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Use of Solar Photovoltaic Systems and Heat Pumps for Achieving Net-Zero Carbon Emission Greenhouses Due to Energy Use: A Case Study in Crete, Greece

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Abstractf

Renewable energies and low-carbon energy technologies have currently limited use in greenhouses. The use of sustainable energy technologies in many sectors, including agricultural greenhouses, is desirable and attractive for reducing the climate impacts of agriculture. Their maturity, reliability and cost-effectiveness has been proved and their use in many applications has been accelerated. Reports regarding net-zero energy and net-zero carbon emission greenhouses are limited so far. However, the global policies for climate change mitigation and creation of a net-zero carbon economy in the coming decades favors the use of benign energy sources replacing the polluting fossil fuels. The use of heat pumps and solar-PV systems for energy generation covering the needs for heat, cooling and electricity in an existing greenhouse located in Crete, Greece has been investigated. The combined use of these green energy technologies can eliminate the use of fossil fuels resulting in a net-zero carbon-emissions greenhouse. The size of the greenhouse studied was 3,300 m^2, the nominal power of the solar-PV system generating all the required electricity was estimated at 254.23 KW_{el} and its installation cost at 233,052 €. A heat pump with COP equal to 3 and power at 254.23 KW_{el} can cover all the peak heat and cooling demand of the greenhouse while its installation cost is at 1,144,035 €. The total installation cost of the abovementioned benign energy systems is at 417.30 €/m^2. Our research indicates that sustainable energy technologies can generate all the required energy in agricultural greenhouses zeroing their net-carbon emissions and promoting the carbon neutral agriculture.

Keywords: agricultural greenhouses; carbon emissions; Crete-Greece; energy use; heat pumps; solar photovoltaics.

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1. Introduction

The use of renewable energies instead of fossil fuels in several sectors is very important for climate change mitigation and the achievement of the global target for zeroing the net-carbon emissions by the middle of the 21st century. The use of renewable energies in agricultural greenhouses is rather limited to day since they use mainly fossil fuels for covering their energy needs. Various studies in several countries have described the use of renewable energies and low-carbon emission technologies in agricultural greenhouses so far [1, 2, 3, 4]. These benign energy sources and technologies include solar-PV systems, wind turbines, geothermal energy, solid biomass, heat pumps, co-generation systems and recycle of rejected industrial heat. These technologies are mature, reliable and cost-effective and they all already used in many applications.

The aim of the current study is the investigation of the possibility of using a solar photovoltaic system and a heat pump for zeroing the net-carbon emissions in a greenhouse due to energy use in Crete, Greece.

The size and the installation cost of a solar photovoltaic system and a heat pump which can cover all the energy needs in an existing modern greenhouse used for flowers cultivation in Crete, Greece are going to be estimated. The text is structured as follows. After the literature review the energy consumption in greenhouses is mentioned as well as the use of sustainable energies in them. In the following sections the concept of net-zero carbon emission greenhouses is described and an estimation of the required solar photovoltaic system and a heat pump covering all the energy requirements in a modern greenhouse located in Crete, Greece is presented. The text ends with discussion of the findings, the conclusions drawn and the citation of the references used. The present study fills the existing gap regarding the use of renewable energy technologies in the creation of net-zero carbon emission greenhouses due to energy use in Greece. It could be useful to all stakeholders of the greenhouse industry including public authorities, farmers, greenhouse construction companies and energy companies.

2. Literature survey

The literature survey is separated in four sections including: a) the energy consumption in greenhouses, b) the use of renewable energies in greenhouses, c) the use of solar photovoltaic systems in greenhouses, and d) the use of heat pumps in them.

