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Creation of Net Zero Carbon Emissions Agricultural Greenhouses Due to Energy Use in Mediterranean Region; Is it Feasible?

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Abstract

Mitigation of climate change requires the decrease of greenhouse gas emissions into the atmosphere and the increasing use of renewable energies replacing fossil fuels. Agricultural greenhouses are energy-intensive agricultural systems using mainly fossil fuels. The use of renewable energies during their operation is limited so far. The possibility of using renewable energies for covering their energy needs has been investigated, focused on the Mediterranean region. Various sustainable energy technologies which are reliable, mature, cost-effective and broadly used in various applications are examined. These include solar-PV systems, low enthalpy geothermal energy, solid biomass burning, co-generation systems, high efficiency heat pumps and reuse of rejected industrial heat. Combined use of these systems in greenhouses can cover all their energy requirements in heat, cooling and electricity, reducing or zeroing their net CO2 emissions into the atmosphere due to operational energy use. It is concluded that depending on their local availability in Mediterranean countries, these benign energy technologies can assist greenhouse crop growers in the reduction of their carbon emissions, contributing in the achievement of the universal goal for climate change mitigation.

Keywords: Energy; Greenhouse; Low carbon energy technologies; Mediterranean region; Net zero carbon Emissions; renewable energies.

1. Introduction

Climate change consists of a severe global environmental problem which threatens the future prosperity of the global community. Its mitigation requires the decrease of the greenhouse gas emissions and replacement of fossil fuels with renewable energies in all sectors of the economy. Cultivation of various crops in greenhouses is an energy-intensive process using mainly fossil fuels. Due to the increasing demand of foodstuff necessary for feeding a growing global population, the cultivation of vegetables in greenhouses is going to multiply in the near future, requiring more energy for their operation. Reduction or zeroing the carbon footprint due to energy use in them will assist in tackling climate change. The scope of the following research is to identify the benign energy sources and technologies which could be used in greenhouses, located in the Mediterranean region, replacing the use of fossil fuels and lowering/zeroing their greenhouse gas emissions. Various renewable energy technologies currently being used are reliable, mature and cost-effective, and are applied in many ways for heat, cooling and electricity generation. They could be also used in agricultural greenhouses covering part or all of their energy needs resulting in low or zero CO_2 emissions. Identification of various renewable energies available in the Mediterranean region which could be used in greenhouses for zeroing their CO_2 emissions into the atmosphere is important for reducing their environmental impacts and mitigating climate change.

