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Recent Advancements in the Energy Performance of Intelligent Green Houses: A Case Study

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Abstract. According to the European Environment Agency, the agricultural sector consumes around 3% of the total energy consumed in the European Union and specifically 28.8 million tones of oil equivalent in 2016. Although between 2005 and 2016, the final energy consumption in the EU decreased in the fishing, agriculture and forestry sectors by 24.7 % the energy required in this sector is considered to have a significant contribution to the energy related policies of the EU. Greenhouses constitute a major energy consumer of the agricultural sector in the European Union. Although strictly speaking, greenhouses differ from buildings in several ways, such as the construction, the building systems and the use, the principles used to analyse the energy consumption of greenhouses, as well as the strategies to control their energy performance are quite similar with those of the building sector.

This study aims to present the recent advancements in the analysis of the energy performance of greenhouses, with a special focus on next generation greenhouses, also known as intelligent greenhouses. The main energy consumption sources in greenhouses, as well as their normalized intensity is presented. State-of-the-art automations to control the energy performance of greenhouses, as well as intelligent systems used to achieve the required thermal conditions in greenhouses, such as automation systems, infrared heating and advanced covering materials are presented. The main challenges of the intelligent greenhouse sector, as well as the requirements for the development of new energy related standards for greenhouses are also discussed. The study concludes with the presentation of the energy performance of a greenhouse, considered as intelligent, of the Department of Agricultural Technology of the Technological Education Institute of Western Greece in Patras, Greece. Detailed data logging of the temperature and indoor conditions of an intelligent greenhouse are analysed and compared with regard to contemporary greenhouses, revealing and quantifying the potentials of this sector in the energy saving strategies of Greece and the EU.

1. Introduction

The use of machinery equipment and mineral fertilisers has enabled the intensification of agricultural productivity and food supply. The mechanization of agriculture has turned though the sector into a major energy consumer, which contributes to the depletion of fossil sources as well as to the global warming through energy-related emissions. In the EU-28, energy consumption by agriculture made up 2.7 % of the final energy consumption. Among the countries with the highest share of agriculture in their final energy consumption is the Netherlands (7.4 %) and Poland (5.3 %). Oil contributed to 54 % of total energy consumption by agriculture in the EU-28 in 2016 and was the main fuel type in most countries (see Figure 1). [1][2]



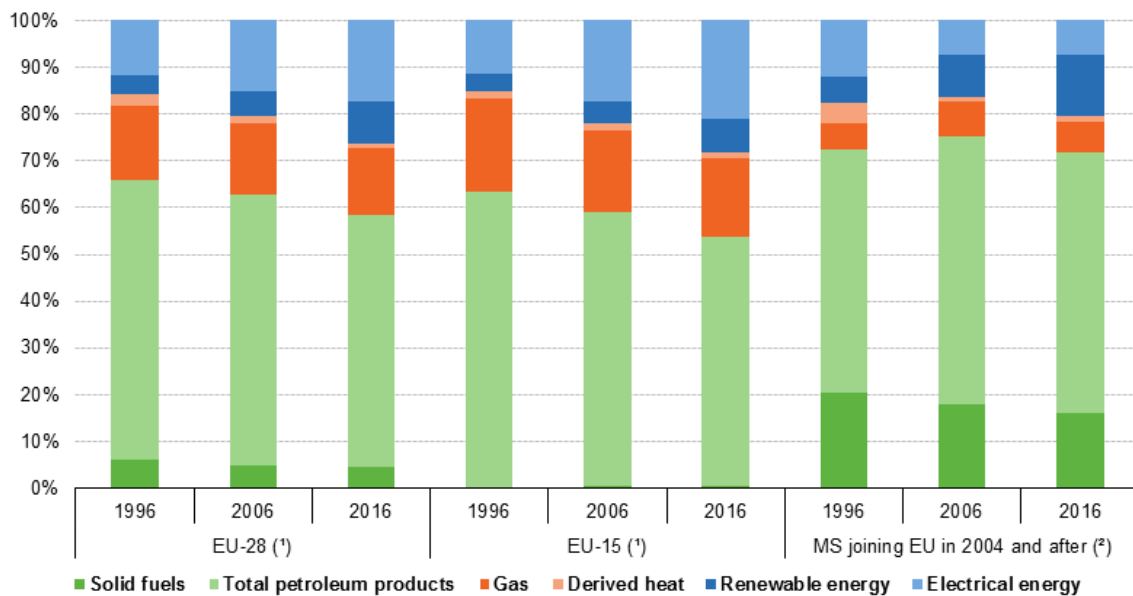


Figure 1 Share of fuel type in energy consumption by agriculture, EU 1996-2016 [1]

Greenhouse crop production constitutes one of the major activities of the agricultural sector. Greenhouses production presents a growing reality throughout Europe and the world with an estimated 405 000 ha of greenhouses spread over all the continents. [3] The experience of greenhouse production, which emerged in northern Europe, stimulated development in other areas of the world.