2.1 Energy consumption in greenhouses

The energy use in greenhouses in EU has been reviewed [5]. The authors stated that the high energy systems are more dominant in northern Europe while the energy consumption in greenhouses in southern Europe is low. They also mentioned that greenhouses mainly use fossil fuels for covering their energy requirements. The energy use in greenhouses has been simulated [6]. The authors stated that lighting amounts to about 30% of its operating costs. They also mentioned that according to their simulation LED lighting could decrease, by approximately 60%, the lighting costs in greenhouses growing lettuce. The use of digital technologies in modern agriculture called “digital agriculture” and “precision agriculture” has been studied [7]. The authors stated that digital technologies facilitate the energy and water saving in greenhouses promoting their energy and environmental sustainability. The energy use and the environmental impacts of greenhouse crops in Tehran province, Iran have been investigated [8]. The authors stated that the energy consumption was estimated at 405,405.75 MJ/ha while for cucumber and tomato production at 412,911.99 MJ/ha. They also mentioned that diesel fuel had the highest share at more than 60% in the total energy consumption.

2.2 Use of renewable energies in greenhouses

The impacts of solar and wind energy systems in agricultural greenhouses have been studied [9]. The authors stated that energy, after labor, has the largest share in the operational cost in greenhouses. Heating has a share at 75% in the total energy consumption, electricity 15% while vehicle's transportation 10%. They also mentioned that solar and wind energy are expected to have an increasing role in the future in covering the energy needs in greenhouses. The use of renewable energies in heating greenhouses in the republic of Korea has been examined [10]. The authors studied three heating systems including a pellet boiler, a hydrothermal heat pump and a solar heat collection system. They stated that, among them, the heating system using the pellet boiler was the most economical system. The use of renewable energies in agriculture has been reviewed [11]. The authors stated that solar energy can be used for heating and electricity generation in agricultural greenhouses replacing the use of fossil fuels and reducing the GHG emissions. The use of renewable energies in agricultural greenhouses has been studied [2]. The authors stated that renewable energies have limited applications in them. They also mentioned that solar photovoltaic systems, solid biomass and geothermal fluids can be used in agricultural greenhouses in a cost-effective way. The heating of agricultural greenhouses located in Elazig, Turkey using biogas, solar energy and ground source heat pumps has been investigated [3]. The authors stated that their results indicated that renewable energies can be used successfully in heating greenhouses. The possibility of creating zero carbon emission greenhouses in Mediterranean region has been studied [4]. The author has examined the use of several reliable, mature and cost-effective energy technologies in greenhouses. He stated that green energy technologies including solar-PV systems, geothermal energy, solid biomass, heat pumps, co-generation systems and rejected industrial heat can cover all the energy requirements in greenhouses minimizing or zeroing their net-carbon emissions due to energy use. Several renewable energy technologies reducing or zeroing carbon emissions in agriculture have been reviewed [11]. The authors stated that while net-zero emission technologies are technically available they have limited adoption in the market due to several reasons. They also mentioned that the use of renewable energy technologies can be combined with carbon capture and storage to achieve net-zero carbon emissions agriculture. The prospects of mitigating GHG emissions in agriculture consistent with the Paris agreement have been studied [12]. The authors stated that there are not countries imposing limitations on carbon emissions in agriculture. The climate policy in agriculture lags far behind the climate policy in the energy sector partly related with food security and livelihoods. They also mentioned that the agricultural sector should contribute to GHG emissions reduction in order to achieve the target of Paris agreement. The economic and environmental impacts of using renewable energies in greenhouses focusing on the island of Crete, Greece have been studied [13]. The author stated that the use of solid biomass and low enthalpy geothermal energy for heating greenhouses is cost-effective. He also mentioned that the use of geothermal heat pumps for heating and cooling them is rather expensive. Additionally, he stated that the use of solar photovoltaic systems in greenhouses is not profitable due to the fact that electricity consumption is subsidized by the Greek government. The applications of solar energy in agricultural greenhouses have been examined [14]. The authors stated that solar thermal systems can be used for heating greenhouses and solar-PV systems for electricity generation. The use of solid biomass for heating an agricultural greenhouse located in Crete, Greece has been evaluated [15]. The author stated that the share of heat energy in the total energy mix in the greenhouse is much higher than the share of electricity which is only 6.14%. He also mentioned that replacing fuel oil with biomass in heating greenhouses results in the creation of nearly-zero carbon emission greenhouses due to energy use.