2. Literature Survey

2.1. Energy Use in Greenhouses

Bartzanas, *et al.* [1], have investigated the influence of the heating method on greenhouse microclimate and energy consumption. The authors experimented in a greenhouse with tomato crop using a double heating system consisting of heating pipes and an air heater placed 2.5 m above the ground. They found that the double heating system increased the total energy consumption by 19%. However it improved the control of the indoor air temperature and the humidity. Ntinas, *et al.* [2], have estimated the energy demand and the carbon footprint of tomato crops in Southern and Central Europe. The authors estimated the annual energy consumption at 0.8-160.5 MJ per kg of tomato grown and the annual carbon emissions at 0.1-10.1 $kgCO_2$ per kg of tomato. They also mentioned that open-field tomato cultivation resulted in lower energy consumption and carbon emissions compared with greenhouse cultivation. Hatirli, *et al.* [3], have investigated the energy input in tomato cultivated in greenhouses located in Antalya, Turkey. The authors estimated the annual energy consumption at 106,716.2 MJ/ha. They mentioned that approximately 50% of it was assigned to diesel oil and electricity while the rest went on fertilizers, chemicals and human power. Hemming [4], has reported on energy consumption in Dutch greenhouses. The author mentioned that energy accounts for 20-30% of their production cost, while the newly built greenhouses in Holland operate almost without fossil fuels. This is achieved by improving their energy efficiency, with the maximum use of solar energy and the replacement of fossil fuels with renewable energies. He also stated that greenhouses can produce electricity with solar panels in Holland at 16-28 KWh/m^2 per year. Ozturk and Kucukerdem [5], have estimated the heating requirements as well as the energy consumption of plastic greenhouses in Adana region, Turkey. The authors mentioned that during the October-May period, the average heating load is 64.4 W/m^2 when the indoor temperature is 18^{o}C, whereas when it is 15^{o}C, the average heating load is 44.5 W/m^2. They also stated that the average energy consumption is at 176 MJ/h when the air temperature is at 15^{o}C. Campiotti, *et al.* [6], have studied the sustainable greenhouse horticulture in Europe. The authors mentioned that energy load in European greenhouses varies from 50-150 W/m^2 in Southern Europe to 200-280 W/m^2 in Central and Northern Europe, while in full air-conditioning greenhouses, it could reach 400 W/m^2. They also stated that renewable energies including low enthalpy geothermal energy, solid biomass and solar photovoltaic (solar-PV) energy could be used for energy generation in greenhouses. De Gerder, *et al.* [7], have studied the possibility of reducing the energy consumption in modern greenhouses in the Netherlands. The authors mentioned that high-tech greenhouses in the country consume a lot of energy producing large amounts of high quality vegetables. They proposed a novel tomato cultivation system which requires 40% less energy compared with a conventional greenhouse, from 1.3 GJ/m^2 per year to 0.75 GJ/m^2 per year, while the annual crop productivity remains high at 60 kg/m^2. Canakci and Akinci [8], have reported on energy use in greenhouse vegetable production in Antalya, Turkey. The authors mentioned that the annual operational energy consumption in the greenhouses varies between the ranges of 23.88-28.03 MJ per m^2. They also stated that the embodied energy of an iron- and glass-based greenhouse with a life span oft 25 years is 17.23 MJ per m^2 per year. Aguilera, *et al.* [9], have studied the embodied energy in agricultural inputs including greenhouses. The authors stated that the useful life and the embodied energy vary among different types of greenhouses. The useful life of plastic greenhouses is 1.5-2 years while that of iron- and aluminium-based greenhouses is 15-20 years. They estimated their embodied energy in the range of 7.6-81.7 MJ per m^2 per year. Boulard, *et al.* [10], have investigated the environmental impacts of greenhouse tomato production in France. The authors mentioned that the energy consumption in tomato production is 31.6 MJ/kg while carbon emissions are 2.02 kg CO_2/kg.

2.2. Use of Renewable Energies in Greenhouses

Vourdoubas [11], has studied the heating of greenhouses with renewable energies with reference to the island of Crete, Greece. The author mentioned that a locally available low-cost biomass source, olive kernel wood, was used to cover all the annual heating requirements in a greenhouse cultivated with flowers while a solar-PV system could cover all its annual electricity needs. Vourdoubas [12], has also presented an economic and environmental assessment of the use of renewable energies in greenhouses, again with reference to the island of Crete, Greece. The author mentioned that the use of renewable energies in greenhouses results in many environmental benefits. He also stated that the use of solid biomass and geothermal energy for heating is profitable. However, the use of heat pumps and solar-PVs is not cost-effective, particularly when grid electricity consumption in greenhouses is subsidized by the government. Bibbiani, *et al.* [13], have studied the use of wood biomass for greenhouse heating in Italy. The authors mentioned that the power load in Italian greenhouses varies from 30 to 175 W/m^2 while their annual energy consumption varies from 21 to 546 KWh_{th}/m^2. They also stated that wood biomass heating is promoted by the EU while the Italian government offers some subsidies to support its use. Wood biomass is considered environmentally neutral regarding greenhouse gas (GHG) emissions excluding GHG generation during its harvesting, transportation and pre-processing. Fahmy, *et al.* [14], have investigated the use of renewable energy sources providing heat and electricity in a greenhouse used for chili production located in the Suez Gulf, Egypt. The authors stated that the required temperature for the crop was 25-35^{o}C. They proposed the use of geothermal water available in local geothermal springs for heating and the use of solar and wind energy for electricity generation. Scott [15], has reported on biomass heating in greenhouses. The author mentioned that energy costs in greenhouses correspond approximately to 10-15% of their total production cost. He also stated that the cost of wood chips is considerably lower than the cost of conventional fuels including natural gas, propane, heating oil or electricity. Moretti and Marucci [16], have investigated a solar-PV greenhouse with variable shading for the optimization of agricultural and energy production. The authors experimented on a greenhouse with rotating solar-PV panels enabling the variation of shading inside it for achieving an optimum indoor microclimate for crop production. Wang, *et al.* [17], have studied the integration of solar energy technologies to modern greenhouses in China. The authors mentioned that progress has been made in the integration of solar energy technologies in greenhouses regarding the problems of heat losses, storage in solar thermal systems and crop shadowing in solar-PV systems. Aroca-Delgado, *et al.* [18], have reported on the compatibility between crops cultivated in greenhouses and solar panels. The authors mentioned that the effective use of solar-PV panels in greenhouses requires more research to determine the optimum percentage of panels on the roof without reducing the crop's productivity. Esen and Yuksel [19], have experimented in the use of various renewable energy technologies for heating a greenhouse in Turkey. The authors used a combination of different renewable energy technologies including biogas produced by digestion of cattle wastes, solar thermal energy and a ground-source heat pump for heating a small greenhouse. They reported that the energy systems tested were able to maintain the indoor temperature at the desired level at 23^{o}C. Yano and Cossu [20], have reviewed the use of solar-PV technologies in agricultural greenhouses. The authors mentioned that although application of solar-PVs to greenhouses can reduce fuel and grid electricity consumption, their use conflicts with crop cultivation since both photosynthesis and electricity depend on sunlight availability.

