3 °C and that of the control greenhouse was 14.2 °C. The respective temperatures in the two plots before the sunrise on November 20 was 7.4 °C and 6.6 °C. The water and soil evening temperatures in the experimental greenhouse was 17.4 °C and 16.4 °C, and the morning temperatures were 15.7 °C and 14.7 °C, correspondingly (Figure 6).

In this experimental period for all the nights from October 18 to November 25, the optimum artificial heating starting temperature was 16 °C as the mean value of the optimum night temperature for C3 plants. During this period, it was found that there was no artificial heating requirement for 14
nights in the experimental greenhouse, while artificial heating was necessary for the remaining period, but with a delay of 1 to 6 h from the control greenhouse.

Applying Equation (2) for a total of 760 min on the night of October 24, the difference in energy between the two greenhouse plots was calculated, and it is shown in the dark area in Figure 7. This difference came to 6140 W·min·m$^{-2}$ per night, and the total greenhouse area (140 m$^2$) was 14.3 kWh per night, which was equal to a 1.23 kg oil equivalent per night. From the above findings, it was concluded that under the existing conditions, the experimental greenhouse captured 8.5% more energy than that of the control greenhouse.

Following the same procedure as above on the night of November 5 to 6, for a total of 840 min (Figure 8), the difference in energy between the two greenhouse plots came to 22.0 kW·min·m$^{-2}$ or 33.1% of that of the control greenhouse or 51.3 kWh/night for the total area.
The experimental trial from the night of November 19 to 20 is characterized by the effect of a sudden drop in the ambient temperature and a greater increase of the energy difference between the experimental and the control greenhouse from 03:20 a.m. to 08:00 a.m.; this phenomenon is explained by the parallel response of the indoor temperature of the control greenhouse to the change in the ambient temperature, unlike that of the experimental greenhouse.

The diagram of Figure 9 was created from Equation (2). During the night of this trial, for a total of 880 min (Figure 9), a difference of 12.32 W·min·m$^{-2}$ or 60.5% in energy between the two greenhouses was shown. The energy difference in the total area (140 m²) of each greenhouse was 43.12 kWh/night.

![Figure 9](image_url)

**Figure 9.** The energy diagrams of the experimental (q exp) and control greenhouse (q ctr) during 19th to 20th of November.

During the whole period of this experimental stage, the total energy in the experimental greenhouse ranged from 10.6 kWh/night to 58.08 kWh/night, which was higher than that of the control greenhouse with an average value of 34.84 kWh/night. For a greenhouse of 1.0 ha, the difference in energy between the two greenhouse plots was 2467 kWh/night. In the total thirty-nine nights of this experimental stage, the total energy gain due to the CO$_2$ enrichment was 96.2 MWh, which is equal to a mean value of 8.3 toe per hectare.

3.3. Third Experimental Stage, During the Springtime with a Passive Solar System

The third experimental stage took place during the spring following the second experimental stage, with a passive solar system as described before; this trial lasted for twenty-eight days. Differences in the air, water sleeve and soil temperatures between the two greenhouse plots, as well as the ambient temperature, were also established during the nights, and a typical example of these differences is given for the night of the May 3 to 4 in Figure 10. The air temperature differences between the experimental and control greenhouses ranged from 0.9 °C to 2.0 °C. The air temperature of the control greenhouse dropped below 16 °C at 4:35, while that of the experimental greenhouse remained marginally over 16 °C until sunrise. For this reason, only the control greenhouse would require artificial heating. The water sleeve temperature difference between the two greenhouses ranged from 2.5 °C to 3.1 °C, while the soil temperature difference between these greenhouse plots, ranged from 1.9 °C to 2.3 °C from sunset until sunrise. It is worth mentioning that on the previous day, the CO$_2$ enrichment was realized during morning and afternoon, and the windows of the experimental greenhouse remained closed for 3 h and 20 min longer than those of the control greenhouse. Figure 10 shows that at 20:15, near sunset, the outside air temperature was 23.7 °C, the air temperature of the experimental greenhouse was 26.9 °C and that of the control greenhouse was 24.9 °C.
The experimental greenhouse remained closed for 3 h and 20 min longer than those of the control greenhouse. Figure 10 shows that at 20:15, near sunset, the outside air temperature was 23.7 °C, the air temperature of the experimental greenhouse was 26.9 °C and that of the control greenhouse was 24.9 °C.

Applying the Equations (1) and (2) for the night of May 3 to 4, the energy diagram of Figure 11 is produced. From these equations, for a total of 610 min/night, the energy difference between the two greenhouse plots was calculated and is represented in the dark brown area. This difference came up to 8370 W·min·m$^{-2}$, and the total area of the greenhouse (140 m$^2$) was 19.2 kWh/night. From the above findings, it is concluded that under the existing conditions, the experimental greenhouse captures 42.5% more energy than that of the control greenhouse.

For the whole period of this experimental trial, the stored energy in the experimental greenhouse ranged from 15.45 kWh/night to 51.76 kWh/night, higher than that of the control greenhouse, with an average value of 33.1 kWh/night. In a greenhouse area of 1.0 ha, the difference in energy between the two
greenhouse plots was 2364.3 kWh·ha$^{-1}$ per night, with a mean value of oil equivalent 203.3 kg·ha$^{-1}$ per night. Over the 28 nights of this stage, the energy gain due to the CO$_2$ enrichment was 66.2 MWh·ha$^{-1}$ or 5.7 toe per hectare.

3.4. Effect of Relative Humidity and Plant Growth

Measurements of relative humidity were conducted during the described experimental stages, and the result of these showed that the relative humidity could not be considered as a restrictive factor of CO$_2$ enrichment in the greenhouses when the intervals of its application depend upon the air temperature and the intensity of solar radiation [40].

