International Journal of Current Science Research and Review
ISSN: 2581-8341
Volume 09 Issue 11 November 2026
DOI: 10.47191/ijcsrr/V9-i11-16, Impact Factor: 8.048
IJCSRR @ 2026
www.ijcsrr.org

Possibilities of Using Solar Photovoltaics and Electric Batteries in Agricultural Greenhouses in The Island of Crete, Greece

Vourdoubas John
Consultant Engineer, 107B El. Venizelou Str., 73132, Chania, Crete, Greece

ABSTRACT: Mitigation of the global environmental challenge of climate change requires the elimination of carbon emissions. Agricultural greenhouses are energy intensive production systems based mainly on fossil fuels. However, several renewable energy technologies are reliable and cost-effective and they could be used in them for heat and power generation. The possibility of using a solar photovoltaic and a battery storage system meeting the electricity demand in a grid-connected greenhouse in Crete, Greece which already uses locally produced solid biomass to cover the heat demand has been investigated. It has been estimated that the use of a solar photovoltaic system with nominal power 31.29 kW_p generating 48,500 kWh/year can meet the annual power demand in an existing greenhouse with covered surface 3,300 m^2 in Crete. The cost of the solar photovoltaic system is estimated at 40,000 €. The capacity of Lithium-ion batteries for achieving one day power autonomy in the greenhouse has been estimated at 147.64 kWh while their cost is estimated at 63,333 €. The combined use of a solar photovoltaic system meeting the electricity demand and solid biomass meeting the heat demand results in a net-zero emissions greenhouse. Both renewable energy technologies are mature and economically attractive and they are currently used in Crete in many sectors. The current work indicates that decarbonization of agricultural greenhouses in Crete replacing the use of fossil fuels with renewable energies is feasible. The results of the present study could be used by all stakeholders of the greenhouse industry.

KEYWORDS: agricultural greenhouses, carbon emissions, Crete-Greece, electric batteries, renewable energies

1. INTRODUCTION

Agricultural greenhouses produce several vegetables necessary to meet the food demand of a growing global population. Their productivity is high compared to conventional agriculture while they consume large amounts of energy controlling the indoor environment [1], [2], [3]. Although greenhouses utilize mainly fossil fuels several renewable energies including solar energy, biomass and geothermal energy, can be used for heat and power generation in them [4], [5], [6], [7], [8]. Use of renewable energies can contribute in the achievement of net-zero emission greenhouses due to operational energy use complying with the EU target for eliminating the net-carbon emissions by 2050 [9], [10], [11]. Solar photovoltaic systems combined with battery storage can be used in greenhouses for meeting part or all of their electricity demand offsetting the grid electricity use [12], [13]. Lithium-ion (Li-ion) batteries are currently used in many applications and they can be used for solar electricity storage in greenhouses [14], [15], [16], [17].

The aim of the current study is to examine the possibility of using a solar photovoltaic system combined with Lithium-ion batteries for meeting all the electricity demand in a grid-connected greenhouse located in Crete, Greece. The greenhouse already meets its heating demand using locally produced solid biomass. Meeting all the heat and electricity demand with solar photovoltaic energy and solid biomass results in a net-zero emission greenhouse due to operational energy use.

The text is structured as follows: After the literature survey the energy consumption in greenhouses and the use of sustainable energies in them are mentioned. Next, the use of renewable energies for elimination of carbon emissions in greenhouses and the use of electric batteries for storing green electricity in them are described. After that, the use of solar photovoltaics (Solar-PV) with battery storage for meeting the power demand in an agricultural greenhouse in Crete, Greece is analyzed. The text ends with discussion of the findings, the conclusions drawn and the citation of the references used.

The text is innovative since there are no many studies related with the use of solar photovoltaics with battery storage in agricultural greenhouses in Crete while it fills a gap regarding the use of renewable energies in Cretan greenhouses. The results of the study could be useful to all stakeholders of the greenhouse industry as well as to energy companies installing solar-PV and power storage systems.