2.3. Use of Low Carbon Energy Technologies in Greenhouses

Russo, *et al.* [21], have investigated the environmental performance of two greenhouse heating systems. The first was using a geothermal heat pump (GHP) combined with a solar-PV system while the second used a conventional hot air generator using liquefied petroleum gas. The authors mentioned that the combined solar-PV-GHP system resulted in significant environmental benefits although its investment cost was high. Vermeulen and Van Der Lans [22], have investigated the use of co-generation of heat and power (CHP) systems in organic greenhouse horticulture. The authors compared the carbon footprint of a conventional and an organic tomato crop using a CHP system. Their findings indicated that the CO_2 footprint of an organic tomato crop grown without CHP is 10% higher than a conventional crop without co-generation and more than double that of a conventional crop grown with CHP. Tong, *et al.* [23], have investigated the heating of greenhouses with high efficiency heat pumps. The authors used ten air to air heat pumps to heat a small experimental greenhouse with a floor area of 151.2 m^2 at night in winter. They estimated that the average hourly coefficient of performance (C.O.P.) was 4.0 while in extreme weather conditions it remained at around 3.0. Anifantis, *et al.* [24], have experimentally investigated the performance of a geothermal heat pump for heating greenhouses in Bari, Italy. The authors mentioned that their findings indicated that the GSHP system was effective, efficient and environmentally friendly in heating greenhouses. Parker and Kiessling [25], have implemented a case study regarding the use of low-grade heat recycling for food production with reference to the European Spallation source. The authors stated that the low-grade surplus heat could be reused and combined with the recycling of society's organic wastes to produce food and animal feed. Manning and Mears [26], have reported on an agricultural greenhouse in USA heated with discharged cooling water from a power plant. The cooling water at 30^{o}C was circulated inside plastic pipes placed on the floor maintaining the indoor temperature at 18^{o}C in the 1.1 hectare's greenhouse. Bartzanas, *et al.* [1], has reported on cooling water reuse from a power plant in Germany for heating a 5.3 hectare greenhouse. The author mentioned that the average cooling water temperature was at 30-40^{o}C while the heating system was able to maintain the indoor air temperature at 22^{o}C even when the ambient temperature was at -14^{o}C. Vourdoubas [27], has investigated the possibility of using industrial heat rejected from power generation plants in Northern Greece for heating greenhouses. The author estimated the heating requirements in greenhouses at 170 W/m^2 and the required hot water temperatures in greenhouses at 50-60^{o}C which is lower than the temperature of the hot water provided. He also stated that the cost of heating greenhouses with rejected heat in Northern Greece is estimated at 0.0435 €/KWh which is low compared with the cost of other heating methods. Martz, *et al.* [28], have investigated the use of CHP systems with thermal storage in modern greenhouses. The authors mentioned that a 4.2 MW CHP unit with thermal storage fueled by natural gas was providing energy in a 128-acre greenhouse located in California, USA. They also stated that the power efficiency of the energy system was at 38% and its thermal efficiency at 50%, while the surplus electricity was sold into the grid.