The relative humidity rose above the optimum level of 80% for plant growth in only two cases during the whole experimental period. The first case was noticed during the morning CO$_2$ enrichment with relatively high air temperatures with the crops at an advanced stage of growth. The second case was found when the plants were also at an advanced stage of growth and with the CO$_2$ enrichment being applied continuously for almost a whole day, as the temperature was kept below 30 to 32 °C (during the second half of November).

In all the other cases, the relative humidity did not affect the duration of CO$_2$ enrichment during morning or afternoon. From the present study, it was also established that the CO$_2$ enrichment at high temperatures did not have a harmful effect on plant growth. Vafiadis et al. [41] investigated the growth and productivity of crops after the application of CO$_2$ enrichment and proved that the above treatment was beneficial since apart from the aforementioned energy advantages, there was also a positive effect on plant productivity and growth. In particular, the cultivation of tomatoes showed faster growth, with the average height of the plants being 8.64% higher, and the central stem circumference was wider by 7.76%. The cultivation of cucumbers showed accelerated growth with precocity and an increase in production. There was a shortening of the harvest time by 4 to 10 days, and the produced fruit quantity was by 16.54% and 12.9%, respectively, greater in the two experiments. The cultivation of peppers showed higher productivity by 14.1%, 17.5% and 12.3% in all three experimental periods.

4. Conclusions

The overall conclusion from this research work was that CO$_2$ enrichment at high greenhouse temperatures results in energy saving, mainly during the night, since no use or at least limited use of artificial heating was needed.

From the analysis of the experimental findings, it was concluded that CO$_2$ enrichment played an important role in better exploitation of solar energy for heating greenhouses, either with or without a passive solar system composed of polyethylene sleeves filled with water. The conservation of high levels of CO$_2$ enrichment decreased the ventilation needs of the experimental greenhouse from 3 to 8 h per day, in all the experiments, resulting in its contribution to the collection of more solar energy; this was demonstrated in the air, soil and sleeve water temperatures and the heat loss differences between the experimental and control greenhouse plots, with an area of 140 m$^2$ each, during the night.

The main results of this research are presented below:

1. The temperatures of air, soil and sleeve water of the experimental greenhouse were always higher than those of the control greenhouse in all the experimental stages. The air temperature differences between the experimental and the control greenhouses ranged from 0 °C to 1.55 °C in the first experimental stage during the spring without the assistance of a passive solar system. The air temperature differences in the other two stages, which incorporated the passive solar system, ranged from 0.3 °C to 2.9 °C in the second stage during the autumn and from 0.75 °C to 2.1 °C in the third stage.

2. The temperature variations of soil and water in the solar sleeves were always smoother than in the air temperature in both greenhouse plots; this was due to the higher thermal capacity of soil and water compared to the corresponding air.
3. By calculating the quantity of energy captured at sunset in the two greenhouse plots, it was concluded that the experimental greenhouse captured 10% to 25% more energy than the control greenhouse during springtime without the assistance of a supplementary passive solar system. In all the rest of the experimental trials, the solar energy obtained ranged from 35% to 70% due to the simultaneous use of a passive solar system. The range of energy gain depended on the duration of CO₂ enrichment during the previous day.

4. From the heat loss analysis of the two greenhouses for all the nights during the experiments, it was concluded that the amount of energy gain in the experimental greenhouse was always higher than that of the control greenhouse. In particular, the average value of the total energy difference between the two greenhouse plots was 0.114 kWh·m⁻² per night, without a passive solar system and 0.236 kWh·m⁻² per night with the use of a passive solar system, during the springtime. The average total energy difference between the two plots was 0.249 kWh·m⁻² per night, during autumn, with the incorporation of a passive solar system, which was close to those of the springtime results under similar conditions.

5. The comparison of the results between the first stage experiments and those of the third clarified that the use of a passive solar system expanded the possibility of energy saving with the application of CO₂ enrichment; this is very important, since this specific passive solar system is used worldwide more than any other system collecting solar energy in greenhouses. The conclusion for the energy saving derives from the comparison between the two greenhouse plots for each experimental period. In all three experiments, spring–autumn–spring, there was energy saving due to CO₂ enrichment. This saving was higher with the use of the passive solar system; this is singularly obvious by comparing the mean values of energy saving per night between the first and third experiment which was 16 kWh/night on the first experiment without the passive solar system while on the third experiment with the passive solar system the energy saving came up to 33.1 kWh/night.

6. Finally, it was found that greenhouses with no CO₂ applications are more sensitive to sudden ambient temperature changes than those greenhouses, where CO₂ applied the previous day, reacting to more normal temperature degradation during the following night.

7. Equations (1) and (2) can be used in the future in order to create energy diagrams for greenhouses and to determine energy savings in greenhouses where CO₂ enrichment is applied compared to other non-CO₂ enriched greenhouses.

Author Contributions: A.M.: Conceptualisation, Methodology, Formal Analysis, Visualisation, Writing—original draft; D.V.: Conceptualisation, Investigation, Data curation, Methodology; V.P.F.: Formal Analysis, Visualisation, Writing—review editing. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

References


12. Ito, T. Physiological aspects of carbon dioxide enrichment to cucumber plants grown in greenhouses. *Acta Hort.* 1978, 87, 139–146. [CrossRef]


17. Zeroni, M.; Gale, J. Response of ‘Sonia’ roses to salinity at three levels of ambient CO$_2$. *J. Hort. Sci.* 1989, 64, 503–511. [CrossRef]


© 2020 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).