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2. LITERATURE SURVEY

The energy consumption in different greenhouses has been studied [1]. The authors investigated four different double plastic covered greenhouses in Serbia region used for lettuce production. They estimated the energy consumption in the range of 9.76 MJ/m^2 to 13.93 MJ/m^2. The adoption of renewable energies in agricultural greenhouses has been examined [2]. The authors stated that energy consumption in greenhouses is variable and generally dependent on fossil fuels. High energy systems are used in greenhouses in northern Europe while low energy systems are dominant in southern European greenhouses. The creation of net-zero emission greenhouses due to energy use in Mediterranean region has been examined [3]. The author stated that several benign energy systems such as solar-PV systems, biomass burning systems, geothermal heat pumps powered by green electricity can be used in Mediterranean basin for heat and power generation reducing or eliminating the energy-related carbon footprint in greenhouses. The concept of an energy system applicable in greenhouses based on renewable energies has been developed [4]. The authors proposed the use of a complex energy system based on fuel cells and solar-PV panels generating heat and electricity combined with heat and power storage. They mentioned that the use of solar energy and biomass in greenhouses will reduce their carbon emissions and increase their sustainability. The integration of renewable energies in greenhouses has been studied [5]. The authors proposed the use of biomass derived from wastes and solar-PV panels to cover the energy demand in greenhouses. They recommended the use of a holistic approach to optimize the use of renewable energies in them. The use of renewable energies in greenhouses has been studied [6]. A hybrid energy system consisted of solar-PV panels, a wind turbine and a battery storage system in a greenhouse has been modelled. The energy system was powering the heat and ventilation in the greenhouse and the simulation indicated that it can control the indoor microclimate. The use of various renewable energy technologies for heating greenhouses has been assessed [7]. The authors examined the use of solar energy, biogas and geothermal heat pumps for heating. They stated that the use of biogas and geothermal heat pumps can cover all the heating needs in greenhouses while solar energy can be combined with heat storage for meeting all the heating needs. The use of low- and zero-carbon energy technologies in agricultural greenhouses has been investigated [8]. The author stated that several renewable energies such as solar energy, wind energy, geothermal energy and biomass can be used for heat, cooling and power generation in greenhouses. Additionally, he mentioned that several low-carbon energy technologies such as heat pumps, cogeneration systems and district heating can be also used in them. The near-zero energy greenhouses have been studied [9]. The authors stated that integration of renewable energies (REs), optimization of energy saving systems and use of advanced controlled technologies can minimize the energy consumption in greenhouses. They mentioned that adoption of hybrid RE systems and improvement of greenhouse design and material selection should be prioritized in achieving near-zero energy greenhouses. An analysis of scope-1, scope-2 and scope-3 emissions in several processes has been conducted [10]. The authors stated that while scope-1 and scope-2 emissions can be easily evaluated, estimation of scope-3 emissions produced by the supply chain is more difficult. The classification of greenhouse gas (GHG) emissions in three categories, scope-1, scope-2 and scope-3 has been reported [11]. They are classified as emissions created by the company and those created by the value chain. The enhancement of energy autonomy in greenhouses with the use of semi-transparent solar-PV systems and electric batteries has been studied [12]. The authors stated that the use of battery storage systems increases significantly the energy autonomy in greenhouses in summer and winter. The use of solar-PV systems and heat pumps for achieving net-zero carbon emission greenhouses has been studied [13]. The author mentioned that an agricultural greenhouse located in the island of Crete, Greece can install a solar-PV system and a high efficiency heat pump, powered by solar electricity, to meet all the electricity, heat and cooling demand. The Lithium-ion batteries and the future of sustainable energies have been reviewed [14]. The authors stated that batteries play a crucial role in the transition to a low-carbon future. They mentioned that they consist of a versatile and reliable energy storage technology. The future of Li-ion batteries has been examined [15]. The authors stated that they achieve densities up to 300 Wh/kg and cycle lives exceeding 2,000. They mentioned their critical role in achieving decarbonization, integration of renewable energies and enhancement of grid stability. The Li-ion batteries have been studied [16]. The authors stated that their energy density is rapidly increasing while their cost is decreasing. A technoeconomic analysis of Li-ion batteries has been conducted [17]. The authors compared the cost of Li-ion and Lead-acid batteries integrated in a solar-PV grid connected system. They stated that the levelized cost of electricity of Li-ion batteries is at 0.32 €/kWh compared to 0.34 €/kWh for Lead-acid batteries. The thermal safety of Li-ion batteries has been examined [18]. The authors stated that Li-ion batteries have high temperature sensitivity and relatively low operating temperature range. They mentioned that heat generation, accumulation and propagation should be prevented with appropriate heat dissipation in batteries pack. The integration of Li-ion batteries with solar energy in large scale systems has been explored [19]. The authors examined the synergy between Li-ion batteries and solar power to achieve a balance between energy supply and demand. The utilization of solar