To facilitate influencing energy consumption levels through policy measures, the factors which influence energy levels in greenhouse crop production should be understood. The temperature of the air, the relative humidity and the solar radiation are the imperative variables of the greenhouse climate that should be controlled. These parameters affect the crop production, as well as the energy consumption of a greenhouse, which can reach up to 40 percent of the total production costs [4]. The majority of plants grown in greenhouses are warm-season species, adapted to average temperatures in the range 17–27 °C, with approximate lower and upper limits of 10 and 35 °C. [3]

- for average ambient temperature of less than 10 °C, the greenhouse will require heating
- for average ambient temperature of less than 27 °C, ventilation will be required in order to prevent excessive internal temperatures
- for average ambient temperature above 27 °C, artificial cooling is required.

In order to achieve these set temperatures under energy saving conditions, it is important to exploit several elements of greenhouses, which include the covering material of the greenhouse, energy efficient heating, cooling and ventilation equipment, as well as other parameters, including the storage of thermal energy and its exploitation when required. Also, the exploitation of non-fossil fuels-based energy technologies, is another significant parameter which may reduce the carbon footprint of greenhouses and turn them into carbon neutral units.

The purpose of this review study is to present the recent advancements in the analysis of the energy performance of greenhouses, with a special focus on next generation greenhouses. An extensive literature review, which presents the current research trends in the field of reduction of greenhouses energy consumption is presented. In this study, the energy related aspects of an intelligent greenhouse at the Department of Agricultural Technology of the Technological Education Institute of Western Greece in Patras, Greece, are also analysed. This study aspires to stimulate the interest of the building physics scientific community to those aspects related to the energy consumption of greenhouses, and to emphasize on the joint issues and challenges of this field and the buildings energy assessment field.

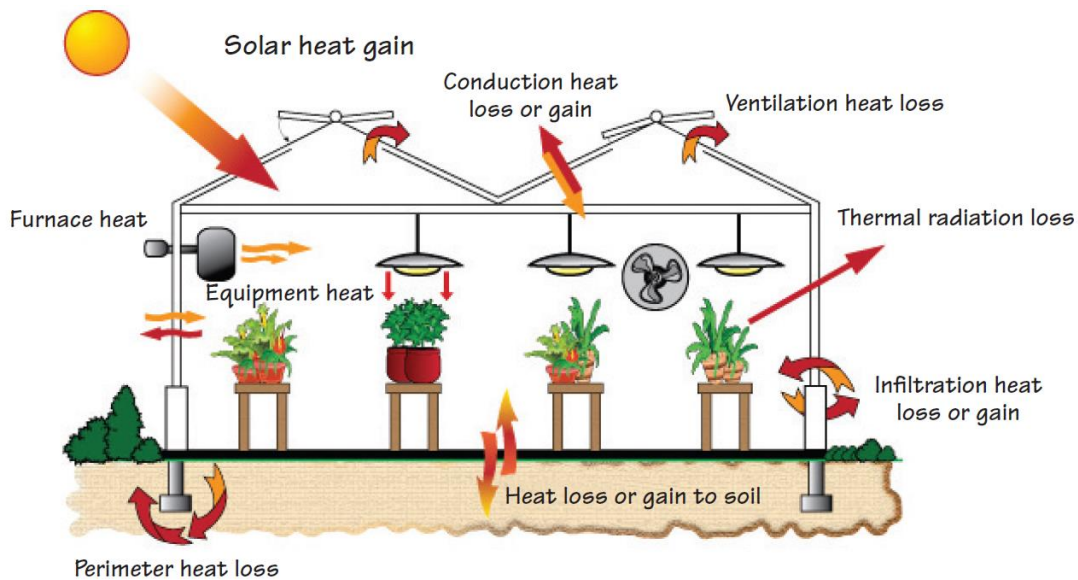


Figure 2 Greenhouse heat loss and gain pathways. [5]

2. Literature Review

In the recent years, numerous studies were implemented, and various configurations were introduced concerning the improvement of the environmental performance of greenhouses. The main trends observed in the literature in this field include

- the installation of renewable energy technologies to satisfy the energy needs of greenhouses [6][7][8][9][10][11][12][13]
- the use of advanced covering materials, as well as Fresnel prisms as greenhouse roofing [14][15][16][17][18][19]
- the adoption of passive techniques to minimize the energy consumption of greenhouses [20][21][22]
- the installation of storage configurations to optimize the energy management in greenhouses [22][23][24]
- the use of advanced simulation tools for the definition of the energy performance, as well as of the indoor microclimate of greenhouses [25][26][27]

2.1 Renewable Energy Technologies in Greenhouses

The location of greenhouses is usually favorable for the use of renewable energy technologies. Greenhouses are usually exposed to elements of nature (sun, wind, earth), allowing the exploitation of technologies related to

- solar energy (photovoltaics, solar thermal panels) [7][8][9][10][11][12]
- wind energy (wind turbines, wind mills) and
- geothermal energy (geothermal heat pumps) [6]

Greenhouses are also producers of agricultural waste, which is a source of biomass and thus biofuels. To this end heating of greenhouses with the use of biomass [13] is also a good practice for the exploitation of renewable energy sources to minimize the carbon footprint of greenhouses.

