THE UNIVERSITY OF HULL

Innovative uses of renewable energy sources in the agricultural sector on the island of Crete, Greece

A Thesis submitted for a Ph.D. by published work

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Foreword

The following work contains the synthesis of research undertaken during the last ten (10) years which has been published in peer-reviewed scientific journals during 2015-2016, as well as the submitted papers for consideration within this thesis. The author, who is a candidate for a Ph.D. by published work, currently lives and works on the island of Crete, Greece. He has been lecturing for the last 12 years at the Technological Education Institute of Crete in the Department of Natural Resources Engineering and Environment. He submitted the current thesis in May 2016 to Hull University, England, in accordance with the regulations of the University of Hull for this degree, which was revised during November 2016.

Declaration

I declare that the work included in this thesis is my own work as a single author and no part of the thesis has been submitted as part of any other degree or qualification.

Acknowledgements

I would like to express my gratitude to the University of Hull which has approved my application for a Ph.D. by published work, to Professor Valerie R. Sanders and particularly to Dr. Vicky Skoulou, who was my supervisor in my effort to prepare and submit the current work. I would also like to thank my family for their valuable support during the period of the implementation of the research and the preparation of the thesis.

Abstract

Although Crete is an island highly utilizing renewable energy sources (RES) for heat and power generation, their further applications in agriculture would result in many socioeconomic and environmental benefits. The use of renewable energies integrated in greenhouses in Crete is nowadays rather limited, and it could be increased in the future since the resources are abundant and the technologies are mature, reliable and cost-effective. Solar energy, solid and gaseous biomass, and low enthalpy geothermal energy could be used in order to provide heat, cooling and electricity to greenhouses to cover part or all of their energy needs. The positive impacts of their use include: additional income to the farmers, a reduction of greenhouse gas emissions due to energy use in them, an increase of employment in the local community and a decrease of energy dependency in Crete.

The establishment of zero CO_2 emissions greenhouses due to energy use in Crete is currently feasible and cost-effective with the use of the existing renewable energies being available on the island. Unexploited renewable energy sources like landfill gas in Crete can also be used effectively for heating them. Biomass is currently used mainly for heat production in Crete, but new applications could be realized in the future including power generation and the production of biofuels. Olive kernel wood, a byproduct of the olive kernel oil producing industry, is extensively used in Crete for heat production. Besides heat generation, it could be used for the co-generation of heat and power and this process could be profitable under some conditions. Olive kernel wood could also be used as a raw material together with olive tree prunings for the manufacture of wood pellets in Crete. The work included in this thesis investigates various innovative uses and applications of sustainable energies in Crete, Greece, which could contribute to the promotion of energy sustainability in the agricultural sector of the island.

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1. Introduction

The promotion of renewable energy technologies targeting the creation of a low-carbon economy comprises a core policy measure in the European Union. Crete is an island with abundant renewable energy resources, particularly solar energy, wind energy and solid biomass. Renewable energy technologies which are extensively used in Crete include (*Zografakis, 2006*):

a) Solar thermal energy for hot water production. It is being used with simple thermosiphonic systems for domestic hot water production since the 70s. The average solar irradiance in Crete is high compared with other EU countries and it varies between 1,700-1,880 KWh/m^2year (*Kagarakis, 1987*), which favors the exploitation of solar energy for heat and power generation. Greece is ranked ninth globally regarding solar thermal heating with an installed capacity in 2013 of 2,195 GWth, and fifth regarding the installed capacity per 1,000 inhabitants with 271 KWth per 1,000 inhabitants (*Solar heat worldwide, Markets and contribution to the energy supply, 2013*).

b) Solar-PV energy for electricity generation. Solar-PV systems have been used since 2006 when the government offered very attractive feed-in tariffs for electricity generated from those systems. Since then, their growth has been explosive. Solar-PV installations in Greece in 2015 were at 2,613 MWp and the country is ranked thirteenth globally regarding total PV installations (*Solar power in various countries).*

c) Wind energy for power generation. Wind energy for power generation has been used since 2000 when the government allowed private investors to generate grid electricity from the wind. The installed capacity of wind farms in Crete is 184.5

MW which corresponds to 20% of the total installed power in Crete (*Gigantidou, 2013*).

d) Solid biomass for heat generation. Solid biomass for heat generation has been used in Crete for heating since many decades. Total solid biomass potential in Crete has been estimated at 246,000 dry tons/year including agricultural and forest by-products and residues (*Zografakis, 2006; Boukis et al, 2009*).

Biogas produced from two sewage treatment plants in Crete is currently used for co-generation of heat and power (CHP). Few micro-hydroelectric plants operate currently in Crete generating electricity. Finally some installations using low enthalpy geothermal energy with heat pumps for heat and cooling production in buildings also exist in Crete. The national target for Greece in 2020 regarding the share of renewable energies in gross final consumption of energy is 18% (*EU directive 2009/28 on the promotion of the use of energy from renewable sources*), which could be approached but it will be difficult to be achieved. The electric grid of Crete is not interconnected with the continental and the European grid and this fact limits the higher penetration of renewable energy technologies (R.E.T.) for power generation in Crete. During the current severe economic crisis in Greece, initiated by the global economic crisis of 2008, the use of fuel and heating oil in Crete has been reduced dramatically during 2007-2013 (*Vourdoubas, 2016*) and many consumers have replaced heating and fuel oil with cheaper alternative fuels in order to cover their heating needs.

Greece is a country with a high number of olive trees, ranking third after Spain and Italy regarding olive oil production (*Olive oil production in various countries*). Crete is the second largest territory in Greece after Peloponnesus regarding olive oil production (*Olive oil production in Greece , 2012*). Its average annual production in olive oil is 150,000 tons (*Olive oil production in Crete, 2012*) and its average annual production of olive kernel wood is 110,000 tons (*Vourdoubas, 2004*). The energy content of olive kernel wood produced is 3,500-4,000 Kcal/year (*Vourdoubas, 2004*) which corresponds to 17% of the total electricity consumption in the island. From 1950 to 1994, the public power corporation was the only electricity producer in Greece. Since 1994, independent producers were allowed to generate electricity and in 1999 the Greek electricity market was deregulated (*Eubionet-Biomass survey in Europe – country report for Greece, 2003*) The Greek laws 3468/2006 and 3851/2010 introduced the feed-in tariffs for power generation from biomass and the duration of power purchase agreements. Since then, they have resulted in the increased use of biomass for power generation in Greece (*Outlook of market segments for biomass uptake by 2020 in Greece, 2011*) .

Due to the mild climate and the high solar irradiance in Crete, the island hosted in 2002 44.1% of the Greek agricultural greenhouses, mainly used for vegetables production (*Olympios, 2004*). However their productivity is low. For tomato production, it has been estimated at 10 Kg/m^2 or less (*Olympios, 2004; Savvas, 2005; Development in the Greek horticultural sector, 2012*) compared to 28 Kg/m^2 in Almeria, Spain, and 60 Kg/m^2 in Holland (*Peet and Welles, 2005*). 55% of the Greek greenhouses are not heated, 27% are partly heated and 18% are properly heated (*Olympios, 2004*). Among the greenhouses in Greece which are heated, 90% of them are using fuel oil and gas, and only 10% are using renewable energies (*Olympios, 2004*). Among the renewable energies used, 70% is biomass, 20% solar thermal energy and 10% geothermal energy (*Olympios, 2004*). Due to different climatic conditions between northern and southern Greece and the mild climate in Crete, the majority of the greenhouses in this island are not heated. The low productivity of the agricultural greenhouses in Crete is partly due to their simple construction. This does not allow to control the indoor parameters, including temperature, in order to obtain the optimum growth conditions and high productivities. Modernization of agricultural greenhouses in Crete, with improvement of their construction and the control of indoor parameters, will result in higher crop productivity, better quality products produced, and increased incomes.

2. Aims and objectives

The aims of the thesis are:

A) The development of new applications of olive kernel wood for energy generation in Crete, Greece, and

B) The development of new uses and applications of renewable energy sources for power and heat generation in agricultural greenhouses in Crete, Greece.

The objectives of the thesis are:

a) In order to achieve the first aim:

A-1 An assessment of the use of olive kernel wood for co-generation of heat and power in Crete, Greece has been implemented, and

A-2 An assessment of pellet production from olive kernel wood and olive tree prunings in Crete, Greece has been implemented.

b) In order to achieve the second aim:

B-1 An investigation of the possibility of using various renewable energy sources for heat and power generation in agricultural greenhouses in Crete, Greece has been implemented,

B-2 An assessment of the cost-effectiveness and the environmental impacts of the use of various renewable energy sources in agricultural greenhouses in Crete, Greece has been implemented,

B-3 An energy analysis of a greenhouse using only olive kernel wood for covering all its heating needs in Crete, Greece has been implemented, and

B-4 A new novel methodology for the creation of zero CO_2 emissions greenhouses due to the energy use in them has been developed. This methodology can be used in any greenhouse anywhere.

3. Literature review

Solid biomass has been used worldwide for power generation and co-generation of heat and power. Biomass burning systems with steam turbines are the most often used technology. A techno-economic analysis of the energy exploitation of biomass residues in Heraklion, Crete, Greece has been presented (*Boukis et al, 2009*). The feasibility of a power plant with a capacity of 8 MWel has been investigated with 23% efficiency installed in Crete and utilizing various types of local solid biomass as fuel. The investment cost was estimated at 1,600-1,700 €/KWel and the operating cost at 0.056 €/KWel. The solid biomass fuel was a mixture of various biomass resources (residues of olives, citrus, vineyard, etc) produced in Heraklion Prefecture and it was found that the plant could be profitable. A techno-economic study of small-scale biomass fuelled combined heat and power plants has been reported (*Wood et al, 2011*). The authors found that the economic viability depends on various factors like the cost of biomass, investment capital grants, good feed-in tariffs, and low-interest loans. It was concluded that smaller plants are less profitable than larger systems and it is important that the generated power and heat can be consumed and not wasted.

A literature review regarding small scale and micro-scale biomass-fuelled CHP systems has been reported (*Dong et al, 2009*). The combination of biomass combustion and steam turbine technologies is the most used combination particularly, for large and medium scale biomass CHP systems. The economic profitability of power generation from biomass in combustion and gasification processes has been investigated (*Caputo et al, 2005; Bridgwater et al, 2002*). A review of the state of the art for decentralized biomass combustion has been presented (*Obernberger, 1998*). It has been reported that for CHP plants working with steam turbines, a minimum size of 5-10 MWth is required; but using alternatives to steam technologies like Stirling engines and Organic

Rankine cycle systems, smaller size plants can be profitable. An investigation of various biomass types which can be used for energy generation with combustion has been reported (*McKendry, 2002*). Solid biomass use utilizing only olive kernel wood for CHP has not been reported so far in Crete apart from the work of *Boukis et al (2009*) concerning power generation and only utilizing various biomass resources. Commercial plants using olive kernel wood for electricity generation do not currently exist in Crete.

Wood pellets from various biomass resources have been produced since the last decades in Europe and worldwide. The European wood pellet market and its prospects for 2020 has been studied by *Sikkema et al (2011)* who found that the final price of pellets for residential heating varied in various countries between 220–310 €/ton at the end of 2010. A comparison of wood pellet production costs in Austrian and Swedish conditions has been presented by *Thek et al (2004)* who found that the production cost of wood pellets depends mainly on the cost of the raw materials and their drying costs if needed. Other factors influencing the cost are plant utilization and availability. The authors found that the production cost of wood pellets in Austria is higher than in Sweden due to the costs of drying and raw materials.

A study of the obstacles and success factors of pellet production in the forest industry in Sweden has been reported (*Wolf et al, 2006*). The authors suggested that an existing pellet market is a success factor for their production as well as the existence of the raw materials found nearby the production plant. A study for the agricultural pellet market in Greece has been presented (*Karkania et al, 2012*). The authors reported that agro-residues constitute the biggest source of biomass in Greece, without being exploited for energy generation. However, since the pellet market in Greece is growing, they should be used in the future for heat production. A report on the potential of biomass residues for energy production in the Marvao region of Portugal has been published by

Fernandes et al (2010) who concluded that the region has a potential for over 10,000 tons/year of agricultural and forest residues which should be used for heat generation replacing fossil fuels. Studies on the production of wood pellets from biomass resources including olive kernel wood and olive tree prunings have so far not been reported in Crete; neither does a plant producing wood pellets from pure olive kernel wood or biomass mixtures containing olive kernel wood currently exist.

The use of various renewable energy sources for covering the energy needs of agricultural greenhouses in commercial and experimental installations has been reported in many countries. Among renewable energy sources, solar energy, biomass and geothermal energy have been used for covering mainly the heating needs of commercial greenhouses (Campio*tti et al, 2010; 2012; Sethi et al, 2008; Vox et al, 2008*). Solar energy has been used mainly with passive systems and energy storage (*Santamouris et al, 1994*). Solar energy can also be used for power generation in greenhouses with photovoltaic cells (*Carlini et al, 2010; Marruci et al, 2012*).

Direct heating of greenhouses with low enthalpy geothermal fluids with temperatures of 40–80 ^{0}C has been reported (*Adaro et al, 1999; Bakos et al, 1999*) and various commercial geothermal greenhouses operate today all over the world. Geothermal energy has been used indirectly with low enthalpy ground source heat pumps (*Esen et al, 2013*). However the use of geothermal heat pumps for heating and cooling greenhouses consists of a rather expensive but effective method, since they are very energy-efficient electric devices (*Ozgener et al, 2007*). Geothermal energy has also been used for cooling greenhouses during the summer with buried tubes inside the ground (*Santamouris et al, 1995*).

The use of wood biomass as a sustainable energy source for heating greenhouses in Italy has been reported (*Babbiani et al, 2016*). The authors stated that energy consumption in greenhouses in Italy has been estimated from 21 to 546 KWth/m^{2}year and it is worth converting existing boilers to wood biomass boilers taking into account the economic incentives of the Italian government. However, they have also reported that, unfortunately, CO_2 enrichment from the exhaust gas of biomass boilers is still challenging and expensive. The use of olive kernel wood, a by-product of the olive processing industry, for heating greenhouses has been reported, and the advantages have been mentioned (*Vourdoubas, 1999*). Use of biogas for heating experimental greenhouses has been also reported (*Jaffrin et al, 2003*).

CHP is a very efficient energy generation technology obtaining an overall energy efficiency of 75-90 %. Different technological systems like gas turbines, steam turbines and diesel engines have been used for that. Since it is a low-carbon energy technology which uses fossil fuels but generates low emissions of greenhouse gases, it is promoted in various sectors by E.U. policies (*Directive 2008/8/EC*). It is currently used in greenhouses for covering their heating needs, part of their power needs and selling the excess electricity to the grid. Various countries currently offer attractive feed-in tariffs for the electricity derived from CHP systems and sold to the grid. CHP systems used in greenhouses are more attractive in northern European countries, where greenhouses need heating almost all over the year, than in warmer climates as in Mediterranean countries (*Garcia et al, 1998*). Natural gas is the most popular fuel used in CHP systems and heat storage can improve the economics of such a system.

Various applications of CHP systems in greenhouses have been reported (*Compernoll et al., 2011*). The authors have implemented two case studies which prove the profitability of CHP systems also resulting in positive environmental impacts. A CHP system in a greenhouse can: 1) generate electricity which can be used in the greenhouse and the excess sold to the grid, 2) produce heat covering its heating needs, 3) Produce cooling with absorption cooling systems when the greenhouse needs cooling instead of heating, and 4) Enrich the greenhouse atmosphere with purified CO_2 from the exit gases, resulting in increasing productivity of the crop and improving its economics. Power plants as well as various other plants reject cooling water at temperatures which can be effectively reused for various heating purposes. Low enthalpy cooling water can be used for heating greenhouses. Use of the water from the cooling towers of the large power plant in NiederauBen, Germany for heating commercial greenhouses has been reported (*Bredenbeck, 1992*). The possibility of using fuel cells for providing energy in commercial greenhouses has also been reported by *Mulloney (1993)* who states that the benefits resulting from this application include: a) Generation of electricity which can cover the greenhouse requirements and the rest can be sold to the grid if this is allowed, b) Heating the greenhouse as well as cooling it during the summer with absorption cooling systems, and c) The exhaust gases from the fuel cell can be used directly in the greenhouse, both for heating and for enriching the atmosphere with CO_2 in order to increase crop productivity.

A review of the existing literature reveals various gaps in knowledge regarding the use of olive kernel wood for energy generation and fuel production in Crete and the use of renewable energies for energy generation in greenhouses in Crete.

More specifically, the possibility of using olive kernel wood which is locally produced in Crete for co-generation of heat and power has so far not been investigated. Due to the attractive feed-in tariffs offered by the government for power generation from biomass, it is interesting to examine this possibility. Production of wood pellets in Crete from various biomass resources including olive tree by-products and residues has not been reported, although it happens in other geographical locations. Since large quantities of olive kernel wood and olive tree prunings are currently produced in Crete, it is interesting to investigate the possibility of co-using them for pellet production. Agricultural greenhouses heated with solid biomass exist but reports related with the energy analysis of a greenhouse heated with olive kernel wood are lacking. Since olive kernel wood is an attractive locally produced fuel used for heat generation in Crete, it is interesting to implement an energy analysis of an existing greenhouse in Crete which covers all its heating needs with this renewable solid fuel. This will give a better insight on the energy use and efficiency in the greenhouses. Although modernization of existing greenhouses is necessary in Crete in order to increase their productivity and the quality of the products produced, reports regarding the assessment of various renewable energies used for energy generation in them do not exist in Crete, as happens in various other countries. Therefore it is interesting to investigate the possibility of using various renewable energy sources for energy generation and to assess the advantages and drawbacks of their use in Cretan greenhouses. Investigation of novel uses of renewable energy sources in greenhouses in Crete, such as semi-transparent PVs and landfill gas, are also lacking. The profitability of various renewable energy resources used for energy generation in greenhouses should be investigated so that farmers will be able to make rational decisions regarding their applications. Since European policies promote the creation of a low-carbon economy, it is interesting to develop a new novel methodology concerning the creation of greenhouses with a cost-effective way achieving zero CO_2 emissions due to energy use in them, which is currently lacking. Such a novel methodology will assist the decrease of carbon emissions in agriculture not only in Crete but in other European territories as well.

4. Presentation of the published work

The current work consists of nine (9) papers, all published in five (5) peer-reviewed international journals, with the candidate being the single author, during the period of 2015-2016, as follows.

1. Vourdoubas, J. (2015). Present and future uses of biomass for energy generation in the island of Crete, Greece. *Journal of Energy and Power Sources*, 2 (4), pp. 158-163.

2. Vourdoubas, J. (2015). Overview of solid biomass use for cogeneration of heat and power: A case study in Crete, Greece. *Journal of Energy and Power Sources*, 2 (6), pp. 239-246.

3. Vourdoubas, J. (2015). Pellet production of olive tree byproducts and residues: A case study in Crete, Greece. *Journal of Agriculture and Environmental Sciences,* 4 (2), pp. 1-13.

4. Vourdoubas, J. (2015). Overview of heating greenhouses with renewable energy sources. A case study in Crete, Greece. *Journal of Agriculture and Environmental Sciences*, 4 (1), pp.72-76.

5. Vourdoubas, J., (2015). Possibilities of using renewable energy sources for covering all the energy needs of agricultural greenhouses, *Journal of Agriculture and Life Sciences,* 2 (1), pp. 111-118.

6. Vourdoubas, J., (2015). Economic and environmental assessment of the use of renewable energies in greenhouses: A case study in Crete, Greece. *Journal of Agricultural Sciences,* 7 (10), pp. 48-57.

7. Vourdoubas, J. (2016). Possibilities of using semi-transparent photovoltaic modulus on rooftops of greenhouses for covering their energy needs. *Journal of Agricultural Studies,* 4 (1), pp. 90-100.

8. Vourdoubas, J. (2016). Overview of the use of sustainable energies in agricultural greenhouses. *Journal of Agricultural Science*, 8 (3), pp. 36-43.

9. Vourdoubas, J. (2016). Possibilities of using landfill biogas for heating agricultural greenhouses in Crete, Greece. *Journal of Agricultural Studies*, 4 (2), pp. 12-21.