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energy in a greenhouse has been studied [20]. The authors estimated the amount of solar energy absorbed by the greenhouse and the amount lost outside of it. The optimization of energy consumption in an agricultural greenhouse has been analyzed [21]. The greenhouse has integrated a solar-PV system, a battery and an energy management system. The perspectives for zero GHG emissions in agricultural greenhouses have been investigated [22]. The authors stated that existing solar thermal collectors, micro-turbines, geothermal heat pumps and rooftop solar-PV systems can assist greenhouses to reduce their energy demand and minimize their carbon emissions. The use of solar energy technology in agricultural greenhouses has been reviewed [23]. The authors stated that many studies were focused on hybrid systems combining solar energy technologies with other benign energy technologies. They mentioned the necessity to integrate energy storage technologies in agricultural greenhouses. The use of combined heating systems involving renewable energies in greenhouses in the Republic of Korea has been investigated [24]. The authors examined the use of three renewable energy systems consisted of a) a pellet boiler, b) a hydrothermal heat pump, and c) solar thermal collectors. They stated that the most economical heating system was the pellet boiler. The use of Li-ion batteries in off-grid applications has been examined [25]. The authors stated that Li-ion batteries are suitable for solar-PV systems with nominal power $1kW_p$-$1\ MW_p$ and size from 2 to 500 kWh. They mentioned that the usable battery energy to solar-PV nominal power is in the range 2.5 to 4. The factors influencing the energy consumption in greenhouses focused on cucumber production in Iran have been explored [26]. The authors stated that a series of factors can anticipate the energy consumption in greenhouses. These factors included: technical knowledge, environmental values, environmental beliefs, environmental norms, educational level, greenhouse's work experience, cost-effectiveness and technical management. The present and future uses of biomass for energy generation in Crete have been studied [27]. The author stated that olive tree byproducts and residues are currently used by burning for heat generation in many sectors. The energy use and the carbon footprint in greenhouses used for tomato cultivation in Almeria, Spain have been estimated [28]. The authors stated that cultivating heated tomato demands 5.4 times more energy while it increases 2.75 times the CO_2 emissions per kg of product. An assessment of scope-1, scope-2 and scope-3 CO_2 emissions in industry has been made [29]. It is stated that scope-1 emissions are related with on-site energy generation, scope-2 emissions with utilities supplied in industry while scope-3 emissions are related with the supply chain. Analysis of the carbon footprint in tomato cultivation in Greece has been conducted [30]. The authors stated that the total carbon footprint in a tomato crop producing 98.4 ton/ha was 0.2 $kgCO_2/kg$. The energy-efficiency optimization strategies in greenhouses have been reviewed [31]. The authors stated than during the last fifteen years a new trend in energy consumption reduction for greener production and microclimate control in greenhouses has been emerged. They mentioned that current advances in control algorithms have contributed in better control of the indoor environment and the reduction of energy use. The solar photovoltaic-integrated greenhouses in the tropics have been studied [32]. The authors stated that the integration of solar-PV technology in greenhouses offers an efficient energy system for sustainable energy usage in agriculture. They mentioned that in addition to meet the energy needs of the crops solar electricity can power cool storage facilities and light vehicles for greenhouse management.

3. ENERGY CONSUMPTION IN GREENHOUSES

Energy consumption in greenhouses depends on several factors, including climatic conditions, greenhouse design, crop type and cultivation practices. The main sources of energy demand are heating, cooling, ventilation, artificial lighting and irrigation. Heating is often the largest energy consumer in greenhouses located in cold climates. During winter, heating systems maintain suitable temperatures for plant growth and prevent crop damage. These systems may use electricity, natural gas, heating oil, biomass, or other energy sources. Heat losses through greenhouse coverings and ventilation can significantly increase energy requirements. Cooling and ventilation are particularly important in warm climates. High temperatures can negatively affect plant development, reduce yields and compromise product quality. Fans, evaporative cooling systems and shading technologies are commonly used to maintain suitable growing conditions. Artificial lighting may also contribute significantly to energy consumption, especially during winter or in greenhouses producing crops with high light requirements. In addition, electricity is needed for irrigation pumps, fertigation equipment, sensors and automated climate-control systems. Several factors influence greenhouse energy consumption. Climate is particularly important because greenhouses in cold regions generally require more heating, whereas those in hot regions may have greater cooling requirements. Greenhouse construction also plays a significant role. The type of covering material, insulation, airtightness and structural design influence heat transfer and energy losses. Crop requirements and production strategies are equally important. Different crops require different temperature, humidity and lighting conditions. Furthermore, intensive year-round production may require more energy than seasonal cultivation. Poorly maintained equipment and inefficient climate-control