2.3 Use of solar photovoltaic systems in greenhouses

The possibility of co-producing vegetables and electricity in agricultural greenhouses in Crete, Greece has been investigated [16]. The author stated that semi-transparent solar photovoltaics can be installed on the rooftop of agricultural greenhouses generating significant amounts of electricity. He also mentioned that the use of solar-PVs in greenhouses can result in economic and environmental benefits. The profitability of using solar-PVs in agricultural greenhouses in Greece has been evaluated [17]. The author stated that solar-PVs are currently a reliable and cost-effective technology used in many applications. He also mentioned that their use in greenhouses in Greece has a payback period at 7.2-14.4 years depending on the capital subsidies achieved. The use of semi-transparent solar photovoltaic systems in greenhouses for covering their energy needs has been investigated [18]. The author stated that semi-transparent PV modules placed on the rooftop of agricultural greenhouses can cover part or all of their heat and electricity requirements depending on the heating method used. A photovoltaic greenhouse with variable shading optimizing both the agricultural and energy production has been assessed [19]. The authors stated that mobile solar-PV panels located on the rooftop of greenhouses can alter the degree of shading according to the needs of the crops and the availability of solar energy optimizing both the electricity and crops production. The use of solar-PV systems in agricultural greenhouses in Sweden has been studied [20]. The author stated that it is not possible to create net-zero energy greenhouses in Stockholm, Sweden due to the low level of solar irradiance in the country in winter time. He mentioned that according to his study the maximum net-zero energy consumption achieved was 34.34%. The use of semi-transparent organic photovoltaics (OPV) in greenhouses has been examined [21]. The authors stated that the OPV used had an overall power conversion efficiency at 1.82% which is significantly lower than the efficiency of the conventional silicon-based solar-PVs. They also mentioned that agricultural greenhouses can be easily used for organic photovoltaic applications.

2.4 Use of heat pumps in greenhouses

The development of an air-to-air heat pump for greenhouse heating in South Korea has been studied [22]. The authors stated that the energy simulation of the system indicated that the average coefficient of performance (COP) of the heat pump was at 2.2 when the outside temperature was at -13^{o}C. The use of a solar assisted heat pump for greenhouse heating in Tunisia has been analyzed [23]. The power of the heat pump was at 10 KW while the surface of the solar collector was at 2 m^2 matching the heating load of the pump. The authors stated that the solar collector had a positive impact on the water-to-water heat pump. A hybrid energy system for a nearly zero energy greenhouse has been evaluated [24]. The authors stated that the hybrid energy system was consisted of a solar-PV system and a ground-source heat pump. They also mentioned that the generation of solar electricity could meet 33.2-67.2% of the demand of the greenhouse during the summer months. Additionally, they stated that the annual energy coverage ratio was 95.7% for tomato crops, 86.8% for cucumber and 104.5% for lettuce. The high annual energy coverage ratio justifies the net-zero energy concept for greenhouses. The COP of air-to-air heat pumps used in heating greenhouses located in Japan has been evaluated experimentally [25]. The authors stated that when the inside air temperature was kept at 16^{o}C and the outside air temperature in the range -5^{o}C to +6^{o}C the average hourly COP was at 3.3 with the highest value at 5.8. The performance of a heat pump for heating greenhouses located in Elazig, Turkey with horizontal and vertical ground source heat exchanger has been evaluated experimentally [26]. The author stated that the COP of the heat pump system was at 2.7-3.3 for the horizontal heat exchanger and at 2.9-3.5 for the vertical heat exchanger. A hybrid greenhouse using a photovoltaic-thermal system and a ground source heat pump in China has been studied [27]. The authors stated that the maximum COP of the heat pump was achieved during peak hours while the efficiency of the photovoltaic thermal system was exceeding 57.88%. They also mentioned that among the four plants cultivated in the greenhouse including cucumber, tomato, lettuce and cowpea, tomato exhibited the highest photosynthetic carbon sequestration at 3,522 $kgCO_2/m^2$. The use of a heat pump for heating, during the summer months, a greenhouse used for flowers cultivation in Wroclaw, Poland has been investigated [28]. The heat pump was going to replace the old heating system of a coal-fired furnace. The authors studied the use of two types of heat pumps. A ground-source heat pump (GSHP) with COP in the range 5.53-5.83 and an air-source heat pump (ASHP) with COP in the range 2.59-4.00. They stated that the payback period of the GSHP was at 18 years, due to the high installation cost, while of the ASHP at 5.5 years. The characteristics of the heat pumps used for heat production in various greenhouses in several countries are presented in table 1.