The use of photovoltaic panels for the fulfilment of the energy requirements of greenhouses has been reported in many studies. Studies concerning the use of PVs for greenhouses are classified in two major fields: studies concerning rigid PVs and studies for semi-transparent or transparent PVs.

Rigid Greenhouse Integrated PVs also constitute a major trend in the scientific studies concerning the use of renewable energies for greenhouses. In a study of Cossu et al. [11], a comprehensive review of the current state-of-art of the PV greenhouse sector is presented. In this study, four representative commercial PV greenhouse types, with a percentage of the area covered with PV panels ranging from 25% to 100%, were assessed. In this study it was concluded that the yearly global radiation in the

greenhouse decreased averagely by 0.8% for each additional 1.0% PV cover ratio and increased by 3.8% for each further meter of gutter height. In this study it was also concluded that the orientation of the greenhouse has a major impact on the solar yield of the investigated PVs. Particularly it was shown that the N-S orientation increased the average cumulated global radiation on the greenhouse area by 24%, compared to the E-W orientation. The findings were much more discouraging in another study of Cossu et al. [9]. In this study the solar radiation and temperature inside an east-west oriented greenhouse with 50% PV coverage, located in Sardinia, Italy, was investigated. The south-oriented roof was completely covered with multicrystalline silicon PV panels, amounting to 68 kWp rated power. A high-light demanding crop was chosen for comparing the environmental data with the achieved yield. The PV array decreased the yearly sunlight availability inside the greenhouse by 64%, compared to the situation without PV panels, while the temperature was averagely 2.8°C higher than outside. The solar radiation under the conventional plastic roof was 305% higher than under the PV roof, causing a high variability of total production between the plant rows, which ranged from 1.9 kg m⁻² in some rows under the PV cover, where plants showed a negative photosynthetic rate (up to -3.72 mmol CO₂ m⁻² s⁻¹), to 5.1 kg m⁻². In this study it was concluded that new design criteria for PV greenhouses, concerning the decrease of the PV array coverage and different installation patterns of the PV panels on the roof were required.