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practices can increase energy consumption unnecessarily. Therefore, appropriate greenhouse design and effective management are essential for improving energy efficiency. High energy consumption can increase production costs and reduce the profitability of greenhouse farming. Energy expenses are particularly important in energy-intensive systems that require continuous heating, cooling, or supplementary lighting. Rising energy prices can also affect the competitiveness of greenhouse-grown products. The environmental impact depends largely on the energy sources used. Greenhouses relying on fossil fuels contribute to greenhouse gas emissions, particularly carbon dioxide, which contributes to climate change. Electricity consumption may also generate indirect emissions when electricity is produced from fossil fuels. Nevertheless, greenhouses can provide environmental benefits by increasing crop production per unit of land, improving water-use efficiency and protecting plants from adverse weather conditions. Their overall sustainability depends on the relationship between energy consumption, crop yield and resource efficiency. Several strategies can reduce energy consumption in greenhouses. Improving insulation through double-layer coverings and thermal screens helps reduce heat losses during winter. Efficient heating systems, heat pumps and heat recovery technologies can further decrease energy requirements. The use of light-emitting diode (LED) lamps can reduce electricity consumption compared with less efficient lighting technologies. Automated climate-control systems can also optimize heating, cooling and ventilation according to indoor conditions and weather forecasts. Energy consumption is a major factor influencing the economic and environmental sustainability of greenhouse production. Heating, cooling, ventilation, lighting and irrigation all contribute to energy demand, although their relative importance varies according to climate and cultivation practices. Improving insulation, adopting efficient technologies and optimizing climate control can reduce energy costs and environmental impacts. Ultimately, sustainable greenhouse production requires an integrated approach that minimizes energy consumption while maintaining high crop productivity, quality and profitability. Table 1 indicates the operational energy consumption and carbon emissions in agricultural greenhouses producing tomato while Table 2 the energy consumption per category in EU greenhouses.

Table 1. Operational energy consumption and carbon emissions in agricultural greenhouses cultivating tomato crops

Crop, country	Energy consumption	Carbon emissions
Tomato, Europe	0.8-160.5 MJ/kg	0.1-10.1 $kgCO_2/kg$
Tomato, Netherlands	21.7 MJ/kg	
Tomato, France	31.6 MJ/kg	2.02 $kgCO_2/kg$
Tomato, Spain	13.4 MJ/kg	0.92 $kgCO_2/kg$
Tomato, Greece		0.20 $kgCO_2/kg$
Tomato, Turkey	5.34 MJ/m^2 year	
Tomato and other vegetables, Turkey	23.8-28 MJ/m^2 year	

Source: [3], [28], [30]

Table 2. 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: [2]

4. THE USE OF SUSTAINABLE ENERGY TECHNOLOGIES IN AGRICULTURAL GREENHOUSES

The increasing cost of conventional energy sources and the environmental impacts associated with fossil fuel consumption have encouraged the adoption of renewable energy technologies in greenhouse production. Solar, geothermal, wind and biomass energy can provide zero emissions heat and electricity reducing the operating costs while supporting more environmentally friendly agricultural systems. Additionally, energy efficient technologies such as heat pumps and cogeneration systems can supply low-

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carbon energy to greenhouses. Solar energy is one of the most promising renewable energy sources for greenhouses because agricultural production often takes place in areas with abundant sunlight. Solar photovoltaic panels convert solar radiation into electricity, which can be used to operate ventilation fans, irrigation pumps, lighting systems, and automated climate-control equipment. Depending on the installation and local regulations, excess electricity can be stored in batteries or supplied to the electricity grid. Solar thermal systems can also be used to capture solar radiation and convert it into heat for greenhouse heating. This heat may be stored in water tanks or other thermal storage systems for use during periods of reduced solar radiation. However, the availability of solar energy varies throughout the day and across seasons, making energy storage and complementary heating systems important for reliable operation. Geothermal energy is another potential solution, particularly in areas with suitable geological conditions. Ground-source heat pumps use the relatively stable temperature of the ground to provide heating in winter and, in some systems, cooling in summer. These systems can improve energy efficiency by transferring heat rather than generating it directly. Their effectiveness depends on local ground conditions, system design, and electricity consumption. Biomass can also provide renewable heat through the combustion of agricultural residues, wood pellets and other suitable organic materials. Biogas can be produced by anaerobic digestion of organic wastes and used for heat generation. This approach may be particularly attractive in agricultural regions where biomass resources are locally available. Nevertheless, sustainable sourcing, emissions control, and equipment maintenance are necessary to ensure environmental benefits. Wind energy may contribute to greenhouse electricity demand when wind resources are sufficient. Small wind turbines can supply electricity for auxiliary equipment, although their feasibility depends on local wind conditions, installation costs and maintenance requirements. Heat pumps are energy efficient devices which can produce heat and cooling in greenhouses. They use electricity and ambient heat generating 3 to 6 times more heating and cooling energy compared to the consumed electricity. When the heat pumps are powered by solar electricity have zero-carbon impacts. Cogeneration systems can generate both heat and electricity with gas or steam turbines from the same fuel achieving energy efficiency in the range of 80-85%. They can use natural gas or biogas having low- or zero-carbon emissions. Fuel cells are cogeneration systems producing heat and electricity via electrochemical processes having high energy efficiency in the range of around 80%. They can use natural gas, biogas or hydrogen having low- or zero-carbon impacts. Electric batteries can store electricity and deliver it to greenhouses when needed. They are useful for storing grid electricity when its price is low and deliver it when the price is high. They can be also used for storing solar electricity generated by solar-PV systems in greenhouses and deliver it when the solar irradiance is low. The use of sustainable energies in greenhouses offers several economic and environmental advantages. First, it can reduce dependence on fossil fuels and limit exposure to fluctuations in conventional energy prices. Lower energy expenses can improve farm profitability, particularly in intensive greenhouse systems with substantial heating, cooling and lighting requirements. Second, they can reduce greenhouse gas emissions associated with agricultural production. Solar and wind electricity, for example, have zero operational emissions. Replacing conventional heating systems with appropriately designed heat pumps powered by renewable electricity can further reduce the carbon footprint of greenhouse operations. Renewable energies can also improve energy security, particularly in remote agricultural areas where access to reliable electricity or conventional fuels may be limited. When combined with energy-efficient equipment and storage technologies, renewable energy systems can contribute to a more resilient and sustainable food production system. Despite these benefits, the adoption of sustainable energies in greenhouses faces several challenges. The initial investment required for photovoltaic panels, heat pumps, storage systems and associated equipment can be substantial. In addition, the intermittent nature of solar and wind energy may create difficulties in meeting energy demand continuously, especially during winter or periods of unfavorable weather. These challenges can be addressed through appropriate system design, financial incentives, energy storage and the integration of multiple energy sources. Smart energy-management systems can coordinate renewable electricity production with heating, cooling, irrigation and lighting requirements. Furthermore, energy-efficient greenhouse coverings, thermal screens and improved insulation can reduce total energy demand, making renewable energy installations more effective and economically viable. Although investment costs and energy-supply variability remain important challenges, combining sustainable energies with energy-efficient technologies and intelligent management can provide effective solutions. Table 3 indicates the sustainable energy technologies that can be used in agricultural greenhouses.