Table 1: Characteristics of heat pumps used for heat production in various greenhouses in several countries.

Author, Country, Year,	Type of heat pump	COP
Rasheed and colleagues South Korea, 2021	Air-to-air	2.2
Tong and colleagues Japan, 2010	Air-to-air	3.3 (aver), 5.8 (max)
Benli, Turkey, 2013	Ground source	2.7-3.3 for horizontal heat exchanger 2.9-3.5 for vertical heat exchanger
Nems and colleagues Poland, 2018	Ground source	5.53-5.83
Nems and colleagues Poland, 2018	Air source	2.59-4.00

Source: various authors

Commercial operation of modern greenhouses using solar-PV systems and heat pumps covering all their annual energy requirements has not been reported so far. Characteristics of other green energy technologies which can reduce or totally eliminate the carbon emissions related with the operational energy in greenhouses have been also reported in various studies. Therefore, our study focusing on the use of the abovementioned green energy technologies in the greenhouse located in Crete, Greece has innovative aspects regarding the elimination of carbon emissions in agricultural greenhouses and the creation of agricultural production systems with net-zero climate impacts.

2.5 Energy consumption in agricultural greenhouses

Greenhouses consume energy in their daily operation covering their requirements for heat, cooling and electricity. Electricity is used for lighting and operation of several equipment (ventilation, pumps, motors et cetera). Depending on the location, the cultivated crop and the technology used they require more or less energy per covered surface [14]. Greenhouses in northern Europe consume higher amounts of energy compared with greenhouses located in Mediterranean region. The majority of greenhouses are using fossil fuels while the use of renewable energies is rather limited [5]. Modern greenhouses consume large amounts of energy achieving high productivity. The share of heating energy in the total energy mix is very high ([5, 15, 29]). The annual electricity consumption in agricultural greenhouses for various heat, cooling and electricity loads in several countries is presented in table 2 while the energy sources used for heating greenhouses in Germany are presented in table 3. The breakdown of energy use in greenhouses is presented in table 4 while the range of energy consumption per category in EU greenhouses in table 5.

Table 2: Annual electricity consumption in agricultural greenhouses for various heat, cooling and electricity loads in several countries.

Location	Annual electricity consumption (KWh/m^2 year)
Mediterranean region	2-9
Spain	7
Greece	20
Greece	14
Sweden	140
Finland	528
Netherlands	417
Southern France	139-444

Source: [14], [15]

Table 3: Energy sources used for heating greenhouses in Germany (%).

Energy source	%
Natural gas	21
Fuel oil	15
Black coal	28
Renewable energies	20
Other	16
Total	100

Source: [5]

Table 4: Breakdown of energy use in greenhouses (%).

Energy use	%
Heating	88
Water heating	11
Miscellaneous	1
Total	100

Source: [29]

Table 5: Range of energy consumption per category in EU greenhouses (%).