5. Coherency of the published work

The published papers included in the current thesis target the promotion of sustainability in the agricultural sector on the island of Crete, Greece, the reduction of the use of fossil fuels, and the increase in the use of renewable energies. They are coherent due to the following reasons:

a) Some of them concern the exploitation of local biomass resources for energy generation and the production of wood fuels. The rest concern the use of renewable energies in agricultural greenhouses.

b) Some of them concern utilization of renewable energies, including solar thermal energy, solar-PV, solid biomass, biogas and geothermal energy, which can generate heat, cooling and electricity in agricultural greenhouses.

c) All of them concern a specific geographical location: the island of Crete, Greece.

d) All of them concern studies for future applications as well as existing applications of sustainable energies, mainly including various renewable energies and low carbon energy technologies. They highlight the possibilities of using local renewable energy resources which are mature, reliable and cost-effective, for renewable fuel production and energy generation in order to replace fossil fuels.

e) They concern the improvement of the overall sustainability in Crete, Greece, by replacing fossil fuels with renewable energies. All of them result in a reduction (or zeroing) of CO_2 emissions, a reduction in fossil fuel consumption and an increase in the use of local renewable resources, while they also create various benefits in the local community such as an increase in employment, which is important given the current economic crisis in the country.

f) Therefore, all published articles investigate and highlight the possibility of using renewable energies either to produce renewable fuels or to generate energy, thereby replacing fossil fuels and lowering CO_2 emissions in order to improve sustainability in agriculture with reference to the island of Crete, Greece.

The main issues concerning the coherency of the published work are presented in Table 1.

Table 1: Coherency of the published work

Main item of the work	**Paper number (according to the numbering in section 4)**
Exploitation of local biomass resources for energy generation and the production of wood fuels.	1,2,3
Utilization of various renewable energy sources for energy generation in greenhouses.	4,5,6,7,8,9
Use of various renewable energy sources produced from agriculture and used in the agricultural sector in Crete ,Greece.	1,2,3,4,5,6,7,8,9
Highlight of the possibilities of using local renewable energy resources which are mature, reliable and cost-effective, for renewable fuel production and energy generation in order to replace fossil fuels.	1,2,3,4,5,6,7,8,9
Improvement of the overall sustainability in Crete, Greece, by replacing fossil fuels with renewable energies.	1,2,3,4,5,6,7,8,9

6. Contribution to knowledge creation

The published work included in this thesis has contributed to the creation of new knowledge in the field of sustainable energy use in agriculture with reference to the island of Crete, Greece. Firstly, part of the work has contributed to the creation of new knowledge regarding alternative uses of olive kernel wood for power generation and wood pellet manufacturing. It should be noted that these applications have not been realized so far in Crete, Greece. There are also no published reports so far regarding these issues. Secondly, the rest of the current work has increased our knowledge regarding the use of various renewable energies in agricultural greenhouses in Crete, Greece, highlighting the resulting benefits to the farmers, the environment and the local communities. The use of semi-transparent photovoltaics in greenhouses in Crete or elsewhere in Greece has not been reported before although there are studies for their use in other locations. The use of landfill gas for heating greenhouses has not been reported in Crete or elsewhere in Greece although there are such studies for other locations. Multi-criteria assessment of the use of various renewable energies for energy generation in greenhouses has not been reported for Crete although there are such studies in other geographical locations.

The methodology presented in the thesis for the creation of zero CO_2 emissions greenhouses due to energy use is novel and it has not been published before. Although there are commercial greenhouses using solid biomass for their heating, there are no published reports regarding the use of olive kernel wood for covering all the heating needs of agricultural greenhouses in Crete or elsewhere. Most of the work presented in these papers and the knowledge created can also be used in geographical locations other than Crete. The methodology developed for the creation of zero CO_2 emissions greenhouses has also been applied in the creation of buildings with zero CO_2 emissions due to energy use, as mentioned in section 8.5. The contribution of each paper to new knowledge creation is presented in Table 2.

Table 2: Contribution to knowledge creation

Main item of the work	**Paper number (according to the numbering in section 4)**
Presentation of the current and future applications of biomass use for energy generation in Crete.	1
Investigation of the possibility of using olive kernel wood for co-generation of heat and power in Crete.	2
Investigation of the possibility of producing wood pellets from olive kernel wood and olive tree prunings in Crete.	3
Investigation of the possibility of using semi-transparent photovoltaics for energy generation in greenhouses in Crete.	7
Investigation of the possibility of using biogas for heat generation in greenhouses in Crete.	9
Development of a novel methodology for the creation of zero CO_2 emissions greenhouses due to the energy use in them.	5
Multi-criteria assessment of the use of various renewable energy sources (olive kernel wood, solar-PV energy, direct geothermal energy and low enthalpy geothermal heat pumps) in greenhouses in Crete.	6,8
Energy analysis of an existing commercial greenhouse using olive kernel wood for covering all its heating needs in Crete, Greece.	4

7. Novelty of the published work

The published work included in the thesis is novel for many reasons:

a) It concerns specific applications of renewable energies in agriculture in Crete, Greece, which have not been investigated before.

b) It concerns the utilization of local biomass resources including olive kernel wood and olive tree prunings for energy generation and renewable fuel production in Crete, Greece, which has not been investigated before.

c) It concerns the multi-criteria assessment of various renewable energy applications, which have already been used in experimental or commercial greenhouses in other locations in greenhouses in Crete, which has not been investigated before.

d) It concerns the investigation of the possibility of using novel applications of renewable energy technologies like semi-transparent PVs and landfill gas for energy generation in greenhouses in Crete which have not been investigated before.

e) It concerns the development of a new methodology for the creation of zero CO_2 emissions greenhouses due to energy use, which has not been reported before**.** The creation of greenhouses with zero CO_2 emissions is based on two axes. Firstly, the greenhouses must replace fossil fuels used with renewable energies. Secondly, they must offset annually the grid electricity used (which is mainly generated from fossil fuels) with solar-PV electricity.

Therefore, the published work in the thesis is novel: it investigates and demonstrates the use of various sustainable energy technologies in agriculture in Crete, Greece, which have not been explored before. Details of the novelty of each paper are presented in Table 3.

Table 3: Novelty of the published work

Main item of the work	**Paper number (according to the numbering in section 4)**
Exploitation of olive kernel wood and olive tree prunings for the production of wood pellets. The use of those raw materials for pellet production has not been reported before in Crete, neither does a commercial application exist for that.	1,3
Exploitation of olive kernel wood for co-generation of heat and power in Crete. Use of mixtures of various agricultural byproducts and residues for power generation has only already been reported in the Heraklion Prefecture, Crete. Studies and commercial applications of plants using various types of solid biomass for co-generation of heat and power have been reported in other countries. However the use of olive kernel wood as a raw material for that in Crete has not been reported before.	1,2
Energy and environmental analysis of a commercial greenhouse in Crete which covers all its heat requirements with olive kernel wood. Although there are commercial greenhouses using various types of solid biomass for their heating, an energy analysis of a greenhouse using olive kernel wood has not been reported before.	4
Development of a novel methodology which has not been presented before concerning the creation of agricultural greenhouses which cover all their energy requirements with renewable energy sources zeroing their CO_2 emissions due to the energy use in them.	5
Multi-criteria assessment of the use of various renewable energy sources in greenhouses in Crete. Solid and gaseous biomass, solar-PV energy, direct geothermal energy and low enthalpy geothermal heat pumps have been investigated which can generate power, heat and cooling in the greenhouses. The use of renewable energies in greenhouses in various countries has been investigated previously but an assessment of the use of various renewable energies in greenhouses in Crete has not been reported before.	6,7,8,9.

8. Impacts of the published work

The published work included in the thesis is useful not only in Crete, Greece but also in other geographical locations and to various users. It is useful in the following ways:

1. Public authorities who are interested in finding out about the possibilities of using new sustainable energy technologies in agriculture could use the findings of the papers in order to promote and facilitate their use with various policy measures and incentives. Probably a new policy measure could be created through the offering of incentives to the greenhouse owners in order to create low or zero CO_2 emissions greenhouses (using renewable energy sources) in accordance with the EU targets for transition to a low carbon economy. Another policy measure could be related with defining optimum feed-in tariffs regarding power generation from olive kernel wood. Training seminars could be organized from public authorities or greenhouse farmers' organizations in Crete in order to present the advantages of using renewable energies for energy generation, sensitizing the greenhouse owners.

2. Private investors could use the results of the implemented analysis in the published work in order to make rational decisions regarding investments in renewable energy technologies in Crete.

3. Farmers active in greenhouse cultivation will be familiar with the benefits and drawbacks of using sustainable energy technologies in their greenhouses for heat production and power generation. They can also use the results of the published work in order to create zero CO_2 emissions greenhouses due to the energy use in them. Some farmers could use the published work for modernizing their greenhouses and increasing their productivity and the quality of the products produced with new heating systems using renewable energies for that. Farmers who currently produce greenhouse crops in Crete requiring indoor temperature control, such as hydroponic or horticulture

greenhouses, could benefit from the published results by replacing their old heating systems utilizing fossil fuels with new ones using solid biomass or other renewable energies since it is economically attractive. Some others could use the published work in order to install solar-PV systems with the net-metering initiative, offsetting the annual grid electricity used.

4. Owners of the existing olive kernel oil producing plants in Crete and elsewhere can assess the possibility of using the olive kernel wood produced in their plants for the co-generation of heat and power or for manufacturing wood pellets, resulting in new investments.

5. The methodology for the creation of zero CO_2 emissions greenhouses has also been applied to the creation of zero CO_2 emissions buildings due to energy use and it has been published in various journals as mentioned in ANNEX 2. The methodology was useful for the realization of zero CO_2 emissions social housing in Crete. It was also successfully used for the preparation of a project proposal in the first call of INTERREG EUROPE (2015) and the proposal was approved with the acronym ZEROCO2 (Promotion of near-zero CO_2 emissions buildings due to energy use).

6. The owners of the landfills in Crete could find a new market for the heat generated from the landfill gas like the greenhouses which could be created in the nearby fields.

The impacts of the published work included in this thesis are presented in Table 4.

Table 4: Impacts of the published work

Main item of the work	**Paper number (according to the numbering in section 4)**
Creation of new policy measures such as: a) Offering incentives to the greenhouse owners in order to create low or zero CO_2 emissions greenhouses (using renewable energy sources) in accordance with the EU targets for transition to a low carbon economy. b) Defining optimum feed-in tariffs regarding power generation from olive kernel wood.	1,2,3,4,5,6,7,8,9
Organization of training seminars to specific target groups in Crete and elsewhere, such as greenhouse farmers.	4,5,6,7,8,9
Use by various investors in order to assess the possibility of producing wood pellets from olive residues in Crete.	1,3
Use by farmers who are active in greenhouse cultivation. They will be familiar with the benefits and drawbacks of using sustainable energy technologies in their greenhouses for heat production and power generation. They can also use the results of the published work in order to create zero CO_2 emissions greenhouses due to the energy use in them.	4,5,6,7,8,9
Owners of the existing olive kernel oil producing plants in Crete and elsewhere can assess the possibility of using the olive kernel wood produced in their plants for the co-generation of heat and power or for manufacturing wood pellets.	2,3
The methodology developed for the creation of zero CO_2 emissions greenhouses could also be used for the creation of buildings or enterprises with zero CO_2 emissions due to the energy use in them.	5
The owners of the landfills in Crete could utilize the landfill gas for energy generation, selling the produced heat to large heat consumers like the greenhouses which could be created in the nearby fields.	9

9. Strengths and weaknesses of the published work

The strengths of the published work included in the current thesis are:

a) The detailed overview of the possible uses of various renewable energy sources for energy generation in greenhouses in Crete. The economic appraisal of various technologies which could be used indicate the attractiveness and profitability of some of them. The analysis also indicates that some renewable energy technologies are highly profitable but others are not.

b) The energy analysis of an existing greenhouse in Crete which covers all its energy needs using solid biomass which is produced locally. This offers a better insight in the energy use and efficiency of the greenhouse. The results of the estimation of the economic and environmental impacts clearly indicate that heating greenhouses with olive kernel wood in Crete is attractive.

c) Development of a novel methodology for the creation of zero CO_2 emissions greenhouses due to energy use, and analysis of the technologies which could be used in Crete together with their economic and environmental impacts. The same methodology can be used in any greenhouse in other territories utilizing different renewable energies which are available locally.

d) Investigation of the possibilities of using two innovative renewable energy technologies in Crete for energy generation in greenhouses like semi-transparent solar-photovoltaics and landfill gas. The results indicate the advantages of their use for energy generation in greenhouses in Crete.

e) Investigation of the viability of two novel processes in Crete utilizing solid biomass for energy generation such as the manufacturing of wood pellets from olive tree byproducts and residues and the co-generation of heat and power from olive kernel wood. The analysis made indicates that those processes are economically viable in Crete under some circumstances.

f) The results have been published in five different peer-reviewed international journals.

<u>The weaknesses</u> of the published work are:

a) Most of the work concerns theoretical studies and investigations without experimental or pilot scale verification. The only exception is the analysis of an existing greenhouse using olive kernel wood for covering all its heating needs.

b) Economic and profitability analyses of various processes could have been made in more detail with an investigation of more scenarios. However it is clear that the use of some renewable energy technologies for heat generation in greenhouses, particularly locally produced solid biomass, and direct geothermal heat, are highly profitable.

10. Conclusions

The published work included in this thesis paves the way for the increase of energy use in the agricultural sector on the island of Crete, Greece by the use of various renewable energy sources. Innovative uses of renewable energies, which are abundant on the island, could result in the improvement of the overall sustainability, a reduction in CO_2 emissions, in the reduction of the energy dependence in Crete and the increase of local development.

- Existing biomass resources like olive kernel wood could be used for co-generation of heat and power and the process could be economically viable under various conditions. The generated electricity could be sold to the grid with attractive feed-in tariffs and the co-produced heat could be sold to a large heat consumer like a hospital.

- Olive kernel wood and olive tree prunings could be used for wood pellet manufacturing while these processes could be cost-effective under various conditions. The produced pellets could be sold in Crete to various consumers and used for heat generation, since pellets are currently not produced on the island and some quantities are imported.

- Renewable energies available in Crete could be used in greenhouses for covering part or all of their energy needs. They could contribute in their modernization, increasing their current productivity and the quality of the produced products.

- An overview of the use of sustainable energies for energy generation in greenhouses has shown that some of them are mature, reliable and cost-effective and they can be used in commercial greenhouses. Some others have proven their technical viability but they are currently not cost-effective.

- The possibility of using semi-transparent PV modules in greenhouses in Crete for electricity generation for covering their electricity needs and selling any surplus to the grid has been investigated and the resulting benefits have been presented. For a modern greenhouse in Crete, semi-transparent PVs can be placed in 50% of its rooftop surface, covering all its electricity requirements and generating a surplus which corresponds to 71.76% of its annual generation which can be sold to the grid according to the current feed-in tariffs.

- The existence of landfills in Crete provides the opportunity to utilize the landfill gas for greenhouse heating and this possibility has also been investigated. It has been proved that the landfill gas can be used effectively for heating greenhouses in Crete and the greenhouse area which could be heated has been estimated at 24.41 hectares.

- A multi-criteria assessment for using various renewable energy resources including olive kernel wood, solar-PVs, direct geothermal energy and low enthalpy geothermal heat pumps in greenhouses has been implemented. The analysis has shown that the use of olive kernel wood and direct geothermal fluids for heat generation in them is very profitable, having pay-back periods for the investment of less than 3 years. However, the use of solar-PVs and low enthalpy geothermal heat pumps is not attractive economically.

- An energy analysis of a commercial greenhouse in Crete which covers all its energy needs with olive kernel wood has shown that due to the use of solid biomass instead of fuel oil, its energy cost has been significantly decreased and its environmental sustainability has been improved.

- A novel methodology for zeroing CO_2 emissions in greenhouses due to energy use in them with the use of renewable energies has been developed and its feasibility and cost effectiveness have been proved. The methodology is based first on the replacement of fossil fuels with renewable energies, and secondly on the offsetting of the grid electricity consumed with solar-PV electricity on annual basis. This methodology increases the sustainability in the greenhouses, lowering their carbon emissions in accordance with the EU policies for a low-carbon economy and it can be used everywhere.

11. Recommendations for other researchers

It is suggested that further research is needed in order to better investigate the attractiveness of various applications of renewable energy sources in agriculture in Crete as follows:

1. A demonstration greenhouse should be created with semi-transparent photovoltaics placed on part of its rooftop in order to investigate its behavior concerning electricity generation, its decreasing cooling needs and the shadowing obtained.

2. An experimental investigation is needed of a demonstration plant producing wood pellets from mixtures of olive kernel wood and olive tree prunings. Wood pellets should also be produced with the addition of other biomass resources available in Crete, like adding citrus tree prunings to the initial raw materials, in order to investigate the quality and the burning characteristics of the produced pellets from different mixtures of raw materials.

3. Two demonstration greenhouses with zero CO_2 emissions due to energy use should be created. The first will use olive kernel wood and solar-PVs and the second geothermal heat pumps and solar-PVs, in order to cover all their energy requirements. Their operation will give useful data regarding their performance in the long run, and it will verify the achievement of the zero CO_2 target.

4. A life cycle analysis on the energy use in greenhouses in Crete should be implemented. The analysis will compare the operation energy used over their life time with the energy used during their construction, maintenance and demolition. A life cycle analysis should also be implemented regarding the use of various renewable energy sources for energy generation in them.

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ANNEX 1: Papers included in the current thesis

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Present and Future Uses of Biomass for Energy Generation in the Island of Crete—Greece

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Abstract: Crete has various biomass recourses which are used currently for energy generation, mainly for heat and in a small extend for power generation. Heat is produced mainly from burning of various types of wood or olive kernel wood, a byproduct of olive oil producing industry. It is used for covering heating needs of buildings, greenhouses and factories. Power is generated from biogas produced in the sewage treatment plants in Chania and Heraklion but the annual generated power is rather small. Biofuels, bioethanol and biodiesel are not currently produced in Crete except small quantities of used fried oils.

Solid biomass is not used to day for power generation in Crete. Some quantities of olive kernel wood are exported depending on its availability and its price. It is estimated that currently biomass contributes to 6.4% of TPES in Crete. Biomass can be used in the future in Crete in a greater extend for energy generation and production of biofuels. Various wood residues like olive tree branches or citrus cuttings and forest residues which are not utilized to day can be used for heat or power generation in the future. Creation of energy crops can also produce the necessary raw materials for the production of biofuels in Crete.

Keywords: Biomass, Crete, energy, heat, power, biofuels.

1. Introduction

Crete is the 13th Greek region and the fifth largest island in the Mediterranean Sea with an area of 8,335 km^2 and population slightly higher than 600,000 inhabitants [1]. Renewable energy sources find currently increased uses for energy generation in Crete—Greece [2]. Among them biomass is used mainly for heat generation and its contribution in covering energy needs of Crete is rather high [3]. Solid biomass is used to day for heat generation and small quantities of biogas are also used for power generation. Biofuels are not currently produced in Crete but this can be done in the future [4].

Various types of solid biomass are usually burnt and heat is generated with traditional technologies. Due to current increase in the prices of fossil fuels, solid biomass is gradually replacing diesel oil in heating buildings. Because of the current economical crisis in Greece and the high heating oil prices many households and various enterprises prefer to utilize solid biomass for heat generation instead of the conventional heating oil.

Biomass use for energy generation in Crete is rather high in comparison with other Greek territories although energy crops have not been developed to day in the island.

2. Use of Renewable Energy Sources in Crete

Crete is a Greek territory with a high potential of renewable energy resources mainly solar energy, wind energy and solid biomass. Although traditionally for many decades solar thermal energy was used for hot water production and solid biomass for space heating, the last twenty years new applications of renewable energy sources find spreading uses in Crete.

The main uses of renewables in Crete currently include:

(a) Use of solar thermal energy for hot water production;

(b) Use of photovoltaics for power generation;

(c) Use of wind energy for power generation;

(d) Use of solid biomass for heat generation.

Additionally other applications in Crete include:

(a) Use of solar thermal energy for space heating mainly with passive solar buildings;

(b) Use of solar thermal energy for space cooling;

(c) Use of solar drying;

(d) Use of biogas produced from sewage treatment plants for cogeneration of heat and power;

(e) Use of low enthalpy geothermal energy with heat pumps for space heating and cooling mainly in buildings;

(f) Use of small hydro power plants for power generation.