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Table 3. Sustainable energy technologies that can be used in agricultural greenhouses

Technology	Energy/fuel used	Generated energy	Type of energy generated	Operational carbon emissions
Solar thermal mirrors	Solar energy	Heat	Intermittent	No
Solar PV panels	Solar energy	Electricity	Intermittent	No
Wind turbines	Wind energy	Electricity	Intermittent	No
Solid biomass burning systems	Solid biomass	Heat	Continuous	No assuming that biomass use has zero carbon emissions
Biogas burning systems	Biogas	Heat	Continuous	No assuming that biomass use has zero carbon emissions
Heat pumps	Electricity and ambient heat	Heat, cooling	Continuous	No if they use green electricity
Geothermal heat exchangers	Geothermal fluids	Heat	Continuous	No
Cogeneration of heat and power	Natural gas, biogas, hydrogen	Heat, electricity	Continuous	No if they use biogas or green hydrogen
Fuel cells	Natural gas, biogas, hydrogen	Heat, electricity	Continuous	No if they use biogas or green hydrogen
Electric batteries	Electricity	Electricity	Continuous	No

Source: own estimations

5. THE USE OF RENEWABLE ENERGIES FOR ELIMINATION OF CARBON EMISSIONS IN GREENHOUSES

A greenhouse can approach net-zero operational energy-related carbon emissions when its energy demand is met by zero-carbon renewable energy sources and on-site fossil-fuel consumption is eliminated. It should be noted that before replacing fossil fuels with renewable energies the energy consumption in greenhouses should be minimized with several energy saving measures. On-site generated direct carbon emissions are considered scope-1 emissions. For example, a greenhouse using biomass or renewable-electricity-powered heat pumps for space heating, LED lighting and thermal energy storage could substantially eliminate its scope-1 emissions. However, achieving complete carbon neutrality is more challenging than eliminating direct emissions from fossil fuel combustion. Electricity imported from a carbon-intensive grid may still generate indirect emissions. These emissions are considered scope-2 emissions. Scope-2 emissions in greenhouses can be eliminated using solar-PV systems and power storage generating carbon-free solar electricity instead of using grid electricity. Emissions in the supply chain that are related to the materials used such as plastics, pesticides, fertilizers, package material et cetera and their transportation are considered scope-3 emissions. Scope-3 emissions are outside of greenhouse's direct control and their elimination is more difficult. Apart from the operational emissions the emissions related to the construction, maintenance and deconstruction of greenhouses are considered embodied emissions. The sum of embodied and operational emissions in greenhouses are their life-cycle carbon emissions. It is therefore important to distinguish between zeroing scope-1, -2, -3 operational emissions, embodied emissions and life-cycle emissions. A comprehensive carbon assessment is necessary to determine whether a greenhouse has genuinely achieved its emissions-reduction targets. Therefore, renewable energies can play a decisive role in eliminating scope-1 and scope-2 operational carbon emissions in greenhouses. Solar energy, biomass, heat pumps, geothermal systems and other suitable renewable technologies can replace fossil fuels, while energy-efficient equipment, thermal insulation and energy storage systems can reduce the overall energy requirements. Nevertheless, complete decarbonization requires an integrated strategy that addresses both energy consumption and emissions from agricultural inputs and infrastructure. By combining renewable energies with efficient greenhouse design and intelligent management, farmers can move toward highly productive, economically viable, and low- or zero-carbon agricultural systems. Ultimately, the goal is to produce high-quality crops while minimizing the contribution of greenhouse cultivation to climate change.