Energy consumption per category	Range of total energy consumption (%)
Heating and cooling	0-99
Irrigation	1-19
Fertilizers	1-27
Pesticides	0-6
Lighting	1%

Source: [5]

3. Use of sustainable energies in agricultural greenhouses

Greenhouses all over the world utilize mainly fossil fuels and grid electricity for covering their energy requirements. The use of renewable energies and low-carbon emission technologies is currently rather limited in greenhouses [2]. Current advances in benign energy technologies have improved their reliability, maturity and cost-effectiveness. Many sustainable energy technologies are currently used in several applications producing heat, cooling and electricity [3, 4]. Their technical and economic viability has been verified although several existing barriers hindering their promotion should be removed for their broad adoption in the agricultural sector. These technologies are also climate friendly with low GHG emissions. Renewable energy sources that can be used in greenhouses for heat and electricity generation include solar energy, biomass and low enthalpy geothermal fluids. Low carbon and high efficiency energy technologies that can be used in greenhouses include co-generation systems, fuel cells, heat pumps and industrial heat rejected from plants. The positive characteristics of benign energy sources and technologies for energy generation in greenhouses include:

A) The use of local energy sources with low or net-zero carbon impact,
B) Less use of carbon-emission fuels and carbon-related electricity,
C) The positive economic impacts for the farmer,
D) The production of more sustainable agricultural products, and
E) The contribution in the achievement of the global target for the transition to a net-zero carbon economy.

Table 6: Renewable and low-carbon emission energy technologies which can be used in greenhouses

Energy source	Energy technology	Energy generation
Solar energy	Solar thermal systems	Heat
Solar energy	Solar-PV panels	Electricity
Wind energy	Wind turbines	Electricity
Solid biomass	Burning systems	Heat
Low enthalpy geothermal fluids	Heat exchange	Heat
Natural gas, biogas	Co-generation systems	Heat, cooling, electricity
Ambient heat and electricity	Heat pumps	Heat, cooling
Natural gas, hydrogen	Fuel cells	Heat, electricity
Rejected heat from industries	Heat exchange	Heat

Source: own estimations

The renewable and low-carbon emission energy technologies which can be used in greenhouses are presented in table 6.

4. The concept of net-zero carbon emission greenhouses due to energy use

Agricultural greenhouses utilize heat and electricity during their operation related mainly with fossil fuels and carbon emissions. The concept of net-zero carbon emission greenhouses is related with the use of renewable energies covering their needs in heat and electricity. Net-zero carbon emission greenhouses can be achieved when:

a) Greenhouses do not use fossil fuels for heat production, and
b) Every year they generate solar electricity equal to the grid electricity consumed. This can be achieved with the installation of solar photovoltaic modulus in them which is allowed with the net-metering regulations.

Alternatively, carbon-free electricity in greenhouses can be generated by other green energy sources and technologies.

It is assumed that greenhouses are connected into the grid and grid electricity is generated only by fossil fuels. However, in many countries grid electricity is partly generated by renewable energy sources. In the case of stand-alone greenhouses all the required heat and electricity should be produced by carbon-free energy sources. Realization of low or net-zero carbon emission greenhouses is important for the achievement of the European and global target for climate change mitigation and the creation of a net-zero carbon economy in the middle of the 21th century. Unfortunately, the absence of incentives for the promotion of sustainable energies in agriculture in Greece does not facilitate the realization of net-zero carbon emission greenhouses.

5. Sizing a solar photovoltaic system and a heat pump covering all the energy requirements in a greenhouse located in Crete, Greece

The energy requirements of a grid-connected agricultural greenhouse used for flowers cultivation located in Crete, Greece can be covered with the use of renewable energy sources instead of fossil fuels. The heating and cooling loads can be covered with a high efficiency heat pump while the required electricity for lighting, operation of several electric machinery and the operation of the heat pump can be covered with green solar electricity generated by a solar photovoltaic system located nearby the greenhouse. The installation of the solar-PV system in the grid-connected greenhouse is allowed by the existing net-metering regulations in Greece. Sizing the heat pump covering all the annual heat requirements and the solar-PV system covering all the annual electricity requirements of the abovementioned greenhouse is made in the following sections. A study related with a greenhouse located in Crete, Greece using solid biomass, covering all the heat demand, and grid electricity has been published [15]. The characteristics and the energy consumption of the abovementioned greenhouse which is used in the current estimations are presented in table 7.

Table 7: Energy consumption in a greenhouse used for flowers cultivation in Crete, Greece.