In the near future there are mature projects under implementation in Crete in the fields of:

(a) Solar thermal use for power generation;

(b) Construction of medium size hydro power plants in existing water dams.

Photovoltaic and wind power contribute to day in approx 14% of the electricity consumption in Crete. The power grid of Crete is not interconnected today with the grid of continental Greece and the European grid. Therefore further use of renewable energies for power generation in Crete is limited due to grid stability reasons and the lack of water pump storage systems.

However pump storage systems are going to be constructed soon in Crete and the grid is going to be interconnected with the Greek continental grid within the next ten years. Therefore the use of wind and Photovoltaic power is expected to grow significantly in the coming years transforming Crete in an island with high penetration of renewables in its energy balance. It is expected in the medium term that Crete will generate annually from Renewable energy sources more electricity than it consumes.

Table 1 Current uses of biomass for energy generation in Crete.

Type of biomass	Technology	Use
Various solid biomass resources	Burning	Heat production
Biogas	Burning	Cogeneration of heat and power

Solid biomass is the only renewable energy source in Crete which can be used for space heating. Solar thermal energy although it has been broadly used for hot water production it has not been used for space heating. Studies have suggested the use of hybrid heating systems combining solid biomass and solar thermal energy for space heating but there are not such commercial systems in operation. Current uses of biomass for energy generation in Crete are presented in Table 1.

Due to current economical crisis in Greece, Greek government has increased the oil taxation, resulting in rather high heating oil prices. This has increased the attractiveness of various endogenous solid biomass resources in Crete as a cheap and easily available fuel for heat generation.

Biomass resources in Crete which are currently used for energy generation include:

- Olive and citrus trees wood;
- Olive tree byproducts and residues;
- Sludge from sewage treatment plants;
- Fried vegetable oils;
- Forest residues;
- Wood and residues from various agricultural crops.

3. Use of Solid Biomass in Crete for Heat Generation

Solid biomass was used extensively in the past for heat generation in Crete and is used also today. Various biomass sources were used but the existence of many olive trees in the island makes possible the use of olive tree wood and olive tree byproducts as a fuel. Crete has approx. 26 millions productive olive trees [5] which produce a lot of solid biomass in the form of tree prunings and olive kernel wood. A commonly used fuel

Table 2 Chemical analysis of olive kernel wood.

Water content	6.30%
Ash	8.0%
Organic matter	65.50%
Sulphur	0.11%
Total Carbon	45.30%
Hydrogen	5.17%
Nitrogen	1.33%
Oxygen	34.30%
Heating value	4,051 Kcal kg^{-1}, 16.96 MJ kg^{-1}
Residual oil	2.44%
Residual hexane	< 10 mg kg^{-1}
Chlorine	0.69%

in Crete is the olive kernel wood, a byproduct of olive oil production industry [6]. Its price (0.10 € kg^{-1}) is rather low in comparison with its heating value (4,051 kcal kg^{-1}) and this is the main reason for its extensive use. Although its use for manufacturing pellets has been proposed its chemical composition restricts its use for the production of high quality wood pellets [7].

Its annual production in Crete is approx 110,000 tons and it is used for heat generation in buildings, greenhouses and in industry. Apart from olive tree wood, olive kernel wood and other types of agricultural or forest woods and residues in the form of firewood are also used for heat production. Pellets are not manufactured currently in Crete but they are imported. The possibilities for manufacturing pellets in Crete from olive kernel wood have been investigated [8]. However the high concentration of ash and various elements in olive kernel wood exceeds the existing EU limits for first quality wood pellets. At the same time the high ash content of olive kernel wood could probably lead to ash slogging for burning temperatures 900-1000°C. Chemical analysis of olive kernel wood is presented in Table 2.

Thermal behavior of olive and citrus prunings has been studied [9] and it was found that they are good quality fuels with high volatility and low ash and sulphur content.

Various types of heating systems based in biomass are used in buildings which include:

(a) Wood fires;
(b) Wood stoves;
(c) Central heating systems;
(d) Pellet stoves.

Apart from traditional agricultural and forest resources there are not energy plantations currently in Crete for exploiting the produced solid biomass for heat generation.

Carbonization of woody biomass from agricultural or forest residues for charcoal production was taking place in small production plants in the past in Crete. Pyrolysis and gasification of olive residues instead of their direct burning has been studied [10-11] but this technology is not mature yet for commercial use.

Past studies in Crete [12] have proposed the use of sewage treated effluents for irrigation of tree plantations and use of the produced biomass for heat generation. This process offers the advantage of using processed sewage liquids for irrigating and fertilizing energy plantations instead of disposing them to water reservoirs. At the same time trees can be irrigated and grown in semi arid areas which are slowly desertified like many areas in Crete.

4. Use of Biomass in Crete for Power Generation

Small quantities of biomass are used to day in Crete for power generation. Biogas produced from the anaerobic digestion of the sludge of sewage treatment plants in Chania and in Heraklion is used for cogeneration of heat and power. Experimental investigation of biogas production from liquid wastes of olive mills has been implemented in Crete but there are not currently such commercial plants since this technology is considered non profitable for small size olive mills. Other studies have suggested the use of cattle wastes from existing farms for biogas production. Solid biomass is not used in Crete for power generation although there are proposals for the use of olive kernel wood for cogeneration of heat and power. The most commonly used technology for generating power from solid biomass is burning but also gasification is a developing technology with various advantages which are expected to have an increasing role in the future. Cogeneration of heat and power with biomass fuels presents the advantage of high efficiency. However the generated heat should be utilized all over the year and such cogeneration plants must be installed nearby large heat consumers like hospitals. Alternatively tri-generation with biomass can be achieved consuming the heat during the winter and cooling during the summer [13-14].

Possible use of biomass resources in Crete for power generation in the future probably will compete with their use for heat production, resulting in the increase of biomass prices.

5. Possibilities for Bioethanol Production in Crete

Bioethanol can be produced in Crete from crops rich in sugars or starch. Although there are not such crops currently in the island the possibility of cultivating Carob trees has been investigated in the past [15]. Carob tree grows in poor soils and it does not need irrigation, fertilization or any cultivation care. Therefore this tree fits very well in the semi-arid climate of Crete and in past centuries the carob tree was abundant in the island like in other Mediterranean areas (Cyprus, South Italy, Portugal, Spain, Northern African countries etc.). Carob tree fruits consist of seeds (8% p.w.) and mass (92% p.w.) that is rich in sugars (30-50% p.w.).

The advantages of the carob fruit for ethanol production are [16]:

(a) The tree grows in poor soils which are not suitable for other cultivation. It does not need much water which is important today with the lack of water resources in the East Mediterranean. Also it does not need any special cultivation care or fertilizers;

(b) It is rich in sugars and therefore the expected yields in ethanol are high.

Additionally the creation of carob tree plantations can offset the expanding land desertification in Mediterranean areas.

Table 3 Chemical composition of carob fruit.

	Dry matter (%)		
	Total fruit	Fruit mass	Seed
Crude protein	5	4	17
Crude fiber	6	6	9
Fat	0.5	0.5	2
Ash	3	3	4
N-free extract	86	87	68
Total sugars	52	55	4
Glucose	9	9	0

The chemical composition of Carob is presented in Table 3.

The production of bioethanol from Carob can be obtained in the following stages:

(a) Grinding the fruit and separation of the seeds from the fruit mass;

(b) Extraction of the sugars from the fruit mass with hot water;

(c) Fermentation of the water-sugars solution with the yeast Saccharomyces cerevisiae;

(d) Separation by distillation of the produced ethanol from the water solution with minimum water content to be useable as a fuel.

6. Possibilities for biodiesel production in Crete

Biodiesel is not currently produced in Crete. Olive groves are abundant and olive oil which is produced today in the island is a high value edible oil and it cannot be used for biodiesel production. In the future biodiesel can be produced in the island either from crop plantations rich in oils or from used vegetable oils.

According to the EU directive 2009/28/EC [17] until 2020 10% of diesel consumption must be biodiesel that corresponds to annual consumption of 12.750 tons of biodiesel in Crete. Total annual diesel demand in Crete is estimated at 127,500 tons [2].

Every year approx 3 million tourists visit Crete and the tourism industry generates a lot of fried vegetable oils which can be recycled and transformed to a valuable

Table 4 Possible future uses of biomass for energy generation in Crete.

Type of biomass	Technology	Use
Various solid biomass resources	Burning	Heat generation Power generation
Biogas	Burning	Cogeneration of heat and power
Sugar based biomass	Fermentation	Bioethanol
Oily biomass	Esterification	Biodiesel

fuel instead of be discharged and pollute the environment. According to recent studies [18] approx 2,000-3,000 tons of fried vegetable oils can be collected annually in Crete and processed to produce a biofuel. Another option for biodiesel production in Crete is related with the creation of vegetable or tree plantations rich in oils which can be used as a raw material for biodiesel production. Currently some quantities of fry vegetable oils are collected and sent outside of Crete for processing and producing biodiesel.

Recent studies for small scale biodiesel production in Crete [1], show that a small-scale biodiesel plant in Crete with annual production of 10,000 tons is economically viable. The initial capital investment is relatively low, estimated at 4 mil Euros and the production cost is estimated at 780 € ton^{-1}. Such a plant will help the local and regional development since the used biomass will be produced locally from energy crops and its price will be independent from oil prices fluctuations. The produced biodiesel will be consumed in Crete since the annual needs for diesel fuel are much higher.

Possible future uses of biomass for energy generation in Crete are presented in Table 4.

7. Conclusions

Biomass is used to day in Crete mainly for heat production but also for power generation. The current economical crisis in Greece combined with the high oil prices favour the use of solid biomass for heating purposes instead of the conventional fuels. Biomass sources which are currently used in Crete for energy generation and biofuels production include:

(a) Olive tree wood, and various byproducts and residues of olive oil industry;

(b) Forest residues;

(c) Wood of various agricultural crops;

(d) Used vegetable oils;

(e) Sludge from sewage treatment plants after its anaerobic digestion and production of biogas.

It is expected that in the future energy generation from biomass in Crete will increase since more biomass resources will be exploited for generation of heat, power and biofuels production. Existing studies show that solid biomass can be used for power generation or cogeneration of heat and power in small size plants in the range of 5-10 MWel and such plants are economically viable to day in Crete. The possibility of cultivating oily crops and producing the required quantities of biodiesel for covering part of the needs of the island according to the EU directive 2009/28/EC has been also proved. Finally wood byproducts and residues can be exploited profitably for producing wood pellets and briquettes to cover the heating needs of Crete and replacing the currently imported pellets.

Therefore the potential for further energy use of biomass in Crete is high and it is expected that it will contribute more in the energy balance of the island in the near future.

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Overview of Solid Biomass Use for Cogeneration of Heat and Power: A Case Study in Crete-Greece

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Abstract: Cogeneration of heat and power presents many advantages due to the fact of high overall efficiency in energy generation. Various fuels are used for cogeneration of heat and power like natural gas, biogas, oil or solid biomass. Since biogas and solid biomass are renewable energy sources their use has not impacts to climate change, compared to fossil fuels like natural gas or oil.

The investigation of using an endogenous renewable energy source in Crete-Greece the olive kernel wood as fuel for cogeneration of heat and power shows that it is feasible and profitable provided that the cogenerated heat can be consumed locally.

A case study of 1 MWel cogeneration plant in Crete-Greece using olive kernel wood as fuel is presented. The generated power will be fed to the grid with an attractive feed-in tariff of 180 Euros/MWh and the cogenerated power can be consumed from the local hospital and from other heat consumers located nearby the plant.

Keywords: Cogeneration of heat and power, solid biomass, olive kernel wood, Crete-Greece.

1. Introduction

Various studies concerning the use of various solid biomass sources for Cogeneration of Heat and Power (CHP) have been made and various such plants are in operation all over the world.

A techno-economic analysis of the energy exploitation of biomass residues in Heraklion Crete Greece has been presented [1]. The feasibility of a power plant with capacity 8 MWel has been investigated with efficiency 23% installed in Crete and utilizing various types of local solid biomass as fuel. The investment cost was estimated at 1,600-1,700 €/KWel and the operating cost at 0.056 €/KWel. The solid biomass was a mixture of various biomass sources (residues of olives, citrus, vineyard, etc). produced in Heraklion Prefecture. Taking into account a 40% investment capital subsidy, it has been estimated an attractive pay-back period of 6.7 years and 10 years IRR 20%. It is expected that instead of generating only electricity with efficiency 23%, the cogeneration of heat and power with overall efficiency approx 80% will improve substantially the profitability of this investment.

The quality of various wood residues as alternative fuels, mainly olive prunings and citrus prunings has been evaluated [2]. It has been concluded that these residues can be characterized as good quality fuels having high volatile and low ash and sulphur content. Their ash is rich in Ca, Si, K and P minerals. However fly ashes obtained from fluidized bed combustion were poorer in alkali compounds implying lower deposition and corrosion problem in boilers.

A techno-economic study of small scale biomass fuelled combined heat and power plants have been reported [3]. The economic viability depends on various factors like the cost of biomass, investment capital grants, good feed-in tariffs, and low interest loans. It has been concluded that smaller plants are less profitable than larger systems and it is important that the generated power and heat can be consumed and not wasted.

The combustion characteristics of different biomass fuels have been investigated [4]. It has been pointed out that biomass has a significantly lower heating value than most coals. This is part due to the generally higher moisture content and in part due to the high oxygen content. Different biomass materials have shown different combustion characteristics.

A literature review regarding small scale and micro-scale biomass-fuelled CHP systems has been reported [5]. The combination of biomass combustion and steam turbine technologies is the most used combination particularly for large and medium scale biomass CHP systems. Recently the combination of biomass combustion and Organic Rankine cycle receives more attention for smaller systems and such a system can achieve electrical efficiency approx 15% and heat efficiency approx 60-70%.

An investigation of the economic feasibility of a plant generating electricity from rice straw in Thailand has been reported (6). The researchers considered five plants with nominal power between 5 to 20 MWe. They estimated that the cost of generated electricity varies between 0.0676 USD/KWh and 0.0899 USD/KWh and the net present value of the investment is negative for the plant of 5 MWe and satisfactory for the plant of 20 MWe. Sensitivity analysis has shown that the profitability of such plants highly depends on the plant size, the selling price of electricity and the biomass price.

The economic profitability of power generation from biomass in combustion and gasification processes has been investigated [7-8]. It has been found that the profitability highly depends on the plant size and that the combustion technology offers to day more advantages than gasification particularly for smaller size plants. It has been found also that the biomass cost and its transportation cost to the plant affect seriously the profitability of the plant.

A review of the state of the art for decentralized biomass combustion has been presented [9]. It has been reported that for CHP plants working with steam turbines a minimum size of 5-10 MWth is required but with alternative to steam technologies like Stirling engines and Organic Rankine cycle systems smaller size plants can be profitable. It has been suggested that the selected technology should ensure the continuous operation and the reliability of the plant.

An investigation of various biomass sources which can be used for energy generation with combustion has been reported [10].

The state of the art for combustion and gasification of solid biomass for heat and power cogeneration in Europe has been presented [11]. For large CHP plants (> 2,000 KWel) based on biomass combustion, the steam turbine process in suitable, and for medium scale plants (200-2,000 KWel) the Organic Rankine cycle system has proved its suitability. The electricity generation costs based on biomass combustion in these cogeneration plants vary between 0.13-0.22 €/KWel mainly depending on plant size, fuel price and annual operation hours. The investment costs vary between 2,600-3,600 €/KWel. It is considered that electricity generation cost in gasification processes is clearly higher than in the combustion processes particularly for smaller size plants. A satisfactory process overall efficiency between 60-80% is of great importance as well as the operation of the plant for more than 6.000 hours/year.

The problems in the boilers during combustion of solid biomass as well as environmental issues related with its combustion have been presented [12]. Inorganic constituents of biomass cause problems of toxic emissions, fouling and slugging. Biomass elements including K, N, S, Cl, P, Ca, Mg, Fe, Si are involved in reactions leading to ash fouling and slugging in biomass combustors. Ash deposits reduce heat transfer and may result in metals corrosion. It has been concluded that biomass combustion systems are non-polluting and offer significant protection of the environment mainly reducing greenhouse gases pollution.

A description of a new biomass fuelled cogeneration plant of 1,000 KWel in Lienz, Austria (using Organic Rankine cycle process) has been presented [13]. This plant fed the generated electricity into the public grid (7,200 MWh/year) and the town of Lienz with district heat (60,000 MWh/year). The thermal power output of the plant was 4,450 KWth. The electricity generation cost of this plant varies between 0.09-0.14 €/KWel depending on biomass price and annual utilization of its capacity.

An investigation of the environmental, technological and social challenges during electricity generation from biomass has been presented [14]. It has been considered that significant attention must be given to reduce the land and water use as well as the social impacts of biomass power generation before sustainability can be achieved. Better sustainability is obtained when biomass is cultivated in marginal or unusable land.

2. Thermochemical Technologies for Energy Exploitation of Solid Biomass

Thermochemical technologies for energy exploitation of solid biomass include:

(a) Combustion
(b) Gasification
(c) Pyrolysis

From the abovementioned technologies combustion finds broad applications for various size plants, gasification is a new technology with few commercial applications preferable for larger size plants and pyrolysis a rather new technology which has not yet proved commercially its viability and profitability. Biomass combustion systems include steam turbines (suitable for large size systems) Organic Rankine cycle systems (suitable for medium size plants) and Stirling engines (suitable for small size plants). Steam turbines are the most broadly used technology having proved already its technical and economical viability. However for smaller size plants, the Organic Rankine cycle system is preferable having various advantages.

Production and uses of olive kernel wood in Crete has been reported [15] as well as the possibilities for future uses of this type of biomass for power generation [16], for cogeneration of heat and power [17] and for trigeneration of heat, power and cooling [18].

3. Production and Characteristics of Olive Kernel Wood and Olive Tree Prunings in Crete

Olive kernel wood is a byproduct of the olive kernel oil producing industry. Its annual production in Crete is approx 110,000 tons but it varies according to the olives production each year. Its chemical composition [19] is presented in Table 1.

Olive kernel wood is extensively used as a fuel for heat production since its price is low compared to its heating value and it has good burning characteristics. It is used mainly for heating buildings, greenhouses as well as in small and medium enterprises. Olive tree cuttings are produced in large quantities in Crete due to many millions olive trees growing in the island. Current practices for their treatment include either burning them in situ in the olive fields or grinding them in the fields and adding them in to the soil for its enrichment with organic matter. In Table 2 is presented the chemical analysis of olive prunings [2].

The quantity of olive prunings available in Crete for commercial exploitation is estimated to approx 45,000 tons/year [1].

Table 1 Chemical analysis of olive kernel wood (% dry weight).

Water content	6.3%
Ash	8.0%
Organic matter	65.50%
Sulphur	0.11%
Total Carbon	45.30%
Hydrogen	5.17%
Nitrogen	1.33%
Oxygen	34.30%
Heating value	4,051Kcal Kg^{-1}, (16.96MJ Kg^{-1})
Residual oil	≤ 10mg Kg^{-1}
Chlorine	0.69%

Table 2 Chemical analysis and calorific value of olive prunings (%dry weight).

Volatile matter	79.6
Fixed carbon	17.2
Ash	3.2
C	48.2
H	5.3
N	0.7
O	44.2
S	0.03
Gross calorific value	19.1MJ Kg^{-1} (4,584 Kcal Kg^{-1})

Olive kernel wood is produced in factories and it can be transported easily in the processing sites. On the contrary olive prunings are produced on the olive tree fields which usually have difficulties in access from transport vehicles.

Therefore the transportation cost of olive prunings from the production to consumption sites is higher than the corresponding cost of olive kernel wood.