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Table 4 indicates the renewable energy systems that can replace fossil fuels in agricultural greenhouses in Crete while Table 5 the sustainable energy technologies that can eliminate scope-1 and scope-2 carbon emissions in greenhouses in Crete.

Table 4. Renewable energy systems that can replace fossil fuels in agricultural greenhouses in Crete

Energy system	Energy used	Generated energy	Is the technology reliable and mature?	Characteristics
Solar Photovoltaic	Solar energy	Electricity	Yes	Solar energy is abundant in Crete
Small-scale wind turbine	Wind energy	Electricity	Yes	It is cost-effective when the average wind speed is satisfactory
Solid biomass/biogas burning	Biomass/biogas	Heat	Yes	Solid biomass is abundant in Crete while biogas is limited
Co-generation of heat and power	Biogas	Electricity and heat	Yes	Biogas is limited in Crete. The technology is attractive only in large-scale greenhouses
High efficiency heat pumps	Green electricity and ambient heat	Heat and cooling	Yes	Heat pumps should be powered by green electricity

Source: own estimations

Table 5. Sustainable energy technologies that can eliminate scope-1 and scope-2 carbon emissions in greenhouses in Crete

Type of emissions	Renewable energy technology	Generated energy
Scope-1 emissions	Solid biomass/biogas burning	Heat
Scope-1 emissions	High efficiency heat pumps powered by solar electricity	Heat
Scope-2 emissions	Solar Photovoltaic systems	Electricity
Scope-2 emissions	Small-scale wind turbines	Electricity

Source: own estimations

6. THE USE OF ELECTRIC BATTERIES FOR STORING GREEN ELECTRICITY IN GREENHOUSES

Electricity is used in greenhouses for heating, cooling, ventilation, irrigation, artificial lighting and automated climate-control systems. The integration of renewable energy systems, particularly solar photovoltaic panels, can reduce dependence on grid electricity and lower carbon emissions. However, generation of renewable electricity is variable and does not always coincide with energy demand. Electric batteries offer an effective solution by storing surplus electricity and supplying it when solar electricity generation is insufficient, thereby improving the energy efficiency and sustainability of greenhouse production. Electric batteries store electrical energy in chemical form and release it when required. In greenhouses equipped with photovoltaic panels, batteries can store excess electricity generated during sunny hours for use during the evening, at night, or during periods of reduced solar radiation. Similarly, batteries can store electricity generated by wind turbines when production exceeds immediate demand. A typical greenhouse energy system consists of renewable electricity generation, a battery storage unit, an inverter and an energy management system. The inverter converts electricity between direct and alternating current, when necessary, while the management system coordinates energy generation, storage, and consumption. This arrangement allows greenhouse operators to use a greater proportion of their own renewable electricity and reduce their dependence on the electricity grid. One of the main advantages of battery storage is the improved utilization of renewable energy. Without storage, excess solar electricity may be exported to the grid or curtailed when it cannot be used immediately. Batteries allow this electricity to be retained and consumed later, increasing the contribution of renewable energy to greenhouse operations. Battery systems can also reduce electricity costs by supplying stored energy during periods when grid electricity prices are high. Depending on the electricity tariff and system configuration, they may