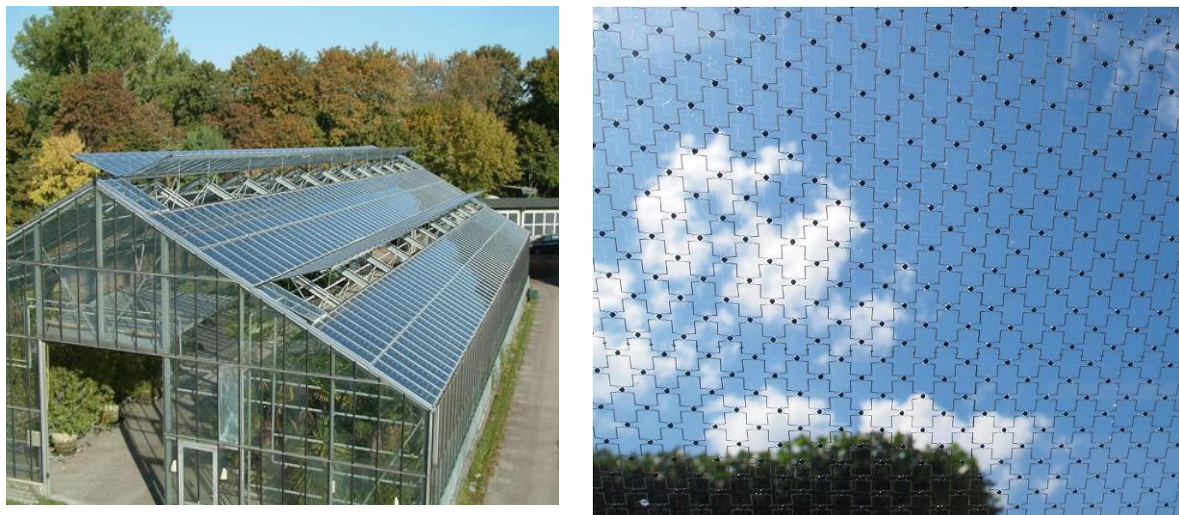


Figure 3 Example of rigid (right) [18] transparent PVs (left) [8] on greenhouses

The current research challenges in the case of the investigation of semitransparent greenhouse integrated photovoltaic modules focuses on the structure of the solar microcells, the coverage percentage, the cells density and the conversion factor. Yano et al. [7] presented two prototypes of semi-transparent-bifacial photovoltaic modules intended for greenhouse roof applications. The modules consisted of 1500 spherical solar microcells (1.8 mm diameter, crystalline silicon) with 15.4 cells cm⁻² density and 500 cells with 5.1 cells cm⁻² density, covering 39% and 13% of the area respectively. The remaining areas were transparent, allowing the most sunlight to enter the greenhouse for promising plant photosynthesis. The peak powers produced by the two configurations were 540 mW and 202 mW for irradiation of 1200 W m⁻² reaching conversion efficiencies of 4.5% and 1.6% respectively. In the study of Cossu et al. [8] prototypes of spherical micro-cells were developed and tested on a real greenhouse roof. The semi-transparent PV module of this study was composed by 4800 spherical silicon micro-cells (1.2 mm diameter) sandwiched between glass plates and integrated on a greenhouse roof with 26.5° slope, with a coverage percentage of 2.3%, reaching 9.7% considering the metallic conductors. The cell density was 2 cells cm⁻² and the measured perpendicular light transmissivity of the semi-transparent area was 73%. The conversion efficiency of the tested module was around 0.2% over wide incident sunlight angle. The yield factor of the semi-transparent module was slightly higher than that of a multi-crystalline silicon module used for comparison in this study, due to the isotropic properties of the spherical cells. Sonneveld et al. [10][12] introduced a novel solution for the exploitation of solar energy in greenhouse coverings, which combines the reflection of near infrared radiation (NIR) with electrical power generation using

hybrid photovoltaic cell/thermal collector modules. Besides the generation of electrical and thermal energy, the reflection of the NIR results in improved climate conditions in the greenhouse. The peak power for Dutch climate circumstances was determined based on the amount of electrical and hot water produced. The typical yearly yield of this greenhouse system was determined as a total power of 20 kW h m^{-2} and heat of 160 kW h m^{-2} with suggested potential improvements which would result to 31 kW h m^{-2} of power and 270 kW h m^{-2} of heat. Should the latter conditions be achieved, the greenhouse would be fossil fuel independent, thus carbon zero.

In addition to the research conducted for the installation of PV panels in greenhouses, research is also conducted for the exploitation of heat pumps for greenhouses, which would exploit low enthalpy geothermal fields for the improvement of the coefficient of performance [6] as well as biomass as sustainable energy for greenhouses heating [13].

2.2 Advanced Covering Materials

Greenhouse covering materials have a significant impact on the greenhouse indoor conditions. Research on the development of alternative materials which can adjust the radiation and the thermal gains in the greenhouse is essential, as the use of such materials can effectively improve the farming conditions as well as reduce the energy needs for space heating, cooling and ventilation. Current research trends in this field include

- the application of Fresnel prisms, [14][18]
- the use of plastics with advanced properties, either due to their texture [15] [16] or due to their composition [16][19]
- the use of claddings [17]

Kurata [14] applied a Fresnel prism to a south roof of an EW-oriented single-span greenhouse. According to the findings of this study, the application of a Fresnel prism increased the light transmissivity in winter and decreased it in summer, revealing though large spatial variations of the light transmissivity in the greenhouse. Tripanagnostopoulos et al. [18] presented the irradiation aspects for the use of glass type fresnel lenses instead of typical glass or plastic covering materials of greenhouses. According to this study, the advantage of the linear Fresnel lenses is that they separate the direct from the diffuse solar radiation, resulting in a suitable configuration for lighting and temperature control of the greenhouse interior space. In this study, design concepts for thermal and photovoltaic absorbers, emphasised to hybrid photovoltaic/thermal type linear absorbers, which convert solar radiation simultaneously into electricity and heat, are also found.

Coverings with advanced properties were recently used in the studies of Sonneveld et al. [15], of Kittas et al. [16] and of Kavga et al. [19]. The scope of the investigation in [15] was the development of a new energy-saving greenhouse with a high light transmittance, using a new Zigzag double-web structure. The novel material fulfilled sufficient light transmittance, insulation properties, material consumed and material strength. The proposed sheet in this study can be built in without glazing bars, combining high light transmittance with good thermal insulation. Kittas et al. [16] tested a twin-span glasshouse and under the same glasshouse with blanked roof, external shading net and internal aluminized shade-screen. In this study, measurements were also implemented under a twin-span polyethylene greenhouse, a multi-span greenhouse with fibreglass and a polyethylene tunnel. For each greenhouse configuration, the measured solar photon flux spectra were used to calculate the solar transmission for the photosynthetically active radiation waveband from 400 to 700 nm, and the near infrared waveband, from 700 to 1100 nm. The results provided a better insight on the quantitative and qualitative properties of the light environment under each greenhouse configuration. These results stressed the need for a more precise characterization of modifications in light quality induced by greenhouse materials. In the study of Kavga et al. [19], polymer prototype nanocomposites were developed through the use of uniform dispersions of highly porous granules, capable of regulating the Photosynthetically Active Radiation (PAR) for a given Infrared (IR) radiation. The investigated nanopowders were processed by a proprietary method for producing heterogeneous granules, which were mixed with Low Density Polyethylene (LDPE) before being processed for film making purposes. The investigated material was

tested against its environmental performance as well as for its nanomechanical behaviour. The findings of this study revealed that the proposed material has such a performance in radiation which allows its employment for temperature tolerant crops and cool growing.