4. Cogeneration of Heat and Power from Solid Biomass in Chania Crete Greece

A preliminary design of a biomass fuelled CHP plant in Chania-Greece has been made. Generated power will be fed into the grid and the produced heat will be consumed in the general hospital of Chania which needs heat all over the year. Hospitals are large heat consumers and their annual heat consumption may exceed 400 KWh m^{-2} mainly in the form of heat [20]. Due to profitability reasons it is considered that the plant will operate more than 6,000 hours annually and the produced heat will be sold to a large heat consumer. Because of the mild climate conditions of Crete, there are not many heat consumers over twelve months period in the island and the general hospital of Chania is one of them. In order to minimize heat losses during hot water transport, the plant should be installed nearby the hospital. The capacity of the CHP plant will be 1 MWel and it is restricted by the fact that it should not consume more than 10% of the annual production of olive kernel wood in Crete in order to avoid increase of its price due to higher demand of it. It is also restricted by the fact that in Crete there are not large heat consumers all over the year and the plant profitability depends highly on the use of the co-produced heat.

For capacity of the CHP plant of 1MWel combustion technology is the only option since biomass gasification technology is not profitable in low capacities.

Among various technology systems for the CHP plant (Stean turbine, Organic Rankine cycle system, Stirling engine) the most preferable for 1MWel is the Organic Rankine cycle system. The plant is considered to have electrical efficiency 15% and heat efficiency 65%. Its overall efficiency (heat produced + electricity generated divided by fuel heat content) is considered 80%.

Biomass sources which will be used in the plant are primarily olive kernel wood and additionally olive tree prunings. Advantages of olive kernel wood are:

(a) Its low price compared with its heating value;

(b) The fact that it can be easily transported from its production sites to the CHP plant;

(c) The fact that it is easily handlable;

(d) Its good combustion characteristics.

Olive tree prunings can also be used in cases with limited availability of olive kernel wood or in periods that its price is high. Other solid biomass sources which can be used in the plant currently available in Crete are vineyards cuttings, citrus prunings and greenhouses residues.

Various assumptions have been made in order to estimate several characteristics of the CHP plant. The capital cost of the CHP plant is estimated at 3,000,000 Euros (3,000 €/KWel). The price of olive kernel wood is estimated currently at 80 €/ton delivered at the plant site. Current feed-in tariffs for power generation in Greece from solid biomass for plants with capacities of 1 MWel is 180 €/MWH. It is assumed that the plant will operate 7,000 hours per year. Finally it is assumed that the produced heat which will be delivered in the hospital of Chania will be priced at 0.022 €/(1,000 Kcal delivered) which corresponds to 50% of the current price of the heat produced from fuel oil in Crete. Apart from the hospital of Chania the produced heat can be sold to various large heat consumers like laundries, greenhouses etc.

Table 3 Characteristics of a biomass fueled cogeneration of heat and power plant 1 MWel in Chania Crete Greece.

Power capacity	1 MWel
Heat capacity	4.33 MWth
Electrical efficiency	15%
Heat efficiency	65%
Overall efficiency	80%
Annual operating time	7,000 hours
Heating value of olive kernel wood	4,051 Kcal/Kg
Price of olive kernel wood	80 €/ton
Annual electricity generation	7,000 MWH
Annual heat production (2.61×10^{10} Kcal)	30,310 MWH
Annual biomass consumption	7,938 tons
Feed-in tariff for electricity fed to the grid	180 €/MWH
Price of heat sold	0,022 €/1000Kcal
Temperature of produced hot water	90-100°C
Annual cost of biomass consumed	635,040 €
Annual revenue from generated electricity	1,260,000 €
Annual revenue from produced heat	574,200 €
Total annual revenues	1,834,200 €
Capital cost of the plant	3,000,000 €
Percentage of olive kernel wood used in the plant to its total production in Crete	7.22%
Total plant operating cost (0.17 €/KWH)	1,190,000 €/year

The characteristics of the CHP plant are presented in Table 3.

Two important parameters have been taken into account for the selection of the plant capacity of 1 MWel:

(a) The current availability of olive kernel wood in Crete. Since a high new consumption of this biomass source will compete other current energy uses of it, it will probably drive its prices up, affecting negatively the profitability of the plant;

(b) The fact that the profitability of the plant depends on the use of the co-generated heat from large heat consumers. Due to mild climate of Crete there are not many large consumers demanding heat all over the year. Therefore higher heat production from the CHP plant is rather difficult to be sold.

5. Environmental Problems from Biomass Combustion in the Plant

The environmental problems during biomass combustion in the plant include:

(a) Pollutant emissions;

(b) Ash production;

(c) Problems in the boiler.

Significant environmental benefits can be obtained using solid biomass like olive kernel wood in direct combustion [4]. CO_2, SO_2 and ash production are lower compared with coal combustion. Primary pollutant emissions include particulate matter, PM, CO, HC, NO_X, SO. Therefore the impacts of the CHP plant regarding greenhouse effect and acid rain are less compared with a similar plant using fossil fuels instead of biomass. Studies from combustion of various biomass sources have shown that air toxic emissions were very low and near or below detection limits [4].

Since biomass based on olive trees has low ash content [2], its burning produces less ash compared with coal burning. However the produced ash is rich in alkali metals like Ca, K, Si, but its concentration in toxic metals is very low. Due to that ash creates fouling, slugging and corrosion in the combustor. This is a common technological problem of the biomass firing technology. The strength of biomass combustion deposits are higher compared to deposits from coal combustion [12].

6. Economic Feasibility of the CHP Plant

For the estimation of the economic feasibility of the CHP plant four scenarios have been examined as follows:

In the basic scenario (S_1) the parameters of the Table 1 are considered and annual revenues, total operating costs, and annual profits are calculated.

In the second scenario (S_2) the total annual operating cost is estimated at 1,330,000 € (0.19 €/KWHel) due to higher prices of the olive kernel wood. All other parameters and costs are the same with the basic scenario.

In the third scenario (S_3) it has been assumed that the annual revenues from the produced heat are 50% of the corresponding revenues of the basic scenario (287,100 €/year) considering the difficulties for selling the co-produced heat in Crete. All other parameters and costs are the same with the basic scenario.

In the final fourth scenario (S_4) it has been assumed that the plant operates 6,000 hours annually instead of 7,000 hours of the basic scenario. All other parameters are the same with the basic scenario.

For each scenario the annual revenues, the annual total operating cost, the annual profits and the payback period have been estimated and presented in Table 4.

Annual revenues are the sum of the income from electricity sold to the grid plus the income from the heat sold to heat consumers. It is assumed that all the produced heat will be sold at a rate 50% of the current rate of heat produced by fuel oil.

Operating costs of the plant include, biomass cost, labour and maintenance costs, capital amortization costs, consumables, overheads, ash disposal costs, utilities, electricity and contingency costs. The total annual operating cost of the plant is estimated at 0.17 € per KWh of generated electricity. This cost is higher compared with the cost reported elsewhere [1, 13] since the price of olive kernel wood is higher than the cost of the biomass sources reported there [1], but it is in the price range of 0.13-0.22 Euro/KWh reported in another study [11].

The net present value of the biomass CHP plant for the abovementioned four scenarios and for interest rates 2%, 3%, 4% and 5% for an operating period of 15 years is presented in Table 5.

The annual profits of the CHP plant under the four scenarios are presented in Fig. 1.

The payback periods of the CHP plant under the four scenarios are presented in Fig. 2.

Table 4 Various economic parameters of a biomass fueled CHP plant 1 MWel in Crete Greece.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual revenues (€)	1,834,200	1,834,200	1,547,100	1,572,171
Annual costs (€)	1,190,000	1,330,000	1,190,000	1,020,000
Annual profit (€)	644,200	504,200	357,100	552,171
Payback period (years)	4.66	5.95	8.40	5.43

Table 5 Net present value of the biomass fueled CHP plant of 1 MWel operated for 15 years.

	NPV (€)			
Interest rate	Scenario 1	Scenario 2	Scenario 3	Scenario 4
2%	5,443,045	3,609,007	1,680,241	4,236,890
3%	4,921,130	3,200,446	1,390,928	3,789,535
4%	4,448,963	2,830,829	1,129,191	3,384,821
5%	4,020,924	2,495,739	891,905	3,017,913

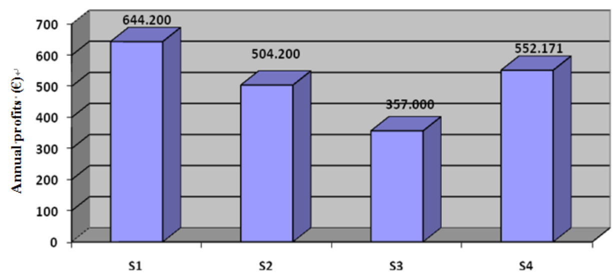

Fig. 1 Annual profits of the biomass fueled CHP plant in Chania for different scenarios.

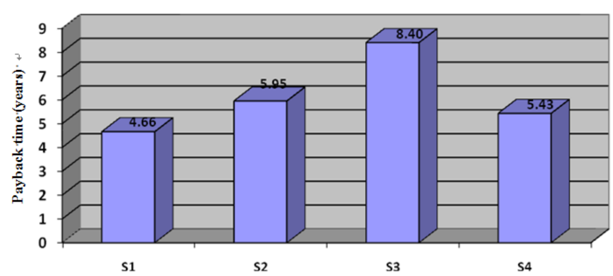

Fig. 2 Payback time of the biomass fueled CHP plant in Chania for different scenarios.

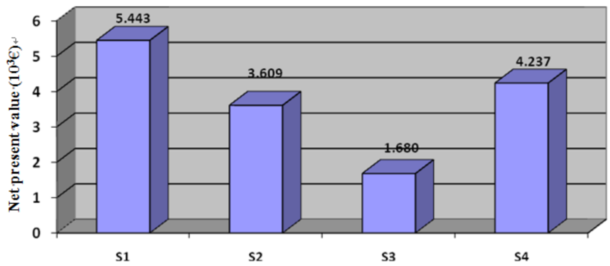

Fig. 3 Net present value of the biomass fueled CHP plant in Chania for different scenarios (15 years and interest rate 2%).

The net present values of the CHP plant for a fifteen years operating period and 2% interest rate are presented in Fig. 3.

7. Conclusions

A biomass fuelled heat and power cogeneration plant has been studied in Chania Crete Greece. Olive kernel wood which is produced locally can be fed into the plant as well as other endogenous solid biomass resources like olive tree prunings. Current high feed-in tariffs of 180 €/MWH guaranted for many years in Greece for electricity generation from solid biomass make economically attractive the creation of this plant. Co-produced heat can be sold to large heat consumers in the nearby to the plant area improving plant economics.

The capacity of the plant was considered 1MWel with total efficiency 80%. Economic analysis proves that this plant can be profitable provided that the co-produced heat can be sold to heat consumers and olive kernel wood prices will remain in current levels. Various scenarios have been examined in order to estimate the profitability of the plant under different conditions and all scenarios have proved the profitability of the plant. The capital investment cost is estimated at 3 mil Euros, payback time varies from 4.66 to 8.40 years and net present value varies from 1.68 to 5.44 mil Euros for fifteen years operation and 2% interest rate.

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Pellets Production from Olive Tree Byproducts and Residues: A case study in Crete – Greece

John Vourdoubas[1]

Abstract

Wood pellet is a renewable solid fuel which finds broad applications mainly for heating buildings all over the world. Wood pellets constitute a non conventional fuel with neutral impacts to the greenhouse effect and they are produced from various agricultural and forest wastes, byproducts and residues. Olive trees are cultivated in the island of Crete – Greece as well as in many other Mediterranean countries producing large quantities of olive oil. Various byproducts and residues of the Olive trees like olive tree wood, olive Kernel wood and olive tree prunings are produced in large quantities and some of them are utilized currently for heat generation in Crete. These olive byproducts and residues have very good burning characteristics and they can be used for the production of wood pellets in Crete. Economic assessment of a pellets production plant in Crete proves that their production under various conditions is economically viable offering additional social and environmental benefits.

Keywords: biomass, Crete, olive Kernel wood, olive tree, olive tree prunings, pellets production.

1. Introduction

The necessity for mitigation of greenhouse effect results in the increasing use of various renewable energy sources including biomass as well as in smaller dependence on fossil fuels. Exploitation of local endogenous biomass resources for energy generation results in higher energy security and lower needs for oil and gas imports for many countries. In various Mediterranean countries olive trees are extensively cultivated and apart from the excellent quality of the produced olive oil various byproducts and residues from those trees are also co-produced. Due to the fact that they have very good burning characteristics and high calorific value they are currently used for heat production.

Because of the current economic crisis in Greece and the increasing energy poverty in the society there is a need of many households to shift from fossil fuels like heating oil and natural gas to cheaper fuels including biofuels. Since the demand for low price unconventional fuels is increasing the exploitation of various agricultural byproducts and residues is of primary importance.

Wood pellets market in Europe is growing and some countries have imposed quality standards for them. However in Greece although there are various local manufacturers of wood pellets, the legal framework for pellets quality specification does not exist.

Pellets can be used for heat generation in houses and in other buildings competing conventional fuels like heating oil, natural gas and electricity. The cost of pellets burning equipments like stoves, open fires or central heating systems is relative low. Agricultural and forest residues which are used as raw materials must have low moisture and ash content in order to produce good quality pellets. Pellets production process is not complicated and includes grinding and drying of the raw materials before pressing them to the required form and size.

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It is expected that in the foreseeable future wood pellets will have growing applications as an unconventional but attractive renewable fuel. Many reports, studies and research results have been published on pellets production and use.

A comparison of wood pellet production cost in Austrian and Swedish conditions has been presented by Thek and Obernberger, 2004. According to them production cost of wood pellets mainly depends on raw materials cost and their drying cost if needed. Other factors influencing the cost are plant utilization and raw materials availability. They found that the production cost of wood pellets in Austria in higher than in Sweden due to drying and raw materials costs.

A study of the obstacles and success factors of pellets production in forest industry in Sweden has been reported by Wolf et al, 2006. They suggested that an existing pellets market is a success factor for their production as well as the existence of the raw material nearby the production plant.

A study of agricultural pellets market in Greece has been presented by Karkania et al, 2012. They have reported that agro-residues constitute the biggest source of biomass in Greece without being exploited for energy generation. However since the pellets market in Greece is growing they should be used in the future for heat production.

An investigation of the economics of producing fuel pellets from biomass for the conditions of North America has been reported by Mani et al, 2006. They found that for plant capacity of 6 tons/h , pellets cost was 51 $/ton. Raw materials cost was the largest cost element, followed by personnel cost, drying cost and pelleting mill cost.

A study of the wood pellets production cost in Northeast Argentina has been reported by Uasuf et al, 2011. They found a relative low cost of 35 to 47 €/ton compared with other studies where the raw materials cost (sawmill residues) represented the main cost factor in the calculation of the final cost.

A report on the potential of biomass residues for energy production in the region Marvao in Portugal has been made by Fernandes et al, 2010. They concluded that the region has a potential over 10,000 tons /year of agricultural and forest residues which should be used for heat generation replacing fossil fuels.

A study on the agri-pellet production cost in Canada has been made from Sultana et al, 2010 . They have estimated that for annual production capacity from 70,000 to 150,000 tons the production cost varies from 170.89 $/ton to 122.17 $/ton.

An analysis on the Portuguese pellets market has been presented by Monteiro et al, 2012. They found that the reasons for the underdevelopment of the Portuguese pellets market, are mainly the lack of internal consumption and the shortage of raw materials mainly due to the competition of the available resources with the existing biomass power plants.

A study of the European wood pellet market and its prospects for 2020 has been implemented by Sikkema et al, 2011. According to them the final price of pellets for residential heating varied in various countries between 220 – 310 €/ton in the end of 2010.

2. Olive residues and byproducts in Crete-Greece

Crete has currently approx. 26 millions productive olive trees which produce various by products, wastes and residues like

a) Olive trees firewood
b) Olive Kernel wood
c) Olive tree prunings

Olive trees firewood is extensively used currently for heat production in wood stoves and wood open fires since it is considered as a very good fuel. Olive Kernel wood is a byproduct of olive Kernel oil producing industry after water removal and oil extraction of the olive mills paste and its annual production in Crete is approx. 110,000 tons . Its low price and its very good combustion characteristics makes it a very attractive fuel for heat generation in buildings, in industry and in agriculture. In tables 1 and 2 the chemical composition of olive kernel wood and olive husks is presented.

Table 1	
Chemical Analysis of olive Kernel wood	
Water content	6.30%
Ash	8.0 %
Organic matter	65.50 %
Sulphur	0.11 %
Total Carbon	45.30%
Hydrogen	5.17%
Nitrogen	1.33%
Oxygen	34.30%
Heating value	4,051 Kcal/kg, 16.96 MJ/kg
Residual oil	2.44 %
Residual hexane	≤ 10 mg/kg
Chlorine	0.69%

(Vourdoubas, 2008)

Table 2	
Chemical composition of Olive husks	
Ash	4.1 (w.t % of dry fuel)
Volatile matter	77.5 (w.t % of dry fuel)
Fixed carbon	18.4 (w.t % of dry fuel)
C	49.9 (w.t % of dry fuel with ash)
H	6.2 (w.t % of dry fuel with ash)
N	1.6 (w.t % of dry fuel with ash)
S	0.05 (w.t % dry fuel with ash)
Cl	0.2 (w.t % of dry fuel with ash)
O	42.0 (w.t % of dry fuel with ash)

(Demirbas, 2004)

Annual production of olive tree prunings in Crete is estimated at 1,550,000 tons. Usually the large size of them is separated and used for heat generation.However smaller sizes either are burnt in the fields, a practice which probably will be banned soon or they are grinded in situ and added into the soil to enrich it with organic matter. Since many olive tree groves are accessed with difficulty from transport vehicles a serious technical barrier exists for their collection and energy use.

In table 3 and 4 the chemical composition of olive tree prunings is presented.

Table 3	
Chemical composition of Olive tree prunings (% dry weight)	
Volatile matter	79.6
Fixed carbon	17.2
Ash	3.2
C	48.2
H	5.3
N	0.7
O	44.2
S	0.03
Gross calorific value	4,584 kcal/kg, 19.1 MJ/kg

(Vamvuka, 2010)

Table 4	
Chemical composition of Olive tree prunings	
Moisture (% w.b)	24.0
Fixed carbon	17.1 (% d.m.)
Volatile compounds	80.2 (% d.m.)
Ash	2.7 (% d.m.)
C	49.4 (% d.m.)
H	6.6 (% d.m.)
N	0.76 (% d.m.)
S	<0.05 (% d.m.)
C	0.03 (% d.m.)
Lower heating value	18.5 MJ/kg (d.m.)
K_2O	0.20 (% d.m.)
Na_2O	0.01 (% d.m.)

* w.b. = wet basis, d.m. = dry matter
(Martinez et.al., 2002)

1. European quality specifications of wood pellets

Various European countries have imposed official standards for wood pellets for non-industrial use. EU proposals published in the report CEN/TC 14961 exist also as suggestions but there are not yet official European quality specifications for wood pellets. In Table 5 the quality standards for wood pellets in Austria, Germany, Sweden and in CEN/TC 14961 are presented.

Table 5				
Various Quality Standards for wood Pellets in EU countries				
	Austria	Sweden (group 1)	Germany	CEN 14961 (for domestic heating use)
Bulk density		> 600 kg/m^3		-
Moisture content	<10 %	<10 %	<10 %	<10 %
Ash content	<0.5%	<0.7 %	<1.5 %	< 0.7 %
Calorific value	≥ 18 MJ/kg	≥ 16.9 MJ/kg	17.5-19.5 MJ/kg	≥ 4,042 kcal/kg 16.9 MJ/kg
Sulphur	≤ 0.04 %	≤ 0.08 %	< 0.04 %	≤ 0.05 %
Nitrogen	≤ 0.3 %	-	<0.3 %	< 0.3 %
Chlorine	≤ 0.02 %	≤ 0.03 %	≤ 0.03 %	<0.03 %
Arsenic			<0.8 mg/kg	
Cadmium			<0.5 mg/kg	
Chromium			<8 mg/kg	
Copper			<5 mg/kg	
Mercury			<0.05 mg/kg	
Lead			< 10 mg/kg	
Zinc			< 100 mg/kg	
Additives	<2 % , only natural			<2%

(www.bioenergynet.com)

2. Production technology of wood pellets

Production technology of wood pellets includes preprocessing, drying, grinding, conditioning, densification, cooling, screening and bagging. Depending on the type of biomass source some of these stages probably are not necessary.