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help reduce peak demand and improve the economic performance of greenhouse production. Another important benefit is the potential reduction in carbon emissions. By replacing electricity generated from fossil fuels with stored renewable electricity, batteries can contribute to the decarbonization of greenhouse operations. They can also provide short-term backup power for essential equipment during grid interruptions, helping maintain irrigation, ventilation and climate-control functions. However, backup capability depends on the system's design and available battery capacity. Despite their benefits, battery storage systems present several challenges. The initial investment can be substantial, particularly for large commercial greenhouses with high electricity demand. Batteries also have limited storage capacity and their performance gradually decreases with repeated charging and discharging. Their environmental impact depends on the materials used in manufacturing, the electricity used for charging, their operational lifetime and recycling practices. Furthermore, batteries are not always the most economical solution for storing energy over long periods. Greenhouse operators must therefore assess daily consumption patterns, renewable electricity production, battery capacity, efficiency and expected financial savings before investing in a storage system. Therefore, electric batteries play an important role in improving the energy efficiency, sustainability and reliability of modern greenhouses. In on-grid greenhouses, batteries can store excess solar electricity produced during the day and supply it during periods of low solar generation or high electricity demand. This reduces dependence on the electricity grid, lowers energy costs and helps avoid peak electricity tariffs where applicable. Batteries can also improve energy management and provide backup power during grid outages, protecting crops from sudden interruptions to critical environmental control systems. In off-grid greenhouses, batteries are particularly valuable because they provide energy independence and help overcome the intermittent nature of renewable energy sources. They store surplus electricity for use at night or during cloudy weather, ensuring a more stable power supply in locations without access to the electricity grid. Combined with renewable electricity generation and an appropriately sized energy management system, batteries can significantly improve operational reliability. Overall, electric batteries support the transition towards sustainable greenhouse production by reducing fossil fuel consumption, lowering greenhouse gas emissions, improving energy efficiency and increasing resilience. Their proper sizing and integration can contribute to more productive, cost-effective and environmentally friendly greenhouse systems. Table 6 indicates the benefits in using electric batteries in agricultural greenhouses in Crete.

Table 6. Benefits in using electric batteries in agricultural greenhouses in Crete

1	Batteries installed in off-grid greenhouses can store excess solar electricity produced during the day and supply it during periods of low or zero solar electricity generation.
2	Batteries installed in greenhouses can avoid peak electricity tariffs
3	Batteries can provide backup power in greenhouses during grid outages
4	In off-grid greenhouses batteries provide energy independence and help overcome the intermittent nature of renewable energies
5	Batteries installed in greenhouses reduce the use of grid electricity generated often by fossil fuels resulting in carbon emissions
6	Batteries installed in greenhouses store solar electricity when its injection into the grid does not offer any financial benefit and use it when it is profitable

Source: own estimations

7. USE OF SOLAR PHOTOVOLTAICS WITH BATTERY STORAGE FOR MEETING THE POWER DEMAND IN AN AGRICULTURAL GREENHOUSE IN CRETE, GREECE

A grid-connected agricultural greenhouse operates in north-western Crete meeting all its heat demand using only locally produced olive kernel wood. Fossil fuels are not used on-site and scope-1 direct emissions are zero. The covered surface of the greenhouses is 3,300 m^2 and the indoor temperature is kept on average at 19°C in the winter. The electricity demand is currently covered by grid electricity. The use of solar-PV electricity compensating the grid electricity use will eliminate the indirect scope-2 emissions in the greenhouse. The annual electricity consumption in the greenhouse is 48,500 kWh/year, the specific electricity consumption is 14.70 kWh/m^2 year and the average daily electricity consumption is 132.88 kWh/day. Assuming that the annual yield of solar-PV systems in Crete is 1,550 kWh/kW_p year the nominal power of a solar-PV system generating annually the required electricity in the greenhouse is 48,500 (kWh/year) /1,550 (kWh/kW_p year) = 31.29 kW_p. The installation cost of the solar-PV system with nominal

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power 32 kW_p is estimated at around 40,000 €. Lithium-ion batteries can be used in the greenhouse storing solar electricity. Assuming that the batteries can provide three days power autonomy in the greenhouse, based on average daily electricity consumption, their recoverable capacity should be 132.88 (kWh/day) X 3 (days) = 398.64 kWh. Assuming that the Lithium-ion batteries have round-trip energy efficiency 90% their nominal capacity should be 442.93 kWh. The approximate cost of a Li-ion battery at 450 kWh installed in Crete is estimated at 190,000 €. For one day autonomy, based on average daily electricity consumption, the nominal capacity of the batteries is estimated at 147.64 kWh and their cost at 63,333 €. Table 7 indicates the size of a solar-PV and battery storage system meeting all the power demand in an agricultural greenhouse in Crete, Greece.

Table 7. Size of a solar-PV and battery storage system meeting all the power demand in an agricultural greenhouse in Crete, Greece

Surface of the greenhouse	3,300 m^2
Annual electricity consumption	48,500 kWh/year
Average daily energy consumption	132.88 kWh/day
Annual yield of solar-PV systems in Crete	1,550 kWh/kW_p
Nominal power of solar-PV system generating 48,500 kWh/year	31.29 kW_p
Installation cost of the solar-PV system	40,000 €
Installation cost of the solar-PV system per m^2	12.12 €/m^2
Capacity of Lithium-ion batteries achieving three days power autonomy in the greenhouse	442.93 kWh
Installation cost of the electric batteries achieving three days power autonomy in the greenhouse	190,000 €
Capacity of Lithium-ion batteries achieving one day power autonomy in the greenhouse	147.64 kWh
Installation cost of the electric batteries achieving one day power autonomy in the greenhouse	63,333 €
Carbon emission coefficient for grid electricity generation in Crete	0.5 kgCO_2/kWh
Annual carbon emissions due to grid electricity use in the greenhouse	24.25 tnCO_2/year
Cost of the required solar-PV system eliminating the annual CO_2 emissions due to grid electricity use in the greenhouse (without power storage)	1.65 € per kgCO_2 annually saved