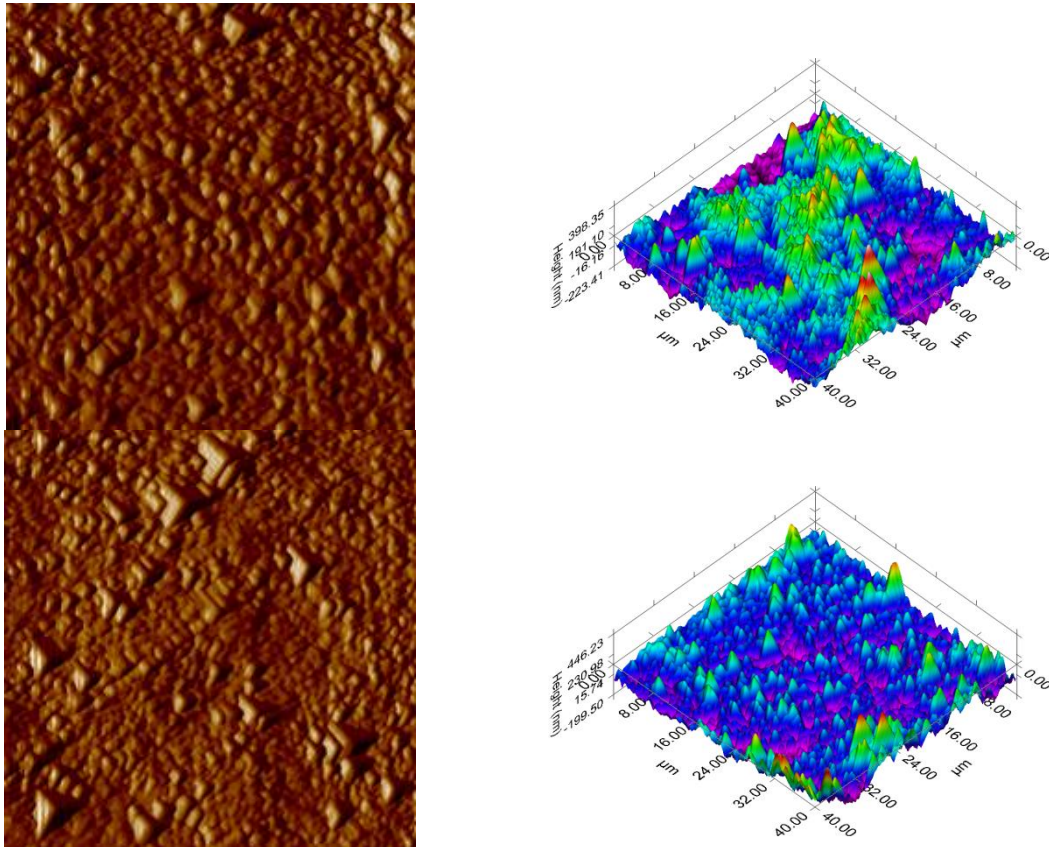


Figure 4: SPM images of reference (*Thermolux*) (top, left and right) and nano (modified with TiO₂ nanoparticles) (bottom, left and right) samples surfaces (40X40 μm^2 scanned area). [19]

Lamnatou and Chemisana [17] presented an overview study regarding specific kinds of cladding materials which may modify the solar radiation entering a greenhouse. Particularly their study presented the results of claddings which modified Red/Far-red (R/FR), Blue/Red (B/R), Blue/Far-red (B/FR) ratios. Their findings revealed that there are some types of covers which have the potential to provide benefits to the greenhouse, provided these are used in a cost-effective way and several critical factors are considered. Additional considerations regarding cladding degradation, greenhouse microclimate in conjunction with the covers etc., were also discussed.

2.3 Passive techniques to minimize the energy consumption of greenhouses

In [20] the Dutch solar greenhouse project which concerns a high value crop production without the use of fossil fuels, was reported. The main approach of this project was highly similar to the approach of nearly zero energy buildings: the design of a greenhouse system requiring much less energy, next to the balance of the availability of natural energy with the system's energy demand. An additional element of the proposed concept concerned the design of a control algorithms for dynamic system control. The steps to achieve this concept were the following:

- the design of an insulation value of the greenhouse cover
- the maintenance of a high light transmission cover
- the exploitation of solar energy from the greenhouse during the summer months

- the storage of heat excess in an underground aquifer at modest temperatures
- the use of the stored energy during the winter months by using heat pumps.