The aim of the current work is the investigation of the possibility of using sustainable energy technologies in agricultural greenhouses for zeroing their net carbon emissions into the atmosphere due to operational energy use in the Mediterranean region.

The methodology used initially includes a literature survey followed by an estimation of energy consumption in greenhouses. Next, various sustainable energies which could be used in greenhouses are mentioned, as well as the requirements for achieving a net-zero carbon emissions greenhouse. Three different options of benign energy technologies which could zero the net carbon footprint in greenhouses are presented. The work ends with a discussion of the findings and conclusions drawn, followed with recommendations for further work.

3. Energy Consumption in Greenhouses

3.1. Operational Energy Consumption in Greenhouses

Energy requirements in greenhouses depend on several factors including the local climate, the type of construction and the materials used, as well as the cultivated crop. Greenhouses located in Northern Europe require almost double the energy than the same greenhouses located in Southern Europe. Energy is used in agricultural greenhouses for covering their needs in space heating and cooling, lighting and the operation of various electric machinery. The cost of energy could reach 20-30% of the total production cost in the greenhouse. In most modern greenhouses, heating energy has a share of approximately more than 90% in the overall energy consumption. The main energy sources used include grid electricity, natural gas and diesel or heating oil. Renewable energy sources are not frequently used so far in greenhouses. However solid biomass and low enthalpy geothermal energy are occasionally used for heating them. The use of solar-PV systems has recently been increased due to the sharp decrease in their installation cost. Among the non-conventional energy sources which could be used in greenhouses are heat and power co-generation systems, high efficiency heat pumps and waste heat rejected from various industries. The operational energy use and the carbon emissions in greenhouses according to published research are presented in Table 1.

Table-1. Operational energy use and CO_2 emissions in agricultural greenhouses with tomato crop

Author/year	Crop	Energy consumption	CO_2 emissions
Ntinas, *et al.* [2]	Tomato, Europe	0.8-160.5 MJ/kg	0.1-10.1 $KgCO_2$ per kg of tomato
Hatirli, *et al.* [3]	Tomato, Turkey	5.34 MJ/m^2 year	
De Gerder, *et al.* [7]	Tomato, Netherlands	21.7 MJ/kg	
Canakci and Akinci [8]	Tomato and other vegetables, Turkey	23.8-28 MJ/m^2 year	
Boulard, *et al.* [10]	Tomato, France	31.6 MJ/kg	2.02 $kgCO_2$/kg

Source: various authors

3.2. Embodied Energy use in Greenhouses

Apart from the energy consumed during the operation in greenhouses, energy is also utilized during their construction, maintenance and demolition, which is called embodied energy. The life cycle energy of greenhouses is the sum of their embodied and operational energy. Embodied energy depends on the type and the materials used in the greenhouse as well as its life time. This has been estimated at 17.23 MJ per m^2 per year [8] and 7.6-81.7 MJ per m^2 per year [9], respectively. The share of embodied energy in the life cycle energy consumption in greenhouses varies significantly depending on the type of the greenhouse, the materials used, the local climate and the cultivated crop. However, it is high compared with the share of embodied energy to life cycle energy consumption in buildings, which is on average 10-20% [29].