After feeded to the plant the raw materials must be dried in most cases in order to decrease their moisture content to 12 % p.w. or slightly less. Since drying cost contributes significantly to the final cost of the pellets, it is important to minimize this cost or to avoid the drying stage if the initial moisture content of biomass is low. After drying, grinding of biomass is necessary in order to reduce its size to the desired levels. Next stage includes conditioning of the biomass where super heated steam at temperatures above 100 ^{0}C is used to soften the raw material.

Densification or pelletization follows and biomass enters in a extruder where it takes its final form. Since pressure is high at this stage lignin is softened and it helps the transformation of biomass to the final pellet form. During pelletization temperature rises to 90-95 ^{0}C due to high pressure and cooling is needed afterwards in order to solidify lignin and to increase the strength of the pellets.

5. Burning systems of wood pellets for heat production

Various burning systems like open fireplaces, stoves and domestic boilers are currently used for heat generation from pellets. The burning characteristics of pellets produced from various biomass sources have been studied (Gonzalez et al, 2004) in a domestic boiler.

They found that pellets produced from tomato residues and olive stones had excellent burning behaviour. Pellets produced from cardoon had high ash content (11.3 %) and low melting point so in this case continual removal of the ash from the fireplace was required.

Cost comparison of pellets which can be derived from olive Kernel wood with heating oil shows that heat from pellets costs 0.071 € /1,000 kcal delivered compared to 0.107 € /1,000 kcal delivered for heating oil. Therefore the cost of those pellets is only 66.36 % of the corresponding cost of heating oil.

6. Possibilities of pellets production from olive byproducts and residues in Crete-Greece

There is currently an increasing demand for wood pellets in households as a fuel substitute to heating oil in Crete and in Greece due to their relatively low price, compared with heating oil.

Also there is high availability of biomass resources like olive Kernel wood and olive tree prunings in Crete. Solid biomass is not used for power generation in Greece. Olive Kernel wood is currently used for heat but not for power generation.

Small size olive tree prunings are not used though for heat generation. However the chemical composition of the abovementioned biomass resources restricts their use for the production of high quality wood pellets.Since there are not quality specifications for wood pellets in Greece, olive Kernel wood and olive tree prunings can be used for the production of second quality pellets. The main drawback of these biomass resources is related with their high ash content, which is significantly higher than the existing upper limits in various EU countries.

The composition of olive Kernel wood in Sulphur and Nitrogen exceeds the upper limits as well. Olive tree prunings have better characteristics but their ash and Nitrogen content exceeds also the upper limits.
Between olive Kernel wood and olive tree prunings, the first has the drawback of relatively high price (0.08 €/kg) but low transportation cost from its production site in the olive Kernel oil producing plants to the pellets factory. The cost of Olive tree prunings is related with the cost of their collection and transport from the olive fields to their processing site.

The capacity of the pellets production plant is restricted from two adverse factors.

Firstly its capacity must be high enough to minimize production cost of pellets and secondly it must be low enough to avoid competition of the new use of olive Kernel wood with its other uses in Crete (as fuel for heat production) which could drive up its price.

To avoid biomass transport cost (which affects significantly the production cost) the pellets production plant must be located nearby the olive Kernel oil producing plants and nearby the olive fields. Currently there are nine olive Kernel oil producing plants operating in Crete.

Apart from heating buildings there is also a high demand of alternative fuels including biomass from large heat consumers in Crete like greenhouses and small size industries. This trend is increasing because of the current economic crisis in Greece and the high taxation and prices of heating oil.

Advantages of olive Kernel wood as a raw material for pellets production are

- It has low moisture content and the drying stage can be avoided.
- It is easily available and handleable in Crete
- It is easily transported to the processing site
- Due to its granular size it does not need grinding

Disadvantages of olive Kernel wood as a raw material for pellets production are

- Its high ash content restricts its use for first quality pellets.
- It has high Nitrogen and Sulphur content
- It has high purchasing cost
- Its use for pellets production could compete its other uses for heat generation in Crete.
- It has undesired odour due to fermentation of olive mills paste before its processing for the production of olive Kernel oil and olive kernel wood.

7. Estimation of capital and operating cost of a wood pellets production plant in Crete-Greece.

A preliminary estimation of the capital and operating cost of a wood pellets production plant in Crete-Greece has been made for two different capacities based on data presented by Thek et.al. , 2004, with reference to Austrian conditions.

a) Annual pellet production 2,253 tons (d.w.)/year
Investment cost (without dryer) 634,000 €
Working days per week 5
Shifts per day 1
Annual operating hours 1,877
Raw materials cost 80 €/ton
Processing cost 130 €/ton
Total production cost 210 €/ton
Selling price of pellets 230 €/ton
Ratio of raw materials cost to total production cost 38.10 %
Percentage of olive Kernel wood used annually to its total annual production in Crete 2.05 %
Annual profit 45,060 €

b) Annual pellet production 16,894 tons (d.w.) / year
Investment cost (without dryer) 1,167,000 €
Working hours per week 5
Shifts per day 3
Annual operating hours 5,631
Raw materials cost 80 € /ton
Processing cost 75 € /ton
Total production cost 155 € /ton
Selling price of pellets 230 € /ton
Ratio of raw materials cost to total production cost 51.61 %
Percentage of olive Kernel wood used annually to its total annual production in Crete 15.36 %
Annual profit 1,267,050 €

According to the estimations, higher plant capacity significantly decreases the total pellets production cost and increases the profit margin. However higher plant capacity will require higher quantities of olive kernel wood and it could probably increase its price since it will compete with other current uses of it. The ratio of raw materials cost to the total operating cost of pellets varies between 38.10% (capacity 2,253 tons/year) and 51.61% (capacity 16,894 tons/year) compared to 36.10% reported for the base case scenario in Austria from Thek et. al.,2004.

The low total production cost of pellets in Austria (90.7 € /ton) reported by the same authors is partly due to the higher plant capacity, 23,652 tons/year and the low raw materials cost, 32.7 € /ton. However it can be assumed that the raw materials for the pellets production plant will be both olive Kernel wood and olive tree prunings.

Analysis of pellets production cost in Sweden for large plant capacities of 79,716 tons/year results in total production cost of 62.4 € /ton (significantly lower than in Austria) and the raw materials cost of 31.28 € /ton represents 50.13% of their total production cost.

8. Profitability analysis of a pellets production plant using olive Kernel wood as raw material.

Estimation of net present values of the pellets production plant for a period of 15 years and an interest rate of 2% for the abovementioned two cases with capacities of 2,253 tons/year and 16,894 tons/year has been made. For each plant capacity seven scenarios have been investigated as follows.

S1 Base case scenario as shown previously
S2 10% increases in the price of raw materials, all other parameters remain the same
S3 20% increases in the price of raw materials, all other parameters remain the same.
S4 10% increases in pellets processing cost, all other parameters remain the same.
S5 20% increases in pellets processing cost, all other parameters remain the same.
S6 10% decreases in selling price of pellets, all other parameters remain the same.
S7 20% decreases in selling price of pellets, all other parameters remain the same.
Cost parameters for various scenarios are presented in table 6

Table 6
Various parameters of pellets production plant for seven different scenarios

	S1	S2	S3	S4	S5	S6	S7
Raw materials cost (€ /ton)	80	88	96	80	80	80	80
Processing cost (€ /ton)	130	130	130	143	156	130	130
Total production cost (€ /ton)	210	218	226	223	236	210	210
Selling price (€ /ton)	230	230	230	230	230	207	184

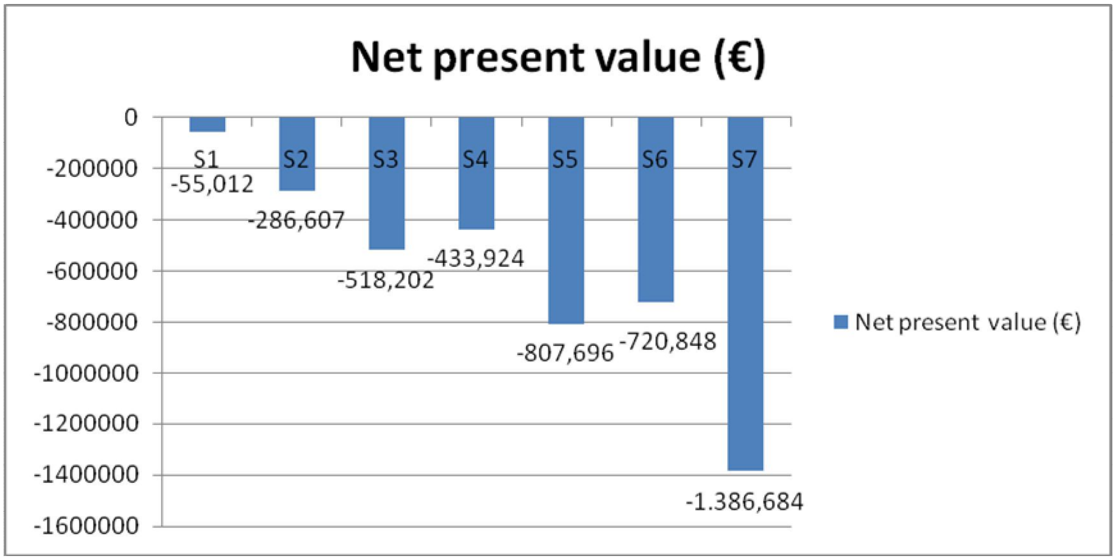
Economic results of the pellets production plant in Crete with capacity 2,253 tons/year are presented in table 7

Table 7
Economic results of the pellets production plant in Crete with capacity 2,253 tons/year

	S1	S2	S3	S4	S5	S6	S7
Annual revenues (€)	518,190	518,190	518,190	518,190	518,190	466,371	414,552
Annual costs (€)	473,130	491,154	509,178	502,419	531,708	473,130	473,130
Annual profit (€)	45,060	27,036	9,012	15,771	-13,518	-6,759	-58,578
Net present value (€)	-55,012	-286,607	-518,202	-433,924	-807,696	-720,848	-1,386,684

Net present value for the seven scenarios for 15 years operation and 2% interest rate of the pellets production plant with capacity 2,253 tons/year is presented in figure 1

Figure 1
Net present value for the pellets production plant in Crete with capacity 2,253 tons/year (seven different scenarios)



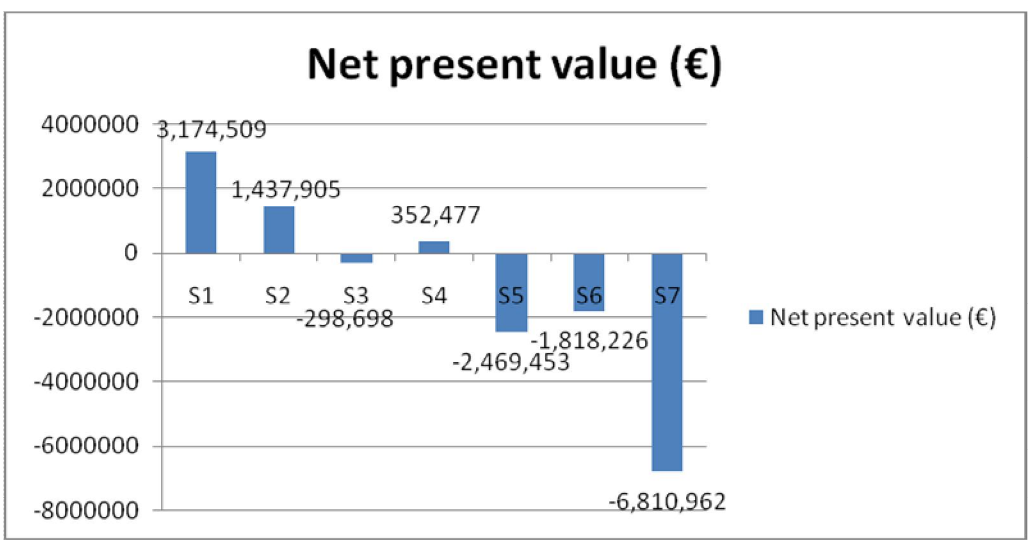
Economic results of the pellets production plant in Crete with capacity 16.894 tons/year are presented in table 8

Table 8
Economic results for the pellets production plant in Crete with capacity 16.894 tons/year

	S1	S2	S3	S4	S5	S6	S7
Annual revenues (€)	3,885,620	3,885,620	3,885,620	3,885,620	3,885,620	3,497.058	3,108,496
Annual costs (€)	3,547,740	3,682,892	3,818.044	3,767,362	3,986,984	3,547,740	3,547,740
Annual profit (€)	337,880	202,728	67,576	118,258	-101,364	-50,682	-439,244
Net present value (€)	3,174,509	1,437,905	-298,698	352,477	-2,469,453	-1,818,226	-6,810,962

Net present value for the seven scenarios for 15 years operation and 2% interest rate of the pellets production plant with capacity 16,894 tons/year in presented in figure 2

Figure 2
Net present value for the pellets production plant in Crete with capacity 16, 894 tons/year (seven different scenarios)



9. Environmental and social benefits

The use of olive residues and byproducts for pellets production results in various environmental and social benefits. Production of pellets in Crete – Greece will

a) Reduce greenhouse gases emissions in the country.
b) Reduce imports of fossil fuels mainly oil and natural gas.
c) Increase energy security
d) Decrease energy dependency

At the same time in local level it will

a) Increase investments in new plants.
b) Create local incomes and profits for the farmers and the local investors.
c) Increase employability and creation of new jobs.
d) Increase the production of heating systems using wood pellets as fuel.

10. Conclusions

There is currently an increasing interest in Greece and in Europe for wood pellets production which are mainly used for heat generation. However in most EU countries including Greece there are not quality specifications for them. In Crete with the cultivation of many millions olive trees, various residues and byproducts of them are produced.

Among various solid biomass sources olive Kernel wood has excellent burning characteristics and it is broadly used for heat production. Olive tree residues like small size tree prunings are not used for heat generation although they also have very good burning characteristics. The chemical composition of olive Kernel wood and olive tree prunings does not allow them to be used as raw materials for production of first quality wood pellets. They can though be used for production of second quality wood pellets suitable for heat generation in industrial boilers and in various buildings since their price is significantly lower than current heating oil prices.

Preliminary cost analysis of a pellets production plant in Crete using primarily olive Kernel wood has shown that it can be profitable under various conditions. A production plant with capacity 16,894 tons/year utilizing mainly olive Kernel wood with price 80 € /ton has satisfactory economic performance with pellets selling price at 230 € /ton. The high cost of olive kernel wood is the main cost factor in the total production cost of pellets, which is relatively high compared with the cost of pellets produced from other biomass sources. However pellets production plants with smaller capacities are not profitable in Crete mainly due to high prices of the olive Kernel wood and high operating costs in smaller capacity plants.

The profitability of this plant is negatively influenced by a lower selling price of wood pellets or a higher price of olive Kernel wood.

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Overview of Heating Greenhouses with Renewable Energy Sources. A Case Study in Crete-Greece

John Vourdoubas[1]

Abstract

Heating greenhouses results in higher productivity and better quality of the produced crops mainly in Northern climates. Apart from conventional fuels already used for heating them renewable energy sources are expected to play an important role in the near future. Among them solar energy, geothermal energy and biomass have been used in various greenhouses all over the world. A successful operation of a greenhouse cultivated with flowers during 2012-2014 in Crete-Greece heated with olive kernel wood proves that this solid fuel is a cheap energy source which can cover all the heating needs of the greenhouse lowering at the same time its CO_2 emissions due to energy use. Olive kernel wood is an endogenous, renewable and CO_2 neutral energy source in areas where olive trees grow. Additional installation of a Photovoltaic system in the greenhouse already heated with solid biomass in Crete will result in zeroing its CO_2 emissions due to energy use in it. Since the heat demand in the greenhouse is much higher than the electricity demand, replacement of fossil fuel with renewable fuels results in significant decrease of CO_2 emissions due to energy use.

Keywords: Heating greenhouses, renewable energy sources, solar energy, geothermal energy, biomass, olive kernel wood

1. Introduction

Growth of high quality vegetables in greenhouses in Northern climates is connected with the creation of optimum growth conditions including optimum temperatures. Due to severe environmental problems caused by fossil fuels there is an increasing interest to use renewable energy resources for heating them particularly if they are cost effective. Among renewable energies the most important for providing the necessary heat in the greenhouses are solar energy, geothermal energy and biomass, (Sethi et.al.,2008, Vourdoubas, 2004) . In areas where olive trees grow a traditional fuel used for heating is the olive kernel wood which is a byproduct of the olive kernel oil producing industry. This solid fuel is used since many decades and its low price, local availability and good combustion characteristics make it very attractive. Therefore it is broadly used for heating in buildings, in small and medium enterprises and in greenhouses replacing heating and fuel oil (Vourdoubas, 1999). The severe economical crisis in Greece the last five years has increased substantially the price of heating oil which has resulted in its replacement with alternative fuels in many cases. In Crete-Greece the cultivation of many millions olive trees makes available the production of solid biomass based on olive trees like olive firewood, olive tree cuttings and olive kernel wood. Current price of olive kernel wood in Crete compared with its heating value makes it very attractive as substitute of fuel and heating oil. At the same time since olive kernel wood is a renewable energy source its use in greenhouses results in a large reduction of CO_2 emissions due to energy use in them. Greenhouses in Crete apart from using solid biomass for covering all their heating needs can also use solar energy with Photovoltaic cells for covering their electricity needs. Generation of electricity from PV cells is cost effective today and the legal framework in Greece for their use in greenhouses with net-metering exists.

2. Use of Various Renewable Energy Sources for Heating Greenhouses

Among various renewable energy sources, solar energy, geothermal energy and biomass have already been used for heating greenhouses. Solar energy has been used mainly with passive systems and energy storage (Santamouris et.al., 1994). Geothermal energy has been used directly utilizing hot fluids with temperatures 50-100 ^{o}C (Bakos et.al., 1999) or indirectly with low enthalpy heat pumps (Esen et. al., 2013). Geothermal energy has also been used for cooling greenhouses during the summer with buried tubes inside the ground (Santamouris et.al.,1995). Finally biomass has been used for heating greenhouses either in gaseous form (biogas) (Jaffrin et. al., 2003) or in solid form (various wood products and byproducts) (Vourdoubas, 1999). Heating needs of greenhouses depend on their construction, on the local climatic conditions and on the cultivated crop. The abovementioned renewable energy sources can cover part or all of their heating needs. Which renewable energy source will be used depend on its availability, its relative price, the initial investment cost, the heating needs of the greenhouse, the possibility of covering part or all of them as well as from

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other factors. The combination of two or more of the abovementioned renewable energy sources can also result in covering all the heating needs of the greenhouse.

2.1. Solar Energy

Many types of passive solar systems have been used for heating greenhouses (Santamouris et.al., 1994). According to the characteristics of the heat storage system they are categorized as greenhouses with:

a) Heat stored in water
b) Heat stored as latent heat in various materials
c) Heat stored in rock bed
d) Heat stored in buried pipes

These passive solar systems can only cover part of the energy needs and can achieve temperatures 3-20 ^{0}C higher than the minimum outdoor temperature. A survey and evaluation of various heating technologies (Sethi et.al., 2008) proves that solar technologies can cover significant part of the heating needs of greenhouses. The operation for two years of an experimental passive solar greenhouse of 1,000 m^2 has shown energy gains equal to 35% of the annual heating requirements (Santamouris et.al., 1994). A literature investigation of various passive solar greenhouse classifies them in three categories according to the phase change materials used (Kurklu, 1998). These phase change materials (salt hydrates, paraffins, polyethylene glycol) can be used both for energy storage and humidity control in the greenhouses. Passive solar systems can also be used for covering the cooling needs of greenhouses (Santamouris et.al., 1995, Chou et. al., 2004). The operation of a passive solar greenhouse with buried pipes has shown that it lowers the heating needs during the winter and its cooling needs during the summer. The investigation of the energy behavior of a greenhouse equipped with PV cells has been implemented in New Delhi ,India (Nayak et.al. ,2008) . The PV cells were integrated in the south wall of the greenhouse and heat and electricity were generated. The heat was convected inside the greenhouse and the electricity was stored in batteries. The overall results during its operation were satisfactory. An exegetic analysis of a greenhouse cooled by an earth to air heat exchanger powered by a solar photovoltaic cell was studied in Izmir, Turkey (Yildiz et.al., 2001). In this greenhouse significant part of its cooling requirements were covered by solar and geothermal energy.