Operating period	2012-2014
Covered area	3,300 m^2
Cultivated crop	Flowers
Indoor temperature	19°C
Outdoor temperature	Rarely below 0°C
Specific gross heat consumption	214 KWh_{th}/m^2 year
Annual consumption of olive kernel wood	220 tn
Efficiency of the biomass heating system	70%
Power of the biomass heating system	750 KW_{th}
Total annual heat consumption	706,200 KWh_{th}/year
CO_2 emissions saving due to solid biomass use	279 tn CO_2/year
Specific electricity consumption	14 KWh_{el}/m^2 year
Total annual electricity consumption	46,200 KWh_{el}/year
CO_2 emissions due to electricity use	39 tn CO_2/year
Specific total energy consumption	228 KWh/m^2 year
Total annual energy consumption	752,400 KWh/year
Share of electricity to total energy consumption	6.14%

Source: [15]

5.1 Sizing the heat pump

The following assumptions have been made for sizing the heat pump:

a) A water-to-water heat pump is going to be used,
b) The average COP of the heat pump is 3,
c) The heat pump operates 5,000 hours annually,
d) The required power of the heat pump covering the average heat load is estimated at 141.24 KW. The heat pump can cover the cooling load in the greenhouse,
e) The maximum heat load in the greenhouse is 1.8 times the average load. The power of the heat pump for covering the maximum heat load is estimated at 254.23 KW,
f) The unit cost of the heat pump is 4,500 €/KW.

Based on the previous assumptions the annual electricity consumption of the heat pump is at 235,400 KWh, while the total installation cost of the heat pump at 254.23 KW is 1,144,035 €.

5.2 Sizing the solar photovoltaic system generating solar electricity

The following assumptions have been made for sizing the solar-PV system:

a) The solar photovoltaic system will be connected into the grid,
b) It will generate annually all the electricity required for lighting, operation of various electric devices in the greenhouse and the operation of the heat pump, 46,200 KWh/year plus 235,400 KWh/year, totally 281,600 KWh/year,
c) A solar-PV system with nominal power 1 KW_p generates annually in Crete 1,450 KWh_{el}, and

d) The installation cost of a solar-PV system is at 1,200 €/KW_p.

Based on the previous assumptions the nominal power of the solar-PV system is estimated at 194.21 KW_p while its installation cost at 233,052 €. The total cost of the heat pump and the solar-PV system which can generate annually all the required heat and electricity in the greenhouse is at 1,377,087 € which corresponds at 417.30 €/m^2 of the covered surface in the greenhouse.

5.3 Electricity storage in batteries

The generated solar electricity in the grid-connected greenhouse can be also stored in electric batteries and used when needed. The recent regulations concerning net-metering in Greece make mandatory the solar electricity storage in batteries. The use of electric batteries increases the cost of the hybrid renewable energy system required in a net-zero carbon emissions greenhouse.

5.4 Use of a solar thermal system for hot water production

The COP of a water-to-water heat pump is increased when the temperature of the water source used for heat absorption is high.

Table 8: Characteristics of the sustainable energy systems which could generate all the required annually heat and electricity in the abovementioned greenhouse zeroing its net-carbon emissions due to energy use.

Annual heat requirements in the greenhouse	706,200 KWh_{th}/year
COP of a water-to-water heat pump	3
Annual electricity consumption by the heat pump	235,400 KWh_{el}/year
Operation of the heat pump	5,000 hours/annually
Maximum heat load to average heat load in the greenhouse	1.8
Electric power of the heat pump covering the peak heat load	254.23 KW_{el}
Installation cost of a water-to-water heat pump	4,500 €/KW_{el}
Installation cost of the required heat pump	1,144,035 €
Annual electricity consumption for lighting and operation of several machinery in the greenhouse	46,200 KWh_{el}/year
Total annual electricity consumption including the consumption of the heat pump	281,600 KWh_{el}/year
Annual solar-PV electricity generation in Crete	1,450 KWh_{el}/KW_p
Nominal power of a solar-PV system generating all the required electricity in the greenhouse	194.21 KW_p
Installation cost of a solar-PV system	1,200 €/KW_p
Total Installation cost of the required solar-PV system	233,052 €
Total installation cost of the heat pump and the solar-PV system	1,377,087 €
Covered surface of the greenhouse	3,300 m^2
Total installation cost of the heat pump and the solar-PV system per covered surface in the greenhouse	417.30 €/m^2