4. Use of Renewable Energies and Low Carbon Energy Technologies in Greenhouses

Various renewable energies and low carbon energy technologies can be used in agricultural greenhouses providing electricity, heat and cooling to them. These include:

1. Solar energy with solar-PV panels can be used for electricity generation in greenhouses. The panels can be opaque or semi-transparent located either on-site or off-site the greenhouse. The semi-transparent modulus can be placed on the rooftop. Net-metering regulations allow the use of the grid for electricity storage, if it is not needed in the greenhouse when generated, avoiding the use of expensive electric batteries. Solar panels can generate more electricity than the amount required in the greenhouse, sending the surplus into the grid, and which case the farmer can get financial compensation due to excess electricity sold to it.
2. Solid biomass burning consists of an old, low cost and well known technology for heat generation. It is considered a zero-carbon emissions energy source, assuming that its emissions during its harvesting, transportation, processing and storage are zero. It can cover all the heating needs in greenhouses. Hot water at 50-60°C is produced during biomass burning which is circulated inside plastic pipes located on the ground among the plants achieving the desired indoor temperature. It is desirable to use locally produced biomass in order to avoid its transportation from long distances and the resulting CO_2 emissions into the atmosphere.
3. Low enthalpy geothermal energy with water temperatures at approximately 50-90°C could be used for heating greenhouses. The geothermal fluid via heat exchangers can heat water at 45-60°C which is then circulated in plastic pipes located inside the greenhouse, maintaining the indoor temperature at the desired level. The geothermal spring is desirable to be located near the greenhouse while all the heating needs of the greenhouse can be covered.
4. High efficiency co-generation systems can be used for heat and power generation in greenhouses covering all their energy requirements while any surplus electricity can be sold into the grid. These co-generation systems with overall efficiency at 80-90% are currently used in large industrial greenhouses. Most of them are fuelled by natural gas while they can also use biomass as a fuel.
5. Reuse of heat rejected by various industries like power generation plants can be used for greenhouse heating, particularly if they are located near the plants. The rejected cooling water, instead of being disposed into a water reservoir resulting in thermal pollution, is recycled inside the greenhouse, heating the cultivated crop.
6. Heat pumps are very efficient energy devices used for air-conditioning in many applications. They can also be used for heating and cooling greenhouses. Their initial installation cost is high but their high COP, which is in the range of 4-5, increases their attractiveness and profitability. Heat pumps can cover all the heating and cooling requirements in greenhouses.

The abovementioned energy sources are available in the Mediterranean region and are being used already in agricultural greenhouses as well as in many other applications. The sustainable energy systems used for energy generation in greenhouses and their characteristics are presented in Tables 2 and 3.

Table-2. Sustainable energy systems used in greenhouses

Energy system	Energy used	Heat generation	Cooling generation	Electricity generation
Solar-PV	Solar energy	No	No	Yes
Heat exchange with geothermal fluids	Geothermal energy	Yes	No	No
Solid biomass burning	Solid biomass	Yes	No	No
Co-generation of heat and power	Natural gas	Yes	No	Yes
Reuse of rejected heat	Waste heat	Yes	No	No
High efficiency heat pumps	Ambient heat and electricity	Yes	Yes	No

Source: Own estimations

Table-3. Characteristics of various sustainable energy systems used in greenhouses

Energy system	Energy generation	Is energy storage required?	Is the technology mature and reliable?	Are there commercial applications?
Solar-PV	Intermittent	No [1]	Yes	Few
Heat exchange with geothermal fluids	Continuous	No	Yes	Yes
Solid biomass burning	Continuous	No	Yes	Yes
Co-generation of heat and power	Continuous	No	Yes	Yes
Reuse of rejected heat	Continuous	No	Yes	Few
High efficiency heat pumps	Continuous	No	Yes	Few

1 In the case of net-metering regulations

5. Requirements for Net Zero Carbon Emissions Greenhouses

Energy use in greenhouses is related with carbon emissions in the atmosphere. In order to achieve a net zero carbon emissions greenhouse due to operational energy use, the following requirements should be fulfilled:

a) The energy consumption should be reduced with the use of energy saving technologies and techniques,
b) Any fossil fuels used should be replaced with renewable energy sources,
c) The grid electricity consumption should be offset annually with green electricity, preferably generated with solar-PV panels placed either on-site or off-site from the greenhouse. This is currently allowed in many countries with the net-metering regulations, and
d) Any remaining emissions should be offset with various carbon compensation schemes which are commercially available.