2.2. Geothermal Energy

Geothermal energy can be used either directly utilizing warm fluid at approx 50-80^{o}C or with low enthalpy heat pumps. A greenhouse heated with geothermal fluid of approx 100^{o}C in Northern Greece has been used for cultivation of roses where an inside temperature of 20^{o}C was required. The used geothermal fluid with mass flow rate of 42 tons/h and temperature of 95^{o}C was maintaining an inside temperature of 20^{o}C when the outside temperature was 7^{o}C. The installed geothermal space-heating system of 2.26 MWth was covering all the heating needs of the greenhouse of 10.000 m^2 (Bakos et. Al., 1999). Another greenhouse operating in Izmir, Turkey using a solar — assisted vertical ground — source heat pump has been reported by (Ozgener et.al.,2007). For ambient temperatures of 5.8- 12.5^{o}C the inside temperatures were 15.8-22.5^{o}C. The C.O.P. of the heat pump was varying between 2 and 3.13 and it was proved that the heating system was operating satisfactorily without serious defects. A greenhouse heated with low enthalpy geothermal water with temperature of 28^{o}C which was circulated in plastic pipes placed on the ground was studied in Argentina (Adaro et.al., 1999).

Experimental operations during three years period have shown satisfactory results regarding its space heating with low temperature geothermal water. The energy behaviour of a greenhouse equipped with a heat pump for heating, cooling and dehumidification was studied in Bangkok(Chou et.al. , 2004) . The heat pump was achieving day temperature of 27 ^{o}C and night temperature of 18^{o}C having C.O.P. 1.2-4.0.

2.3. Biomass

The experimental investigation of a combined heated system with biogas, solar energy and ground-source heat pump has been reported in Elazig, Turkey (Esenet.al.,2013). Biogas was produced in situ using cow manure and the reactor was heated using solar energy. The project aimed to prove that a combination of various renewable energy sources like biogas, solar energy and low enthalpy geothermal energy can be used for the effective heating of a greenhouse. During the experimental operation of the greenhouse the outside air temperature was varying between 0^{o}C and 13^{o}C, the ground temperature between 8^{o}C-11^{o}C and the inside air temperature in the greenhouse was kept at 23^{o}C. The possibility of heating greenhouses with biogas with simultaneous enrichment of the inside air with CO_2 was investigated in France(Jaffrin et.al., 2003) . The exhaust gases after burning the biogas were injected inside the greenhouse where roses were cultivated. During the experimental period of 24 months high productivity was obtained and the gains due to better productivity were higher than the heating cost reduction due to biogas use. This method offers the possibility of greenhouses construction nearby landfill sites and use of the produced biogas in the greenhouses. Heating greenhouses in Crete with olive kernel wood has been presented (Vourdoubas, 1999) as well as a multicriteria comparison of heating them with solar energy, geothermal energy and solid biomass (Vourdoubas, 2004). Possibilities for zeroing CO_2 emissions from greenhouses due to energy use has been presented (Vourdoubas , 2009) as well as the current use of olive kernel wood in Crete for heat production (Vourdoubas, 2015) . Renewable energy sources which have been used for covering energy needs in greenhouses are presented in table 1.

Table 1: Renewable Energy Sources which have been used for Heating Greenhouses

Energy source	Characteristics of the systems	Cover of heating needs	Cover of cooling needs
Solar energy	Heat storage in various materials	Partly	No
Solar energy	Heat storage in buried pipes	Partly	Partly
Geothermal energy	Hot fluid 50-80^{o}C circulated in pipes	All	No
Geothermal energy	Low enthalpy ground source heat pump	All	All
Biomass (biogas)		All	No
Biomass (solid)	Hot water circulated in pipes	All	No

3. Characteristics of Olive Kernel Wood

Olive kernel wood is a byproduct of the olive kernel oil producing industry and its annual production in Crete Greece is approx 110,000 tons. Biomass fuels including olive kernel wood cover currently 8.5 % of the energy needs of Crete (Zografakis, 2005). Its current price is 0.08 €/kg and its heating value is 4,051 Kcal/kg (16.96 MJ/Kg). It is easily transported from the production plant to the consumption site since its form is granular. In table 2 the chemical composition of olive kernel wood is presented.

Table 2: Chemical Composition of Olive Kernel Wood

Water content	6.3%
Ash	8.0%
Organic matter	65.50%
Sulphur	0.11%
Total Carbon	45.30%
Hydrogen	5.17%
Nitrogen	1.33%
Oxygen	34.30%
Heating value	4.051 Kcal/kg, 16.96 MJ/Kg
Residual oil	2.44%
Residual hexane	<10mg/kg
Chlorine	0.69%

The price of olive kernel wood is low compared with other energy sources in Crete. However its burning efficiency is lower than the corresponding efficiency of fuel or heating oil. In Table 3 the current price of olive kernel wood together with the prices of other energy sources in Crete are presented.

Table 3: Prices of Various Energy Sources in Crete

Energy source	Price (€/1,000 Kcal)	Efficiency (%)	Price (€/1,000 Kcal delivered)
Olive kernel wood	0,022	70	0,036
Fuel oil Heating oil	0,045 0.095	90 90	0,050 0.106
Electricity	0,116	100	0,116
Electricity/heat pump	0,116	200-250	0,046- 0,058

4. Description of a Greenhouse in Crete Heated with Olive Kernel Wood

A commercial greenhouse in Chania Crete [35^o, 30\ 40" N, 24^o 01^{v}45" E] for cultivation of flowers has been constructed and it used olive kernel wood as a fuel for covering all its heating needs during 2012-2014. The total area of the greenhouse is 3,300 m^2 and the required indoor temperature is 19^{o}C. The mean monthly average ambient temperatures for Chania are presented in Table 4

Table 4: Monthly Average air Temperatures in Chania Crete

January	10,8°C
February	11,0°C
March	12,4°C
April	15,8°C
May	20,1°C
June	24,7°C
July	26,6°C
August	25,9°C
September	23,2°C
October	19,4°C
November	15,3°C
December	12,4°C

Heating of the greenhouse is required for many months during the year. The power of the heating system is 750 KW. The annual average consumption of olive Kernel wood the last three years is estimated at 220 tons/year with heating value of 8.91×10^9 Kcal (1,035,099 KWh). The average annual heat demand of the greenhouse is estimated at 220 KWh /m^2-year. The greenhouse is equipped with aeration, humidity and irrigation control as well as cooling during summer and it uses electricity for the operation of various machinery. The efficiency of the heating system and the hot water distribution system is estimated at 70% depending on the regular cleaning and maintenance of the boiler. Since the existing system covers all the heating needs of the greenhouse it does not use any additional heating system. The annual consumption of electricity is estimated at 48,500 KWh and it corresponds to a specific consumption of 14 KWh/m^2-year. The characteristics of the greenhouse are presented in Table 5

Table 5: Characteristics of the Greenhouse Heated with Olive Kernel Wood in Crete — Greece

Operation period	2012-2014
Area	3,300 m^2
Cultivated crop	Flowers
Inside air temperature	19 °C
Annual consumption of olive kernel wood	220 tons
Heating value of the used olive kernel wood annually Annual heat demand of the greenhouse	1,035,099 KWh 724,569 KWh
Power of the heating system	750 KW
Efficiency of the heating system	70%
Annual consumption of electricity	48,500 KWh
Total energy consumption annually	1,083,599 KWh
Total Specific energy consumption	328 KWh/m^2-year
Heating value of olive kernel wood	4,051 Kcal/Kg
CO2 emissions avoided due to solid biomass use	279 tons CO_2/year
Specific gross heat consumption	314 KWh/ m^2-year
Specific electricity consumption	14 KWh/ m^2-year
Specific heat demand of the greenhouse	220 KWh/ m^2-year
Percentage of electricity to total energy consumed CO2 emissions due to electricity use	4.69 % 39 tons CO_2 /year

5. Use of a Photovoltaic System for Zeroing the CO_2 Emissions in the Greenhouse Due to Energy Use

Since solid biomass is used instead of fossil fuels for heating the greenhouse, the only CO_2 emissions due to energy use are created because of the electricity consumption. Solar irradiance in Crete is rather high and the monthly and annual solar irradiance in Chania Crete is presented and in Table6.

Table 6: Solar Irradiance in Chania — Creece Angle 30°, KWh/m²

January	83
February	97
March	128
April	152
May	183
June	191
July	208
August	207
September	172
October	127
November	107
December	83
TOTAL	1.738

The used electricity from the grid can be substituted with PV-solar electricity fed into the grid. Installation of a PV system in the abovementioned greenhouse connected with the grid can generate annually the same electricity that the greenhouse consumes. Therefore an offsetting of the fossil fuel generated electricity of the grid and used in the greenhouse can be obtained since the P.V. system will generate annually the same amount of electricity which will be fed in to the grid. It is estimated that a PV system with nominal power of 32.3 KWp in Crete can generate annually 48,500 KWh (Kagarakis, 1987) , Since the greenhouse uses the same amount of grid electricity that the PV system generates and feeds to the grid , there is not any net grid electricity consumed. Alternatively an autonomous PV system can generate the electricity consumed in the greenhouse but since electricity storage is needed the cost of such a system is substantially higher than in the previous case of the interconnected with the grid PV system. The cost of such a system in Greece currently is estimated at 45,000 Euros.

6. Environmental Considerations

Since olive kernel wood is a CO_2 neutral fuel its use for heating the abovementioned greenhouse results in less CO_2 emissions due to energy use. If instead of solid biomass fuel oil was used then significant amounts of CO_2 were going to be emitted. It is estimated that if in the same greenhouse fuel oil was used it would result in the emissions of 279 tons of CO_2 annually. Additional CO_2 emissions are created due to the use of electricity in the greenhouse. It is estimated that 39 tons/year of CO_2 are emitted due to electricity consumption in it. Therefore the use of solid biomass and PV electricity in the greenhouse will save 318 tons of CO_2 annually, zeroing its emissions due to energy use.

7. Conclusions

Renewable energy sources are expected to find more applications in the daily life the coming years. Among them their use in heating greenhouses is going to increase since many of renewable energies technologies are becoming cost effective and they are environmentally friendly. Various studies for using solar energy, geothermal energy and biomass have been implemented and various commercial applications already exist. Operation for three years (2012-2014) in Chania Crete Greece of a commercial greenhouse for flowers cultivation using olive kernel wood as fuel for covering all its heating needs has proved its reliability and profitability. Olive kernel wood, a local endogeneous and CO_2 neutral solid biomass source in Crete, is cheap compared with its heating value. Its current price in Crete is lower than the prices of other fuels including electricity. The investment cost of the described heating system is significantly lower than a corresponding heating system using low enthalpy geothermal heat pump which also can cover all the heating needs of the greenhouse. The fuel is easily transportable from the producing factory to the greenhouse and it is easily handlable. Electricity consumption corresponds to 4.69% of total annual energy needs of the greenhouse, therefore the demand of heat which corresponds to 95.31 % of the energy needs, is much higher than its electricity demand. The fact that a renewable and CO_2 neutral energy source is used for heating the greenhouse results in a significant decrease of CO_2 emissions due to energy use. Future use of photovoltaic cells in the greenhouse will generate all the electricity which is demanded in it and the cost of such a system is currently not prohibitive. The combined use of solid biomass for heating and of solar-PV cells for electricity generation will result in the production of flowers and various crops with zero CO_2 emissions due to energy use.

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Possibilities of Using Renewable Energy Sources for Covering all the Energy Needs of Agricultural Greenhouses

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Abstract

Renewable energy sources are used worldwide for generation of heat, power and the production of vehicle fuels. They can cover all the energy needs of agricultural greenhouses with a cost effective way. Among renewable energies solar energy, biomass and geothermal energy can be used for providing heat, cooling and electricity to them. Production of various crops from agricultural greenhouses with zero CO_2 emissions due to energy use could make their products very attractive to environmentally conscious consumers and this could be an effective marketing tool. Agricultural greenhouses consume energy for heating and cooling as well as for lighting and operation of various machinery. Depending on the local climate greenhouses consume mainly energy for heating, approx 90-95% of the total annual needs and the rest for electricity. The abovementioned renewable energy sources can be used in a reliable and cost effective way for covering all their energy needs. Two greenhouses are presented where in the first use of solid biomass and solar PV energy and in the second use of low enthalpy geothermal energy and solar PV energy cover all their energy requirement s increasing their sustainability and reducing their CO_2 emissions due to energy use.

Keywords: biomass, cooling, electricity, geothermal energy, greenhouses, heat, renewable energy sources, solar energy.

1. Introduction

Use of renewable energy resources is of primary importance in order to cope with the climate changes which threaten the global growth and prosperity and create severe natural disasters in various countries all over the world. They are used for power and heat generation as well as for the production of biological fuels used in various vehicles. Costs for energy and biofuels production from renewable energy sources are decreasing so in many cases they compete with the cost of energy derived from fossil fuels. Use of renewable energies instead of fossil fuels has many environmental, social and economic benefits and results in mitigation of the greenhouse effect. They are currently used broadly for power and heat generation in buildings, in industry and in agriculture where successfully substitute fossil fuels. Greenhouses require heat and power for the production of various crops. The quantities of electricity and heat needed depend on the local climate, the greenhouse construction and the cultivated crop. In general it can be said that the most of energy used is consumed for their heating.

Among renewable energy sources solar energy, biomass and geothermal energy have been used for covering the heating needs of the greenhouses (Campiotti et.al., 2010 , Campiotti et.al., 2012 , Sethi et.al.,2008 , Vox et.al , 2008). Various experimental installations have been tested and many commercial greenhouses operate today using renewable energy sources instead of fossil fuels, like fuel oil , heating oil , LPG and natural gas, for their heating. Depending of the specific area, the local availability of the abovementioned renewable energy sources is an important factor for their use in greenhouses. However greenhouses apart from heating require electricity for lighting, cooling and operation of various electric devices (motors, valves, pumps, fans e.t.c.). Due to many technological improvements and breakthroughs the recent years the cost of electricity generated from solar-photovoltaic cells has been reduced substantially and competes with the cost of grid electricity.

Therefore PV cells can be installed and they can cover all the electricity needs of a modern greenhouse in a cost effective way (Carlini et.al., 2010, Marruci et.al., 2012 , Tudisca et.al., 2013). The use of renewable energy sources for covering all the energy needs of a greenhouse results in the production of crops with zero CO_2 emissions due to energy use. The production of green eco-friendly products like vegetables, fruits and flowers from greenhouses makes them very attractive to environmentally conscious consumers and offers them a competitive advantage related to the same products produced from conventional greenhouses. Currently the use of renewable energies in European greenhouses is very low and there is not any legal framework regarding their use in them (Campiotti et.al. , 2012) .

2. Solar Energy

Solar energy can be used in greenhouses for heating and power generation.

2.1. Solar Heating of Greenhouses

Solar heating can be achieved with storage of thermal energy which is collected during day time and it can be used when it is needed (Chikaire et.al., 2010) . Heat can be stored in water (Santamouris et.al., 1994), in various solutions with or without phase change (Kurklu , 1998) , in the soil or in a wall constructed in the north side of the greenhouse. Solar heating can increase few degrees (3-10 ^oC) the indoor temperature but it is difficult to cover all the heating needs of the greenhouse. However the cost of solar heating is low and this method can be combined with another heating system to cover all the heating needs of the greenhouse.

2.2. Solar Cooling of Greenhouses

Solar cooling in greenhouses can be obtained with a system of empty plastic tubes buried in the ground beneath them (Santamouris et.al., 1995, Yildiz et.al., 2011) . The tubes are connected with a fan which circulates air from inside the greenhouse through the plastic tubes which is cooled as it passes through the tubes since the temperature of the ground is relatively constant and lower in the summer than the inside temperature of the greenhouse.

2.3. Solar-PV Electricity Generation in Greenhouses

Solar energy can also be used for power generation in greenhouses with photovoltaic cells (Carlini et.al., 2010, Marruci at.al., 2012). Depending on the power needs of the greenhouse and the size of the PV system it can cover part or all of the electricity needs of it. Due to high cost of electricity storage in batteries it is preferable to use solar-PV cells connected with the electricity grid. In this case the PV system can be sized to generate annually the same amount of electricity as the greenhouse consumes. Since net-metering becomes a common practice in many countries solar-PV generated electricity can offset annually the grid electricity consumption of the greenhouse. Rapid fall of PV cell prices and the gradual increase of grid electricity prices result in increasing the attractiveness of the installation of solar-PV systems in agricultural greenhouses for covering all the power needs of them. Combination of PV cells generating electricity in greenhouses and partly used for water electrolysis for hydrogen production has been reported. Hydrogen can be stored and used later for power generation via fuel cells. This system offers the possibility of storing excess electricity in hydrogen instead of batteries but it is not currently economically viable (Ganguly et.al., 2010). Covering the greenhouse with semi-transparent solar-PV cells offers the possibility of electricity generation and simultaneously allowing solar irradiance to enter inside the greenhouse. Mono- and poly-crystalline as well as thin film solar cells are currently available but they have to prove their economic viability in the future. In table 1 the characteristics of various heating systems using renewable energies in the greenhouses are presented.

3. Biomass

Gaseous and solid biomass have been used for heating greenhouses. Biogas produced from landfills has been used in nearby greenhouses for covering their heating needs (Jaffrin et.al., 2003) . The flue gases after biogas burning contain CO_2 and they can enrich the atmosphere inside the greenhouse improving crops growth and productivity. Since biogas is produced from wastes (either from landfills, or from cattle wastes or from sewage treatment plants) its cost is low. Its heating value (5,000 Kcal/NM^3) is approx the half of heating oil and it can cover all the heating needs of the greenhouse. Apart from biogas, solid biomass in the form of agricultural byproducts and residues has been used for covering all the heating needs of greenhouses. Burning solid biomass results in hot water production with temperatures 40-55 ^oC which can be circulated in plastic pipes placed on the ground of the greenhouse.

Alternatively burning solid biomass can result in hot air production which can be circulated inside the greenhouse. In areas with cultivation of olive trees a byproduct of olives processing, the olive kernel wood, has been used successfully for heat generation in greenhouses (Vourdoubas , 1999) . Its high heating value which is estimated at 4,051 Kcal/kg combined with its good burning characteristics and its low price makes it an attractive alternative renewable fuel for heat production. Other types of woody biomass like peaches and apricots kernels or forest residues can be used also for heat generation in greenhouses. Due to high cost of solid biomass transport, greenhouses using solid biomass as fuel must be situated nearby the biomass production sites. In the case of biogas use for heating, greenhouses must be situated also nearby the biogas production sites in order to avoid biogas transport. Environmental impacts due to biomass use for heating greenhouses are local and unimportant. They are limited to burnt gases which can be processed (filtered and water washed) in the case of solid biomass. Small quantities of the produced ash can be disposed in a landfill site or it can be recycled as fertilizer in some tree cultivations. Environmental impacts from biogas use are negligible.

4. Geothermal Energy

Geothermal Energy can be used either directly or indirectly for heating greenhouses. Geothermal fluids with temperatures between 40-80 ^{o}C can be used directly for heating (Bakos et.al. , 1999) . Depending on the chemical composition of the fluid it can be either circulated in plastic pipes inside the greenhouse or it can be used with heat exchangers for heating water or air. The geothermal fluid after transferring its heat must be either processed to remove any pollutants which are contained in the fluid or rejected back into the ground. In order to avoid transport of the geothermal fluid and heat losses the greenhouses should be located nearby the geothermal spring. Depending on the heating needs of the greenhouse and on the flow rate and temperature of the geothermal fluid all the heating needs of the greenhouse can be covered. Low enthalpy geothermal fluids are used broadly today to heat greenhouses in various parts of the world. The cost of heat is low but the cost of pollutants removal in some cases may be high.