Source: own estimations

A solar-thermal system producing hot water used for heat absorption can be installed in the greenhouse while the hot water can be stored in a water tank and used from the heat pump when needed. The cost of the solar thermal system and its benefits due to the higher efficiency of the heat pump should be calculated in order to assess its profitability. The characteristics of the sustainable energy systems which could generate all the required heat and electricity in the abovementioned greenhouse zeroing its net-carbon emissions due to energy use are presented in table 8.

6. Discussion

Our findings indicate that the creation of net-zero carbon emission greenhouses due to energy use in Crete, Greece is technically feasible using solar photovoltaic systems and heat pumps. The cost-effectiveness of the solar photovoltaic system depends on the annual solar irradiance which is abundant in Crete. In other regions it could have lower values and the installation of a solar-PV system might not be profitable. The estimated size of the sustainable energy systems depends on the local climate conditions and the accuracy of our results depend on the local climate variations. The heat pump can cover all the heating and cooling needs in greenhouses while the solar photovoltaic system can cover all the annual electricity needs for lighting, operation of several electric machinery as well as the operation of the heat pump in grid-connected greenhouses. It should be noticed that our approach is related only with the operational energy in the abovementioned greenhouse without considering its embodied energy. In other regions where the use of solar-PV systems is not profitable zero-carbon electricity can be generated with other green energy technologies. Instead of heat pumps other heat energy technologies that can be used include the burning of solid biomass the use of industrial rejected heat et cetera. Alternative cooling in the greenhouse can be achieved with solar thermal absorption cooling and chilling systems powered by green electricity. Heat pumps are broadly used to day in many sectors while the high solar irradiance in Crete, Greece favors the use of solar photovoltaic systems. Taking into account that almost 40% of the greenhouses in Greece are located in Crete, an island with abundant solar irradiance, the use of solar photovoltaic systems is desirable and challenging. Since the creation of net-zero carbon emission agricultural greenhouses due to energy use in Crete, Greece is technically feasible using the abovementioned sustainable energy technologies the government should try to incentivize and propagate their creation in order to comply with the EU and global policies for climate change mitigation and the elimination of carbon emissions in the next decades. Our results do not indicate the economic viability of using the abovementioned green energy systems in greenhouses which is important for their promotion with or without state subsidies. Further research should be focused on the technical and economic assessment of using other benign energy technologies for covering the energy needs in greenhouses in Crete. Additionally, in the economic assessment of using heat pumps and solar-PV systems in agricultural greenhouses in Crete, Greece.

7. Conclusions

The possibility of using benign energy systems for covering the energy requirements of agricultural greenhouses located in Crete, Greece has been investigated. A heat pump can cover the heating and cooling requirements while a solar-PV system can cover all the electricity requirements in a grid-connected greenhouse used for flowers cultivation with covered surface at 3,300 m^2 located in Crete, Greece. Both energy systems are mature, reliable and cost-effective. A heat pump with COP at 3 and power at 254.23 KW_{el} can cover the peak heat load in the greenhouse. The installation cost of the heat pump has been estimated at 1,144,035 €. A solar-PV system with nominal power at 194.21 KW_p can generate all the electricity required annually in the greenhouse. The cost of the solar-PV system has been estimated at 233,052 € while the unit cost of both the abovementioned energy systems is at 417.30 €/m^2. Our results indicate that the combined use of solar photovoltaic energy and heat pumps can cover all the energy needs in modern agricultural greenhouses in Crete, Greece eliminating their net-carbon emissions due to energy use. Therefore, already commercialized benign energy technologies can be used in greenhouses assisting the creation of agricultural production systems with neutral climate impacts.

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