It has been assumed that a) The use of renewable energy sources like solid biomass and geothermal energy result in net zero carbon emissions into the atmosphere, and b) All grid electricity is generated by fossil fuels. This, in fact, is not true since part of the grid electricity is generated by renewable energies and/or nuclear power.

6. Use of Various Sustainable Energy Technologies Which Could Zero the Net Carbon Emissions in Greenhouses Due to Operational Energy Use

6.1. Use of Solid Biomass and Solar-PV Panels for Achieving Net Zero Carbon Emissions Greenhouses

Solid biomass can be used for covering all the heating needs of greenhouses while solar-PV panels can generate all the electricity required annually. Greenhouses should be connected with the grid according to net-metering regulations, and use the grid for electricity storage when the solar electricity generated is not needed. The solar panels can be either opaque or semi-transparent. In the case of semi-transparent panels, they can be placed on the rooftop of the greenhouse covering part of its surface avoiding over-shading and reduction of crop productivity.

6.2. Use of Geothermal Energy and Solar-PV Panels for Achieving Net Zero Carbon Emissions Greenhouses

Low enthalpy geothermal energy can be used for heating greenhouses while solar-PV electricity can be used for covering all its power requirements, selling any surplus electricity into the grid. The presence of a geothermal field near the greenhouse is a prerequisite for using this benign energy source.

6.3. Use of Heat Pumps and Solar-PV Panels for Achieving Net Zero Carbon Emissions Greenhouses

High efficiency heat pumps can be used for providing air-conditioning in the greenhouse while solar-PV electricity can be used for covering all its power requirements, selling any surplus electricity into the grid. Heat pumps are powered by electricity which can be generated by the solar-PV system which should additionally generate the electricity needed for lighting and the operation of various electric devices in the greenhouse. The abovementioned benign energy systems which could zero the net carbon emissions in greenhouses due to operational energy use are presented in Table 4.

Table-4. Sustainable energy systems which could zero the net carbon emissions in greenhouses due to operational energy use

System	Energy sources used	Electricity generation	Heat generation
A	Solar energy and solid biomass	Solar-PV energy	Solid biomass
B	Solar energy and geothermal energy	Solar-PV energy	Geothermal energy
C	Solar energy and high efficiency heat pump	Solar-PV energy	High efficiency heat pump

Source: Own estimations

7. Discussion

Our results indicate that various sustainable energy technologies could be used in agricultural greenhouses covering part or all of their operational energy needs. Among them solar energy, solid biomass and low enthalpy geothermal energy are available in the Mediterranean basin, while they have been used separately so far in greenhouses. Their use could reduce or zero their CO_2 emissions into the atmosphere, contributing to the global efforts for climate change mitigation. Therefore, these findings could be used for the design of appropriate governmental policies for the reduction of GHG emissions in agriculture. Our findings do not quantify the economic and environmental benefits that farmers could achieve by using the abovementioned renewable energy technologies in their greenhouses by replacing the use of fossil fuels. Taking into account that currently many farmers are not familiar with these benign energy technologies and their use in their crops, it is recommended that they should be sensitized and trained, so that they can become more familiar with their use and the resulting benefits.

8. Conclusions

The possibility of using renewable energy sources available in the Mediterranean region for providing heat, cooling and electricity in agricultural greenhouses has been investigated. It has been shown that the combined use of solid biomass, low enthalpy geothermal energy, high efficiency heat pumps and solar-PV energy can cover all the energy requirements in greenhouses, replacing fossil fuels used and zeroing the net carbon emissions into the atmosphere due to operational energy use. The abovementioned renewable energy technologies are mature, reliable and cost-effective, and they are currently used in many applications. Our results indicate that agricultural greenhouses in the Mediterranean region could zero their net CO_2 footprint due to operational energy consumption, avoiding the use of the polluting fossil fuels and promoting the use of locally available benign energy sources. Further research should be focused on the detailed design of net zero carbon emissions greenhouses using the abovementioned benign energy technologies, combined with an estimation of the investment costs of the energy systems required. It should also investigate the appropriate policies and incentives which should be offered by the government for the promotion of commercial greenhouses with net zero CO_2 emissions.

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