Geothermal energy can be also used indirectly with heat pumps for heating greenhouses (Ozgener et.al., 2007) . Low enthalpy ground source geothermal heat pumps are used for heating them. In these cases vertical or horizontal heat exchangers inside the soil are used. Recent technological improvements in these systems allow them to operate very efficiently obtaining C.O.P. in the range of 3-4 or even higher. Geothermal heat pumps can cover all the heating needs of the greenhouses during the winter and all the cooling needs during the summer. However their initial capital cost is high and they are capital intensive heating systems. Since the heat pumps consume electricity during their operation, the greenhouse heating cost in that case is higher compared with their direct heating with geothermal fluids. However among the advantages of geothermal heat pumps are the absence of any pollution during their operation and the easiness of automatic temperature control in the greenhouse. The most common used systems are ground to water heat pumps which produce heating water in the desired temperatures. Low enthalpy geothermal energy has been also used for partly heating and cooling greenhouses with an underground heat exchanger. In this case the soil underneath the greenhouse is excavated in depth approx. of two meters and empty plastic tubes are placed inside covered with the soil. The tubes are connected with a fan and the inside air of the greenhouse. The soil temperature is relatively stable almost equal with the yearly local average air temperature. The plastic tubes underneath the greenhouse behave like a heat exchanger. During the winter when heat is needed the aerator is forcing air through the plastic tubes which is partly heated and returns inside the greenhouse. During the summer when cooling is needed the hot air inside the greenhouse is circulated with the help of the fan inside the plastic tubes and being partly cooled returns back inside the greenhouse. The underground heat exchanger can partly cover the heating and cooling needs of the greenhouse utilizing the low enthalpy geothermal energy of the ground.

5. Energy needs of Greenhouses

Agricultural greenhouses use energy to cover their heating needs and to operate their electric equipments and machinery. They use energy for:

a) Space heating
b) Space cooling
c) Lighting
d) Operation of various equipments and machinery

Usually they use electricity, natural gas, LPG, heating oil and fuel oil. Conventional energy use results though in the emissions of greenhouse gases. Depending on the specific greenhouse and the cultivated crop they use more energy for their heating than for supplying electricity to various electric equipment. In many cases the required heat corresponds up to 90-95% of the annual energy needs. In order to reduce energy consumption in the greenhouses various energy saving techniques and systems can be used including thermal curtins, double plastic or glass cover or equipments of high energy class. In many cases the energy cost in the greenhouse contributes significantly to the final production cost of various crops. Therefore the decrease of this cost can increase the competitiveness of the produced vegetables or flowers.

Modern greenhouses are energy intensive agricultural systems and annual energy consumption of 300 KWh/m^2 has been reported. Apart from reducing their energy consumption the use of renewable energies is of primary importance in order to cover part or all of their energy needs. The use of renewable energies in the greenhouses must comply with the following criteria:

1) The energy systems must be reliable
2) They must be cost effective
3) The operation of the energy systems must not be complex.

Various renewable energies like solar energy, geothermal energy and biomass comply with those criteria and can be used in them (Vourdoubas , 2004). Use of renewable energies in the greenhouses results in the additional benefit of reducing the emmitted greenhouse gases due to energy use.

6. Use of Solar Energy and solid Biomass for Covering all the Energy requirements of a Greenhouse

Heat and electricity generation in a greenhouse can be obtained without the use of fossil fuels. In this case solid biomass can be used for space heating and solar – photovoltaic cells can be used to generate the power required in the greenhouse. The solar – PV system can be either connected with the electric grid or it can be autonomous and in this case batteries for storing electricity must be used. Burning solid biomass technology is a well known and reliable technology without presenting any serious problem. Therefore the combination of a solid biomass burning system for space heating and a solar – PV system for electricity generation can cover all the annual energy requirements of a greenhouse resulting in the production of crops with zero CO_2 emissions due to energy use. Data for sizing the necessary heating and power generation system are presented in table 3. It has been assumed that the solar – PV system will be interconnected with the electric grid and it will generate annually the same amount of electricity that the greenhouse consumes from it according to the net-metering initiative.

7. Use of Solar Energy and low Enthalpy Geothermal Energy with Heat Pumps for Covering all the Energy requirements of a Greenhouse

The heating and cooling requirements of the greenhouse can be covered with low enthalpy geothermal heat pumps and its power needs with solar-PV cells. Heat pumps are energy efficient devices and for a ground to water heat pump a COP of 3-4 can be easily obtained. Therefore for each KWh of electricity consumed 3-4 KWh of heat or cooling are produced. It is considered that the electricity needed for the operation of the heat pump will be generated from the solar-PV system, together with the electricity needed for the operation of other electric devices. The operation of the heat pump does not have environmental impacts in the site of the greenhouse compared with the operation of a solid biomass burning system which produces exit gases containing pollutants. However its cost is much higher compared with the cost of a solid biomass burning system which can cover only the heating needs of the greenhouse but not its cooling needs. In table 4 various parameters of a greenhouse covering all its energy needs with solar-PV cells and a geothermal heat pump are presented. It has been assumed that the heat pump covers all the heating requirements and not its cooling needs.

8. Comparison of the Two Previous Systems Covering all the Energy needs of the Greenhouses

Comparison of the two previous systems which cover all the energy needs of the greenhouses has been made regarding

a) The capital cost of the energy systems
b) The annual fuel cost of the two systems
c) Total annual CO_2 savings due to energy use
d) Local environmental impacts

The following assumptions have been made

- The capital cost of the solid biomass boiler is 80 Euros per KW
- The solid biomass cost delivered to the greenhouse (in the form of olive kernel wood) is 0.08 Euros per kg
- The cost of the solar-PV system is 1,400 Euros per KWp
- The cost of the ground source heat pump is 2,300 Euros per KW

The results of the estimation are presented in table 5

9. Conclusions

Modern agricultural greenhouses require significant amounts of energy in their daily operation. Although they use mostly conventional fuels recent advances in renewable energy technologies combined with the requirements for cleaner environment and mitigation of the greenhouse effect have changed the traditional energy use pattern towards increased use of renewable energy sources in cultivated crops. Greenhouses use mainly energy for their heating and small amounts of electricity for the operation of various electric equipment. Replacement of fossil fuels with renewable energy sources can be obtained without many difficulties. Solar energy, biomass and geothermal energy can be used today with cost effective technologies. Since greenhouses can cover all their energy needs with renewable energies they can zero their CO_2 emissions due to energy use and their ecological footprint. Two case studies have been examined related with the replacement of conventional fuels with renewable energies in agricultural greenhouses.

In the first solid biomass is used for covering all the heating needs and solar-PV electricity with an interconnected with the grid system for covering all the power needs. In the second low enthalpy geothermal energy with ground source heat pumps is used for covering all the heating needs of the greenhouse and solar-PV electricity with an interconnected with the grid system for covering all the power needs. In both cases there is an offsetting of the electricity consumed annually from the grid with the electricity fed to the grid from the solar PV system with the net-metering framework. Both systems are technically and commercially viable and reliable and can be used without any problems. The use of geothermal heat pump requires a larger solar – PV system to cover the electricity needs of the electric devices of the greenhouse including the electricity needs of the heat pump. In that case the overall capital cost of the heat and electricity generating systems is higher compared with the first case due to the fact that the cost of the solid biomass burning system is relatively low and the required solar-PV system in smaller. However local environmental impacts from the operation of the heat pump are negligible and the fuel cost is zero compared with the first case. In the solid biomass burning system exit gases are produced and they must be processed in order to minimize local environmental degradation.

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Table 1: Characteristics of Heating Greenhouses with Various Renewable Energy Sources

	Investment Cost	Fuel Cost	Heating / Cooling	Cover of heating and cooling needs
1.Solar-heat-storage	Low	0	Heating	Part of heating needs
2.Biomass-biogas	Low	Low	Heating	All
2. Biomass-solid	Low-Medium	Low-Medium	Heating	All
3.Geothermal fluids (40-80^{0}C)	Low	Low	Heating	All
3.Geothermal-Low enthalpy ground heat-buried tubes	Low	Low	Heating and Cooling	Part of the needs
3.Geothermal-low enthalpy ground heat pumps	High	High	Heating and Cooling	All

Table 2: Factors Influencing the use of Renewable Energy Sources in Greenhouses

1. Availability of the energy source
2. Capital cost of the energy system
3. Cost of the fuel and total operating cost of the energy system
4. Reliability of the energy system
5. Environmental impacts of the energy system

Table 3: Sizing a Biomass Heating System and a Solar – PV Power Generation System for Covering all the Energy Needs of an Agricultural Greenhouse

Surface of the greenhouse	1,000 m^2
Specific Electricity	14 KWh/m^2 year
Consumption of electricity	14,000 KWh/year
Specific heating needs	220 KWh/m^2 year
Heating needs of the greenhouse	220,000 KWh/year
Total energy requirements	234,000 KWh/year
Peak heating load	160,000 Kcal/h
Power of the heating boiler	185.8 KW
Efficiency of heating system	70%
Annual power generation from the PV system	1,500 KWh/KWp
Heating value of solid biomass	$4{,}051\frac{Kcal}{Kg}\left(4{,}70\frac{KWh}{Kg}\right)$
Nominal power of the PV system	9.33 KWp
Annual consumption of solid biomass	66.87 tons/year
Annual saving of heating oil	26.75 tons/year
Annual saving of CO_2 due to biomass use	85.60 tons/year
Annual saving of CO_2 due to solar-PV	13.85 tons/year
Total annual savings of CO_2	99.45 tons/year

- Conversion factors
- electricity 0,989 kg CO_2/KWh ,
- heating oil 3,2 kgCO_2/kg fuel

Table 4: Sizing of a low Enthalpy Geothermal Heat Pump for Heating and Cooling and a solar-PV Power Generation System for covering all the Energy needs of an Agricultural Greenhouse

Surface of the greenhouse	1,000 m^2
Consumption of electricity	14,000 KWh/year
Specific heating needs	220 KWh/m^2 year
Heating needs of the greenhouse	220,000 $\frac{KWh}{Year}$
Total energy requirements	234,000 KWh/year
Peak heating load	160,000 Kcal/h
Efficiency of heat pump	350 %
Power of heat pump	53.1 KW
Electricity consumption from the heat pump	62,857 $\frac{KWh}{Year}$
Electricity consumption for the operation of other electric devices	14,000 $\frac{KWh}{Year}$
Total electricity consumption	76,857 $\frac{KWh}{Year}$
Annual power generation from the PV system	1,500 $\frac{KWh}{KWp}$
Nominal power of the PV system	51.24 KWp
Savings of CO_2 emissions due to the use of the PV system	76.01 $\frac{tons\,CO_2}{Year}$

Conversion factor for electricity 0.989 kg CO_2/KWh

Table 5: Comparison of Two Systems covering all the Energy needs of Agricultural Greenhouses

	Use of solid biomass* and PV system	Use of geothermal heat pump and PV system
Capital cost (Euros)	27,926	191,990
Annual fuel cost (Euros)	5,350	0
Annual CO_2 savings (kg)	99,450	76,012
Local environmental Impacts	Due to burnt gases which must be processed	None

* Solid biomass use is considered to have neutral impacts to greenhouse effect

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Economic and Environmental Assessment of the Use of Renewable Energies in Greenhouses: A Case Study in Crete-Greece

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Abstract

The use of various renewable energy resources in agricultural greenhouses for heat and power generation has been studied extensively and several applications already exist. Among renewable energy resources solar energy, geothermal energy and biomass have been more or less used mainly for heat production in them.

Currently economic and environmental considerations favour the replacement of fossil fuels with renewable energies for energy generation in greenhouses. The necessity of mitigation of greenhouse gases emissions and the decrease in the cost of energy generation from renewables make their use more attractive in various commercial applications including in agricultural greenhouses. In the case of Crete-Greece, cost analysis of the use of solid biomass and geothermal energy for direct heating and cooling greenhouses shows that these investments are very profitable and attractive. However, the use of geothermal heat pumps for heating and cooling them is not cost effective. Use of solar photovoltaic cells for power generation is not cost effective, particularly when electricity generation in greenhouses is subsidized by the government. The decrease of CO_2 emissions due to the use of renewables in the greenhouses is considered as an additional benefit.

Keywords: agricultural greenhouses, biomass, geothermal energy, heat, heat pumps, power, renewable energy resources, solar energy

1. Introduction

The use of renewable energy sources in various applications results in many environmental benefits. The necessity to cope with climate changes restricts the use of fossil fuels and favours their replacement with renewable fuels. Recent technological advances in renewable energy technologies favour their use in heat and power generation, which in many cases is profitable without any financial support and subsidies from the governments.

Agricultural greenhouses use energy for covering their needs in:

a) Space heating

b) Space cooling

c) Lighting

d) Operation of various electric devices.

Among renewable energy resources, solar energy can be used for space heating and cooling, as well as for power generation. Solid biomass including agricultural and forest residues and byproducts can be used for space heating. Geothermal energy is due to the existing heat inside the earth since below the surface of the planet and in the way to the centre of the earth temperatures rise steadily. Geothermal energy can be used for heating greenhouses in two ways. A) From the hot water which is coming out from a water spring or is collected with underground pumping. B) Pumping the heat from the water or the soil in low depth where the temperature is slightly higher than the ambient with heat pumps. For cooling the greenhouse the heat pump absorbs the heat from inside the greenhouse and dissipates it in the soil or in the water in low depth. Geothermal energy can be used for space heating utilizing directly low or medium enthalpy geothermal fluids or for space heating and cooling with low enthalpy geothermal heat pumps.

Agricultural greenhouses need more energy for space heating in order to maintain indoor temperatures at 18–19 ^{o}C if needed and less energy for lighting and operation of various electric devices. The conventional fuels which they use include fuel oil, diesel oil and natural gas for space heating and grid electricity for their power needs. In some countries, including Greece, the government subsidies the electricity use in agriculture in order to support food production resulting in significantly lower electricity prices in greenhouses compared with the corresponding prices in households or in commercial enterprises.

2. Use of Renewable Energy Sources in Agricultural Greenhouses

Various renewable energy resources are used today for covering mainly the heating needs of agricultural greenhouses like solar energy, solid biomass and geothermal energy. Extensive research has been made and various experimental and demonstration systems for using photovoltaic cells, wind mills, biogas and geothermal heat pumps in them, already exist.

The availability of a renewable energy resource in a location affects its possible use in greenhouses. Presence of a geothermal spring, high solar irradiance or availability and low prices of solid biomass nearby the location of the greenhouses is a critical factor for their utilization. The abovementioned renewable energy technologies are currently mature, reliable and cost effective and particularly for solar PV cells their prices have decreased substantially the last few years. Renewable energy sources which can be used in greenhouses are presented in Table 1.

Table 1. Renewable energy sources which can be used for energy generation in greenhouses

Renewable Energy	Generated Energy	Covering of energy needs	Investment cost	Operating cost
Solar thermal	Thermal	Part	Medium	Very low
Solid biomass	Thermal	All	Medium	Medium - high
Direct geothermal fluids	Thermal	All	Low	Low
Geothermal heat pumps	Thermal	All	High	High
Solar PV	Electricity	All	Medium	Very low

It has been reported (Campiotti et al., 2012) that nowdays the proportion of renewable use in the total energy consumption in agricultural greenhouses in Europe is very low and there are not clear priorities and policies set in this area yet.

3. Solar Thermal Energy

Solar energy has been used for heating and cooling greenhouses. Passive solar systems in greenhouses have been reviewed (Santamouris et al., 1994). They have presented the results of 95 solar greenhouses from around the world representing the state of the art in this field. Another study (Sethi et al., 2008) evaluates some solar heating technologies in them. A passive solar greenhouse offering heat and cooling with an earth to air heat exchanger and buried pipes has been reported (Santamouris et al., 1994). A survey of thermal performances of a solar system has been studied (Santamouris et al., 1995). Solar energy used for heating of an agricultural greenhouse in Morocco has been proposed (Bargach et al., 2000).

In general solar thermal energy can be used for covering only part of the heating and cooling needs of a greenhouse. Depending on the local climate and the energy needs solar thermal energy can increase in the winter and decrease during the summer few degrees the indoor temperature of the greenhouse.

4. Solid Biomass

Various types of agricultural and forest byproducts and residues can be used for heat generation in greenhouses. A greenhouse cultivated with flowers and heated with solid biomass in Crete-Greece has been reported (Vourdoubas, 2015). Olive Kernel wood with a current cost 0.08 Euros/kg is used as fuel and the heating system covers all the heating needs of the greenhouse maintaining an indoor temperature approx. at 19 ^{o}C. The cost of heating depends on the price of biomass, the local climate and the type of the construction of the greenhouse.

5. Direct Heating with Geothermal Fluids

Direct heating of greenhouses with low enthalpy geothermal fluids with temperatures 40–80 ^{o}C has been reported (Adaro et al., 1999; Bakos et al., 1999) and various geothermal greenhouses operate to day all over the world. In the case that a geothermal spring in located nearby the greenhouse, a low cost heat source can be used and the greenhouse has a potential competitive advantage regarding its heating compared with other greenhouses. The cost of the heating system includes the cost of pumps and the tubes for transferring the geothermal fluid to the greenhouse as well as the cost of disposing the used geothermal fluid.

Geothermal fluids depending on their temperatures and flow rates can cover all the heating needs of agricultural greenhouses.

6. Geothermal Heat Pumps

Use of geothermal heat pumps for heating and cooling greenhouses consists of a rather expensive but effective method since they are very energy efficient electric devices (Ozgener et al., 2007).

They can cover all the heating and cooling needs of a greenhouse utilizing the low enthalpy ground heat obtaining high C.O.P. in the range of 3-4.

7. Photovoltaic Cells

Photovoltaic (PV) cells installed in a greenhouse can generate electricity covering all the power needs of it. Interconnected with the electric grid they can generate annually all the electricity that the greenhouse consumes zeroing its electricity payments and contributing in energy saving in it.

The decrease of PV cells cost during the recent years has made their use in various applications, including greenhouses, more attractive. However, existing policies in many countries regarding state subsidies in electricity cost for the agricultural sector reduces the attractiveness of PV cells.

8. Economic Assessment of a Solid Biomass System for Space Heating in a Greenhouse

Economic assessment of a heating system using solid biomass as a fuel in Crete-Greece has been made. It has been assumed that an existing greenhouse has a heating system utilizing fuel oil and it will replace it with a new one utilizing solid biomass (olive kernel wood). Since the price of solid biomass is cheaper than the price of fuel oil an economic benefit will result due to the change from a fossil fuel to a renewable fuel. An additional investment for the solid biomass heating system is required in the greenhouse. Data for the economic estimation of the solid biomass heating system are presented in Table 2.

Table 2. Data of economic analysis of a solid biomass heating system in a greenhouse

Area of the greenhouse	1000 m^2
Annual heat consumption	220 000 KWH
Peak heating load	160 000 KCAL/H
Power of Biomass boiler	185.8 KW
Unit cost of biomass boiler	80 €/KW
Cost of biomass heating system	14 864 €
Price of biomass	0.08 €/kg
Annual consumption of biomass	66.87 tons
Annual cost of biomass	5350 €
Fuel oil needed to head the greenhouse	26.75 tons/year
Cost of fuel oil	40 €/ton
Annual cost of fuel oil	10 700 €
Annual benefit due to change of the heating fuel	5350 €
Period of operation	15 years
Interest rate	2%

Net present value of the investment in a new heating system as well as the payback period are presented in Figure 1.

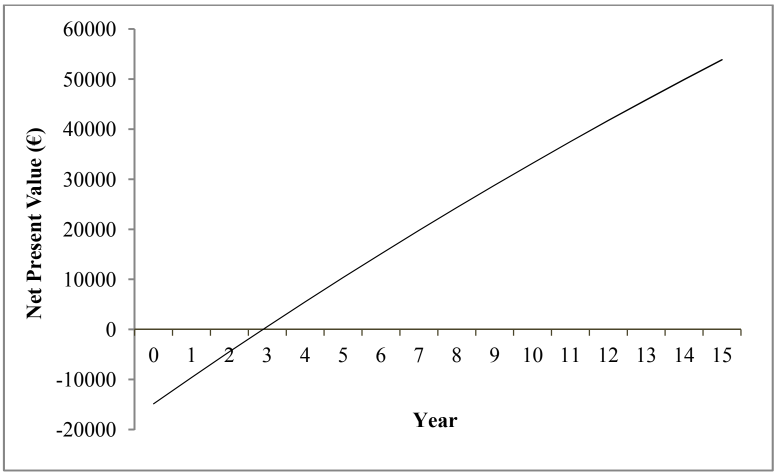

Figure 1. Net present value and payback period for an investment of a new solid biomass heating system in a greenhouse (Operating period: 15 years, interest rate: 2%)

It should be noted that the solid biomass heating system has higher maintenance cost compared with the heating system using fuel oil which has not been taken into account.