Source: own estimations

8. DISCUSSION

The possibility of meeting the electricity demand in an agricultural greenhouse in Crete, Greece with a solar-PV and a power storage system has been studied. The greenhouse already uses solid biomass, produced by byproducts and residues of the local olive oil industry, for meeting all its heating demand avoiding the use of fossil fuels. Solar photovoltaic energy is economically attractive and it is currently used in many sectors in Crete. The use of solar electricity and solid biomass for meeting all the power and heat demand in the greenhouse studied eliminates all the carbon emissions related to operational energy use. Many greenhouses in Crete are not heated due to the mild climate in the island. These greenhouses can meet all their requirements in lighting, irrigation, cooling and operation of various machinery with solar-PV electricity. Power storage in the greenhouse using Li-ion batteries has many advantages. Batteries can store solar electricity when it is not needed in the greenhouse or in the grid and use it later. However, although the installation cost of Li-ion batteries has decreased nowadays it remains high. The combined use of solar-PV energy and solid biomass in the greenhouse studied for meeting all their energy requirements avoids the use of fossil fuels and can eliminate all the energy-related operational carbon emissions. In greenhouses which are not heated in Crete the solar-PV system and the electric battery can be seized to generate solar electricity equal to grid electricity consumption and to achieve the desired power autonomy. The technology of solar-PV and solid biomass burning systems is well-known, reliable and cost-efficient. The accuracy of our estimations depends on the accuracy of the energy data of the greenhouse and the assumptions made. Future work should be focused on the estimation of a solar-PV system meeting the total electricity demand in the greenhouse which uses a high-efficiency heat pump powered by solar electricity for meeting all its heat and cooling requirements.

International Journal of Current Science Research and Review
ISSN: 2581-8341
Volume 09 Issue 11 November 2026
DOI: 10.47191/ijcsrr/V9-i11-16, Impact Factor: 8.048
IJCSRR @ 2026
www.ijcsrr.org

9. CONCLUSIONS

The possibility of using a solar photovoltaic system combined with Li-ion batteries for meeting all the electricity demand in a grid-connected greenhouse located in Crete, Greece has been explored. The results can be summarized as follows:

a) Solar-PV systems consist of a reliable, mature and cost-effective technology used nowadays in many sectors in Crete. Use of this technology in greenhouses in Crete is attractive.
b) The use of solar photovoltaics can eliminate the indirect scope-2 carbon emissions related to grid electricity use in greenhouses in Crete.
c) The use of solar-PV systems in greenhouses can be combined with the use of li-ion batteries storing the solar electricity when it is not needed and use it when is needed.
d) The use of electric batteries in agricultural greenhouses has many benefits.
e) The use of a solar-PV system with nominal power 31.29 kW_p generating 48,500 kWh/year can meet the power needs of an existing greenhouse with covered surface 3,300 m^2 in Crete. The cost of the solar-PV system is estimated at 40,000 €.
f) The capacity of Lithium-ion batteries achieving three days power autonomy in the greenhouse is 442.93 kWh and their cost is estimated at 190,000 €. Their capacity for achieving one day power autonomy is 147.64 kWh while their cost is estimated at 63,333 €.
g) The combined use of solar-PV energy and solid biomass in Cretan greenhouses can eliminate all their scope-1 and scope-2 emissions.

The main takeaways of the present study are: a) the use of solar-PV systems combined with battery storage in greenhouses in Crete is technically feasible while the cost of the electric batteries is higher than the cost of the solar-PV system, and b) the use of the abovementioned sustainable energy systems combined with a heating system using locally produced solid biomass can eliminate all scope-1 and scope-2 operational emissions in Cretan greenhouses achieving their decarbonization due to energy use.

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International Journal of Current Science Research and Review
ISSN: 2581-8341
Volume 09 Issue 11 November 2026
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International Journal of Current Science Research and Review
ISSN: 2581-8341
Volume 09 Issue 11 November 2026
DOI: 10.47191/ijcsrr/V9-i11-16, Impact Factor: 8.048
IJCSRR @ 2026
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Cite this Article: John, V. (2026). Possibilities of Using Solar Photovoltaics and Electric Batteries in Agricultural Greenhouses in The Island of Crete, Greece. International Journal of Current Science Research and Review, 9(11), pp. 5679-5690. DOI: https://doi.org/10.47191/ijcsrr/V9-i11-16