Following the above steps, the energy of the examined greenhouse was reduced 60% compared to the energy required under normal conditions. In this study, the requirements in renewable energies were also calculated, towards a carbon neutral greenhouse.

Ecofys [21] developed and tested a new concept of an integrated climate and energy system for greenhouses. The technical concept consisted of a combined heat and power unit, a heat pump, an underground (aquifer) seasonal energy storage as well as daytime storage, an air treatment unit and air distribution ducts. This concept was demonstrated in a fully closed 1400 m² greenhouse. The results of this study are summarized as follows:

- reduction in primary energy (fossil fuel) use of 20 and 35% respectively
- increase in crop yield of 20%
- 80% reduction in chemical crop protection
- 50% reduction in use of irrigation water.
- energy efficiency improvement by 50%.

Chul-sung et al. [22] examined the climate adaptive shell concept. These shells are capable of changing their thermal and optical properties on an hourly, daily, or seasonal basis to optimize performance. The results provided by this concept were rather positive. In this study it was shown that climate adaptive greenhouse shells increased the net profit between 7% and 20% for crop production. Greenhouse adaptation also resulted in considerable primary energy savings, namely 23% and 37%, respectively.

2.4 Energy storage to optimize the energy management in greenhouses

In northern European countries, greenhouses have to be heated for optimal growing conditions, whereas in the southern countries with the combination of high global radiation and high outdoor temperatures during summer, cooling of greenhouses is needed during this period. Solutions for energy supply in winter and cooling in summer can be combined applying seasonal storage of excess solar energy and exploiting this for heating in winter. [24] Studies concerning energy storage in greenhouses do not present a major trend but are diversified in different scientific fields and different storage technologies. For example in [22] a greenhouse cooling system with heat storage for completely closed greenhouses was demonstrated, assuming the use of a heat exchanger. The performance of the fine wire heat exchangers was tested under laboratory conditions and in a small greenhouse compartment. The effects of the system under the environmental conditions in the greenhouse were simulated to decide on the final layout of the system. The system was also implemented on a large scale in a pot plant greenhouse complex of 2500 m², and compared to a traditional heating and ventilation system. Sonneveld et al. [24] examined the feasibility of a novel approach of a greenhouse design combining cooling with energy supply in such a way that excess solar energy is directly converted to high grade electric energy. In this study, a prototype greenhouse according to this design under construction was also described.

2.5 Advanced simulation tools

Simulation tools for the energy performance of the built environment, as well as to mimic the thermal conditions in a greenhouse constitute an integral part of the energy assessment of the built environment, and in a similar manner of greenhouses. In recent years there are several studies presenting either the adoption of existing software for buildings for the calculation of the indoor conditions in greenhouses, or the development of new tools and algorithms for this purpose. Fitz-Rodríguez et al. [25] presented an interactive, dynamic greenhouse environment simulator. This greenhouse environment model, based on energy and mass balance principles, was implemented in a web-based interactive application that allowed for the selection of the greenhouse design, weather conditions, and operational strategies. The greenhouse environment simulator was designed to be used as an educational tool for demonstrating the physics of greenhouse systems and environmental control principles. In the study of Lee et al. [26] the possibility of using BES, a software used for the simulation of the energy performance of buildings, is

explored for the evaluation of commercial agricultural greenhouses, focusing on the necessary adaptations and additional models required to obtain reliable results. In this study the evaluation of the relevant physical phenomena for energy performance of greenhouses are also evaluated.

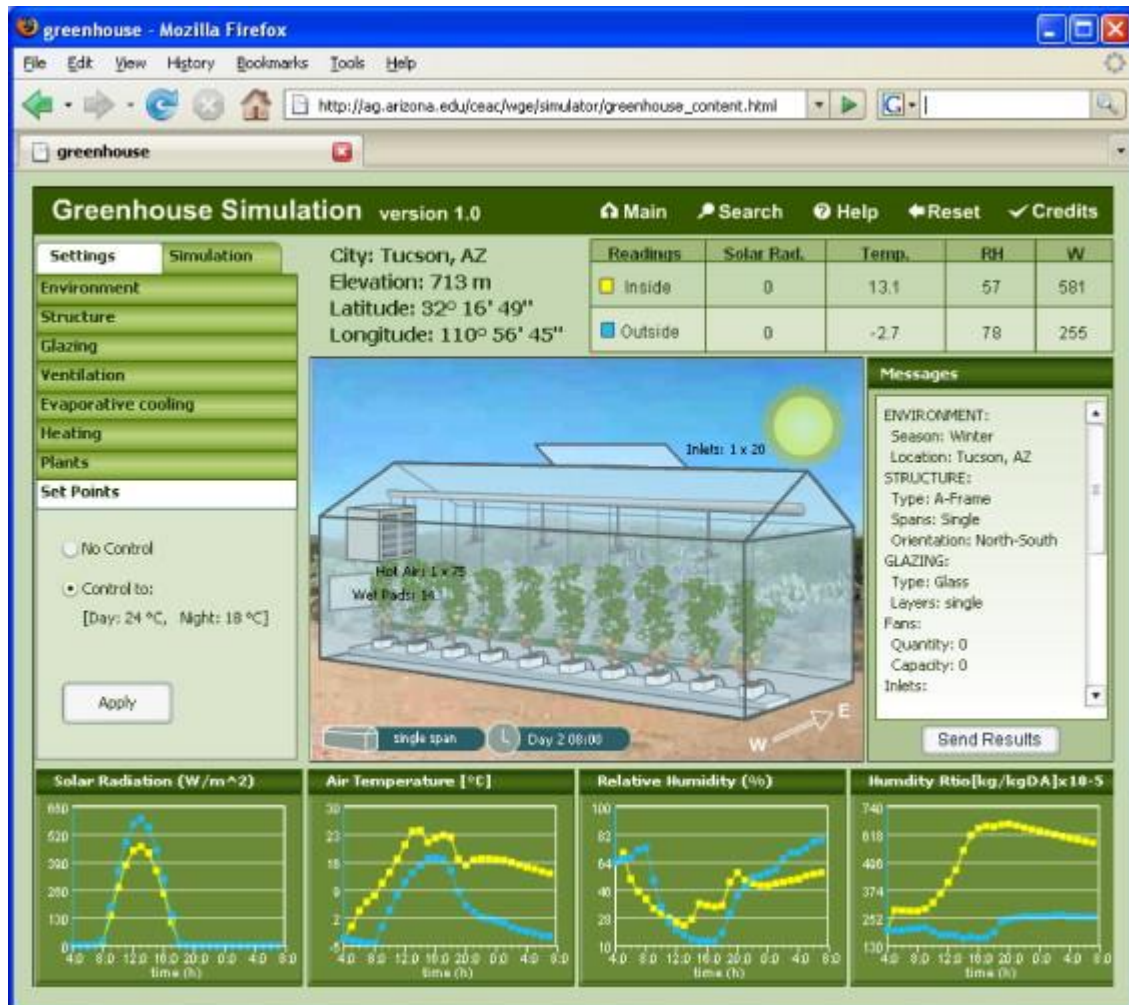


Figure 5: Screen capture of the dynamic greenhouse environment simulator presented in [25]

Vanthoor et al. [27] developed an economic model to design greenhouses for a broad range of climatic and economic conditions. This economic model was linked to an existing greenhouse climate-crop yield model to calculate the annual Net Financial Result of a greenhouse. The aim of this study was to identify – among ten predefined design alternatives – the greenhouse with the highest annual Net Financial Result.

3. Case Study – Intelligent Greenhouse

In this study, an intelligent small-scale experimental greenhouse, located at the Technological Educational Institute of Western Greece (Amaliada, South-West Greece) is presented. In order to allow the comparison of the intelligent greenhouse with a contemporary one, this greenhouse is located next to a reference greenhouse, with compatible material. The greenhouses are located at longitude 21°21'51.01"E, latitude 37°47'33.87"N and have an East-West ridge orientation. Both greenhouses are constructed of aluminium framework, of 3 mm thick glass panes.

The dimensions of the greenhouses are the following

- Width: 2.13 m
- Length: 2.00 m,
- Eaves height: 1.00 m
- Total height up to the top: 1.50 m.

- Occupied land surface area of each greenhouse: 4.26 m²,
- Area of the greenhouse cover: 14.05 m²
- Volume of the greenhouse: 5.33 m³

Two polycrystalline silicon (pc-Si) PV panels are fixed (facing South) on the roof of the glass PV greenhouse with a total surface equal to 0.85 m². The PV array cover 12.4% of the greenhouse roof surface, while the ratio of the PV panels' total surface per the greenhouse area is equal to 20%. This configuration of the PV panels is selected in order to achieve a shading "moving" mode during the day and consequently to minimize the possible permanent shading for some plants in East-West orientation greenhouses. The coverage percentage of the experiment is similar with other studies which applicate 9.8-12.9% greenhouse PV coverage [28][29].

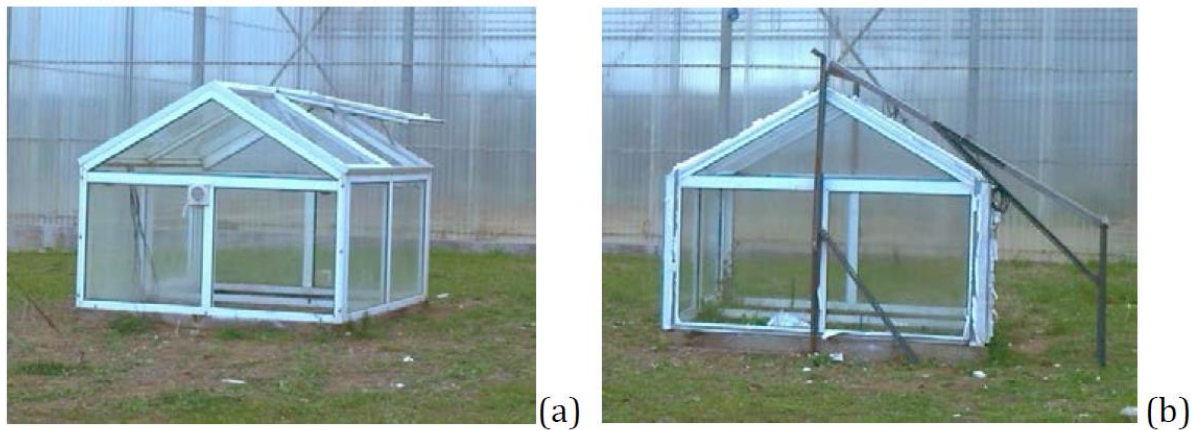


Figure 6: The experimental greenhouse units: (a) the reference greenhouse and (b) the greenhouse unit with PV panels on the South facing roof. [30]

Table 1: Instrumentation and sensors in test greenhouses

Greenhouses	
SR, SRPV	Silicon-type pyranometer (model SP-LITE, range 400-1100 nm, accuracy $\pm 5\%$, Kipp & Zonen, Delft, The Netherlands)
PAR	Photosynthetic active radiometer (model PAR-LITE, 400-700 nm, accuracy $\pm 5\%$, Kipp & Zonen, Delft, The Netherlands)
RH-T₂	Temperature and relative humidity probe (model S3CO3, accuracy $\pm 1\%$ RH, ± 0.3 K, Rotronic, Bassersdorf, Switzerland)
T₂, T_{PV}, T_{c_in}, T_{c_out}	Thermocouples (type τ , copper-constantan, 0.2 mm diameter, accuracy 0.5 °C, TC Ltd., UXBRIDGE, United Kingdom)
Meteorological mast	
Data logger	Data logger with two relay analog multiplexer units, (CR1000X, Measurement and control module, Campbell Scientific, Logan, USA)
SR	Thermopile-type pyranometer (model CMP3, range 300-3000 nm, accuracy $\pm 5\%$, Kipp & Zonen, Delft, The Netherlands)
RH₀-T₀	Temperature and relative humidity probe (model MP101A, accuracy $\pm 1\%$ RH, ± 0.2 °C, Rotronic, Bassersdorf, Switzerland)
Rain	Rain gauge (model 52203, accuracy 2%, R.M. Young Company, Traverse City, Michigan, USA)
WS	Anemometer (model A100K, accuracy 1%, threshold sensitivity 0.15 m s ⁻¹ , Windspeed Ltd, North Wales, United Kingdom)
T_{sky}	Pyrgometer (model CGR3, spectral range 4500 - 42000 nm, accuracy $\pm 10\%$, Kipp & Zonen, Delft, The Netherlands)

The interior microclimatic parameters as temperature at several locations at the inside air (T_N) and at the inside and outside surface of the greenhouse glazing cover (T_c), as well as the relative humidity (RH), the incoming solar radiation (SR) and the photosynthetically active radiation (PAR) are monitored in both greenhouses (see Table 1). In addition, the PV temperature (T_{PV}) and the incoming solar radiation on them (SRPV) are recorded. The outdoor environmental conditions including temperature (T_{out}),

wind speed (WS), relative humidity (RH_o), sky temperature (T_{sky}) and rain level are monitored at a height of 2.50 m above the ground level, on a meteorological mast close to the greenhouses. The time step of data logging of the greenhouses is one minute. An Analyzer 4.5 Data logger Software is used for the processing and statistical analysis of the data.

4 Conclusions

This study presented an overview based on recent scientific announcements as well as on best practices available in the agricultural sector, concerning those elements of greenhouses which are required to achieve an intelligent greenhouse. An intelligent greenhouse integrates renewable energy technologies, advanced covering materials passive techniques to minimize the energy consumption, energy storage equipment as well as advanced monitoring and simulation tools of its performance. The relation between the physics of intelligent greenhouses as well as of green buildings was emphasized in this study, providing food for thought for engineers in the field of building physics for further developments in the field. The integration of intelligent building automation systems, renewable energy technologies as well as monitoring configurations is anticipated to mitigate the environmental impact of greenhouses. At the same time advanced building energy performance tools are anticipated to dominate in the design of future intelligent greenhouses as well as for decision making regarding the materials to be used.

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