9. Economic Assessment of a Photovoltaic System Generating Electricity in a Greenhouse

Economic assessment of a grid interconnected photovoltaic system installed in a greenhouse located in Crete-Greece generating the electricity consumed annually by the greenhouse is made. In that case based on a net-metering system the annual net consumption of a grid electricity from the greenhouse will be zero. The economic benefit of this investment will be equal to the annual cost of grid electricity which will be paid without the installation of the PV system. Data for the economic analysis are presented in Table 3.

Table 3. Data of economic analysis of a grid interconnected PV system installed in a greenhouse generating annually the electricity used from it

Area of greenhouse	1000 m^2
Annual consumption of electricity	14 000 KWH
Price of grid electricity	0.07 €/KWH
Cost of electricity	980 €/year
Annual electricity generation from PV	1500 KWH/KWp
Nominal power of PV system	9.33 KWp
Unit cost of PV system	1400 €/KWp
Total investment cost of the PV system	13 062 €
Annual decrease of electricity generated from the PV system in 20 years period	1%
Period of operation	20 years
Interest rate	2%

Net present value of the investment and payback period are presented in Figure 2.

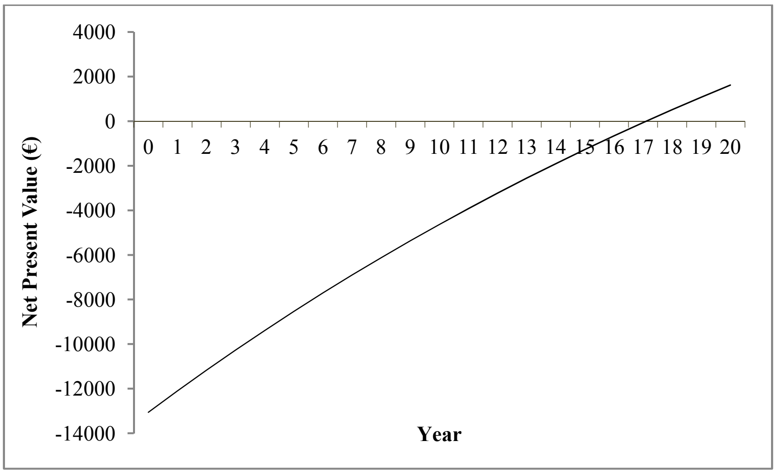

Figure 2. Net present value and payback period for a PV investment in a greenhouse (Operating period: 20 years, interest rate: 2%, grid electricity cost: 0.07 €/KWH)

Electricity cost in greenhouses in Greece is low due to governmental subsidies to agricultural sector. Net present value and payback period of the same investment is presented in figure 3 provided that grid electricity cost is 30% higher than the current cost (0.091 €/KWH instead of 0.07 €/KWH).

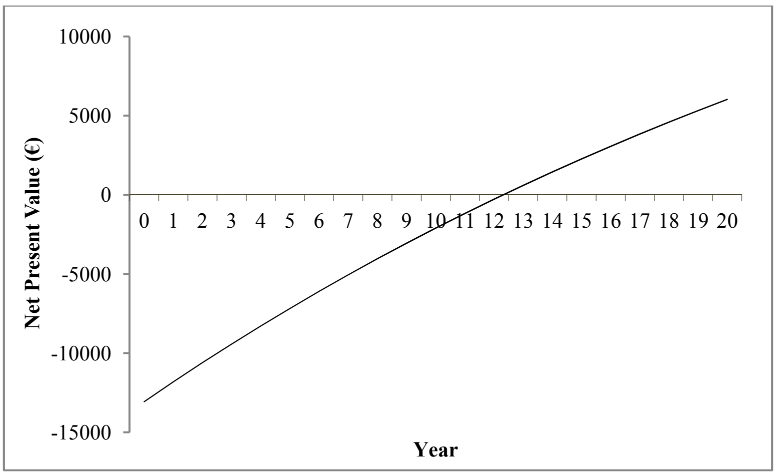

Figure 3. Net present value and payback period for a PV investment in a greenhouse (Operating period 20 years, interest rate 2%, grid electricity cost 0.091 €/KWH)

Comparing Figures 1 and 2 it can be seen that when grid electricity cost is higher the net present value is higher and the payback period shorter. Therefore, the governmental subsidies to grid electricity cost in agricultural sector in Greece discourage photovoltaic cell investments in greenhouses.

10. Economic Assessment of a Low Enthalpy Geothermal Heat Pump for Space Heating in a Greenhouse

Economic assessment of a heating system using a low enthalpy geothermal heat pump for space heating which will replace the conventional heating system with fuel oil has been made.

The heat pump can be used also for space cooling during summer. Heat pump is expensive equipment and utilizes electricity. However, it has high C.O.P and it is considered as a valuable energy saving device. The annual benefit of the greenhouse is the difference of the cost of the fuel oil used for space heating and the cost of the required electricity for the operation of the heat pump. Since electricity is subsidized in the agricultural sector in Greece, it favours the use of heat pumps which consume electricity. Data for the economic estimation of the geothermal heat pump are presented in Table 4.

Table 4. Data for economic analysis of a greenhouse heating system with geothermal heat pump

Area of greenhouse	1000 m^2
Annual heat consumption	220 000 KWH
Peak heating load	160 000 KCAL/H
C.O.P. of heat pump	3.5
Nominal power of heat pump	53.1 KW
Unit cost of heat pump	2 300 € /KW
Annual electricity consumption of the heat pump	62 857 KWH
Electricity cost	0.07 Euro/KWH
Annual cost of electricity consumed by the heat pump	4 400 €
Investment cost of heat pump	122 130 €
Annual consumption of fuel oil for heating	26.75 tons
Cost of fuel oil	40 € /ton
Annual cost of fuel oil	10 700 €
Benefit due to change of the heating system	6300 € /year
Period of operation	20 years
Interest rate	2%

The benefit which results from the use of geothermal heat pump for space cooling is small and it has not been taken into account.

It should be noted that heat pump has been rated to cover the peak heating load of the greenhouse and this increases its size and its price.

Net present value and payback period for an investment of a geothermal heat pump for heating a greenhouse are presented in Figure 4.

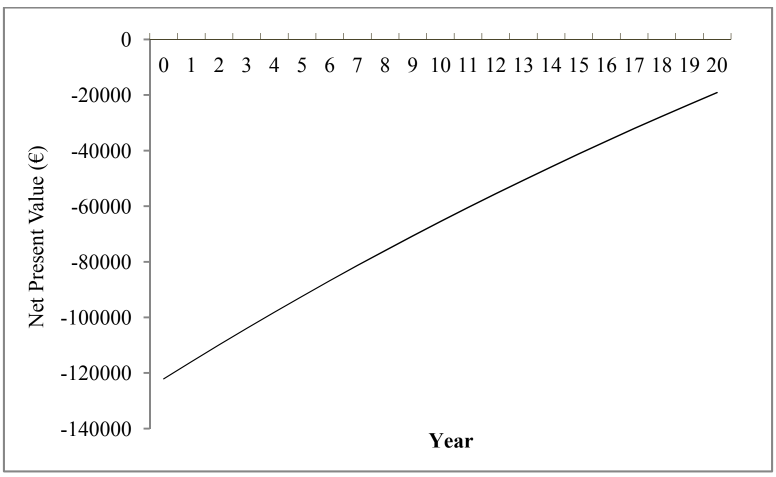

Figure 4. Net present value and payback period for an investment of a geothermal heat pump for heating a greenhouse (Operating period: 20 years, interest rate: 2%)

11. Economic Assessment of a Greenhouse Directly Heated with Low Enthalpy Geothermal Fluid

Economic assessment of a direct heating system of a greenhouse with low enthalpy geothermal fluid in Crete-Greece has been made. It has been assumed that a geothermal spring with hot water 50–60 °C is located nearby the greenhouse and the hot water is transferred to the greenhouse directly for heating. The fluid after its use is disposed in a nearby well. In that case the heating cost is estimated at 20% of the initial fuel cost (http://energy.gov/eere/geothermal/direct-use-geothermal-energy), and the economic benefit equals 80% of the cost of the initially used fuel oil.

Results for the economic analysis of heating greenhouses directly with geothermal fluids are presented in Table 5. The initial investment cost depends on the distance of the geothermal spring from the greenhouse, the temperature and the flow rate of the fluid.

Table 5. Data of economic analysis of direct heating of a greenhouse with low enthalpy geothermal fluids

Area of greenhouse	1 000 m^2
Annual heat consumption	220 000 KWH
Peak heating load	160 000 KCAL/H
Annual consumption of fuel oil for heating	26.75 tons
Cost of fuel oil	40 €/ton
Annual cost of fuel oil	10 700 €
Annual benefit due to geothermal system	8560 €
Investment cost of the geothermal heating system (includes insulated pipes, pumps, disposal system etc)	12 500 €
Operating period	20 years
Interest rate	2%

Direct heating with geothermal fluids is possible only in the case of presence of geothermal springs nearby the location of the greenhouses.

Net present value and payback period for the investment of direct greenhouse heating with geothermal fluids are presented in Figure 5.

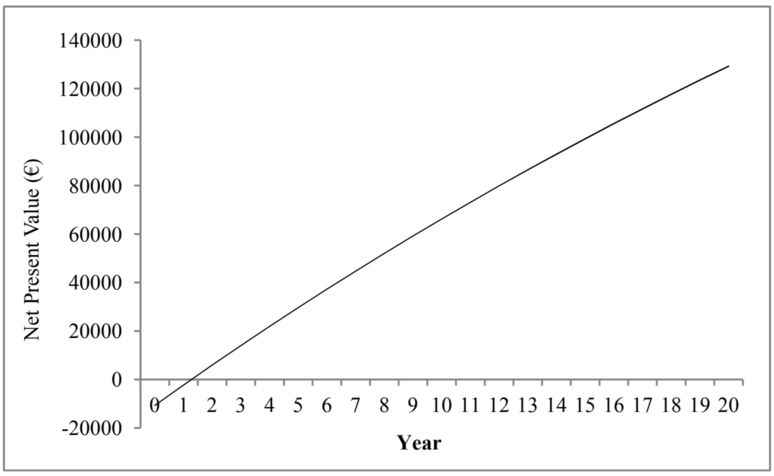

Figure 5. Net present value and payback period for the investment of direct greenhouse heating with geothermal fluids (Operating period: 20 years, interest rate: 2%)

12. Profitability Analysis of Energy Generation with Various Renewable Energy Systems in Agricultural Greenhouses

Results of the abovementioned applications of renewable energy systems in agricultural greenhouses in Crete-Greece are presented in Table 6.

Table 6. Profitability analysis data of various applications of renewable energies in greenhouses in Crete-Greece

Type of renewable energy	Energy generated	Operating period (years)	Initial investment (€)	Payback period (years)	NPV (€)
Solar PV	Electricity	20	13 062	16.98 12.30*	1622 6030*
Solid biomass	Heat	15	14 864	2.95	53 880
Direct heating with geothermal fluid	Heat	20	12 500	1.25	129 268
Geothermal heat pumps	Heat (and cooling)	20	122 130	---	-19 116

Note. * In the case of 30% higher than current electricity prices.

Among the three abovementioned heating methods in greenhouses in Crete the most profitable is direct heating with geothermal fluids. Solid biomass use is also attractive provided that solid biomass is available in the presumed cost. Heating with geothermal heat pumps is not profitable although the subsidies in the electricity prices favour its use. However, heat pump cost can be reduced assuming that it will cover only the base heat load in the greenhouse and not the peak load.

In such a case the attractiveness of this technology will be improved. PV cells for electricity generation are not attractive with the current electricity prices in greenhouses which are subsidized in Greece. Increase of electricity prices in the agricultural sector will improve the attractiveness of grid interconnected solar cells installed in greenhouses with net-metering system.

13. Environmental Benefits due to the Use of Renewable Energy Systems

Use of the abovementioned renewable energy systems for heat and power generation in the greenhouses will result in reduction of greenhouses gases emitted due to energy use in them. The reductions are estimated as the difference of the emissions due to fossil fuels use minus the emissions due to renewable energy use. In the case of using PV cells, direct heating with geothermal fluids and heating with solid biomass the CO_2 emissions are zero. In the case of using the geothermal heat pump the emissions are estimated from the consumption of grid electricity for the operation of the heat pump.

It is assumed that for grid electricity use the emission coefficient is 0.989 kg of CO_2 per KWH and for fuel oil use 3.2 kg of CO_2 per kg of fuel oil. Environmental benefits due to the use of renewable energy sources in agricultural greenhouses are presented in Table 7.

Table 7. Environmental benefits due to renewable energy use in greenhouses

Type of renewable energy used	Energy used initially	Energy generated	Initial CO_2 emissions (tons/year *10^3 m^2)	CO_2 emissions due to renewable (tons/year *10^3 m^2)	Reduction of CO_2 emissions (tons/year*10^3 m^2)
Solar PV	Grid electricity	Electricity	13.85	0	13.85
Solid biomass	Fuel oil	Heat	85.60	0	85.60
Direct heating with geothermal fluid	Fuel oil	Heat	85.60	0	85.60
Geothermal heat pumps	Fuel oil	Heat (and cooling)	85.60	62.17	23.43

14. Conclusions

Renewable energy sources can replace fossil fuels for covering all the energy needs of agricultural greenhouses. Among them solar energy, geothermal energy and biomass can be used for generation of heat, cooling and electricity in them. Profitability analysis has shown that heating of greenhouses in Crete – Greece either directly with low enthalpy geothermal fluids or with solid biomass is profitable and very attractive compared with heating them with fuel oil.

However, their heating with low enthalpy geothermal heat pumps is not cost effective although the price of electricity in the agricultural sector in Greece is low due to state subsidies. Use of PV cells interconnected with the electrical grid for covering the electricity needs of the greenhouses is not either cost effective due to state subsidies in the price of electricity. However, in the case that the price of electricity will be 30% higher than the current then the use of PV cells in the greenhouses is becoming more attractive. Regarding environmental benefits due to the use of renewable, the higher reductions in CO_2 emissions are obtained with the use of solid biomass and with direct heating with geothermal fluids. Lower environmental benefits are obtained with the use of PV cells and geothermal heat pumps in the greenhouses. Therefore, the use of solid biomass and geothermal fluids for direct heating in the greenhouses has important economic and environmental benefits and it should be promoted with various policies.

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Possibilities of Using Semi-Transparent Photovoltaic Modules on Rooftops of Greenhouses for Covering Their Energy Needs

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Abstract

Semi-transparent photovoltaic cells allow the transmittance of solar irradiance through them and they have been used in building's skylights and facades. Their use on rooftops of greenhouses can result in electricity generation which can cover part or all of their energy needs without affecting the growth of the plants. This also results in the decrease of cooling requirements during the summer since less solar irradiance is entering the greenhouse and lower CO_2 emissions due to energy use in it. However, their current prices are high compared with the prices of opaque PV cells. The purpose of the present work is to investigate the possible use of semi-transparent PV modules placed on the roof of energy intensive greenhouses in Crete-Greece in order to cover their energy requirements and sell the surplus electricity into the grid. Two different cases have been studied where greenhouses of 1,000 m^2 each cover their high heating needs using heat pumps and solid biomass. PV modules of 42.5 KWp can be placed on their roofs covering slightly less than 50 % of their surface allowing enough solar irradiance to enter the greenhouse. In the first case the generated electricity can cover more than 80 % of total energy needs and in the second all the energy needs offering the possibility of selling the surplus electricity to the grid. However, the current high prices of semi-transparent PVs do not favour their use by farmers since their installation costs are high. Future financial support from the government could increase their attractiveness for commercial applications in greenhouses.

Keywords: Semi-transparent photovoltaics, energy, electricity generation, greenhouses, cost, environmental impacts

1. Introduction

Greenhouses need energy to cover their requirements for heating, cooling, lighting and operation of various electric devices. In Mediterranean region, greenhouse construction is rather simple using light materials compared to central and northern Europe and their energy requirements are relatively low. The majority of greenhouses use conventional energy sources in order to cover their energy needs like heating oil, gas and electricity and the use of renewable energy sources in them is rather limited. However, the necessity to mitigate climate changes results in higher use of renewable energies in various sectors, including greenhouses. The possibility of using agricultural greenhouses in order to grow various crops and at the same time to generate energy, increasing farmer's income has attracted little attention until now. However, the advances of renewable energy technologies make it possible since greenhouses can generate useful energy not only for covering their own needs, but also for selling the surplus into the grid. This reduces the greenhouse gases emitted due to fossil fuels use in them. The effect of installing opaque PV cells on the roofs of greenhouses has been studied (Castellano, 2014). He found that, if they cover 25-50% of the horizontal greenhouse roof, the growth of the plants was not affected. A feasibility study of semi-transparent PV cells integrated on greenhouse covering has been presented (Gossu et.al., 2010). PV moduli were connected to the grid, they had transparency in the range of 50-75% and they were covering south oriented roof only. Shading level was 10-19%, nominal power was 94-188 KWp and annual electricity production was 112,800- 260,200 KWh. PV cells investment had a positive net present value and its payback time was 10-13 years. Limits and prospects of PV cells on the rooftops of Mediterranean greenhouses has been studied (Marucci et. al., 2013, Marucci et.al., 2012). They differentiated the light greenhouses with cheap coverings used in Mediterranean region with the heavier greenhouses used in central and northern Europe. They have investigated the possibility of using flexible semi-transparent photovoltaics in order to generate an additional income to the farmers and to reduce the cooling loads during the summer. An experimental evaluation and an energy modeling of a greenhouse concept have been presented (Bambara et. al., 2015). With reference to the vertical farm concept which requires less energy for heating and the same energy for cooling compared with conventional greenhouses, semi-transparent photovoltaics generate electricity and provide shading to them. A prototype semi-transparent PV cell for greenhouse roof applications has been reported (Akira et. al., 2014). Two different types of cells have been studied comparing electricity generation and greenhouse shading. The possibility of using semi-transparent photovoltaics in Mediterranean greenhouses in order to generate electricity and to shade them has been studied (Marucci et. al., 2013). The possibilities of using renewable energies in order to cover all the energy needs of greenhouses have been investigated (Vourdoubas, 2015). Two case studies have been analyzed where PV cells and solid biomass were used in the first and PV cells and geothermal heat pumps in the second. A performance analysis of greenhouses using integrated photovoltaic modulus supported by computer simulation has been presented (Carlnini et. al.,2010). A study of the use of semi-transparent PV films for Mediterranean greenhouses regarding the transmittance of the PV films in the visible range and in the infrared range has been presented (Marucci et. al., 2012). An assessment of a greenhouse cooling system using earth to air heat exchanger assisted with solar-PV cells has been made (Yildiz et. al., 2011). The Italian policy regarding photovoltaic investments in greenhouses has been presented (Tudisca et.al., 2013). Performance parameters of a heat pump used to meet the heating and the dehumidification requirements in a greenhouse has been studied (Chou et.al., 2004). Trends and perspectives for using renewable energy sources in the greenhouse industry have been discussed (Vox et. al., 2008). Use of a ground source heat pump assisted with a solar energy system for heating a greenhouse has been assessed (Ozgener et. al., 2007). Sustainable greenhouse horticulture in Europe has been analyzed and suggestions for the use of various renewable energies like low temperature geothermal energy, solid biomass, solar PV which should be supported have been made (Campiotti et. al., 2012). An assessment of using various renewable energies like geothermal energy, solar PV, solid biomass and geothermal heat pumps in greenhouses has been reported (Vourdoubas, 2015). The author concluded that solid biomass and geothermal energy are economically attractive, but solar-PV and geothermal heat pumps are not.

2. Semi-transparent photovoltaic cells

Semi-transparent photovoltaic cells allow solar irradiance to pass partly through them presenting some benefits in various applications compared with opaque PV cells. Although their prices are relatively high compared with opaque photovoltaic prices their use in buildings (facades, skylights, etc) is increasing. Energy and cost parameters of crystalline semi-transparent photovoltaics integrated in building’s skylights have been investigated (Li et. al., 2009). Light transmittances of 20.1 % and 21.5 % have been found and power conversion of 10.83%. Energy and cost parameters of applications of amorphous semi-transparent PV cells integrated in office buildings have been also investigated (Li et. al., 2009). Solar irradiance transmittance was estimated at 11.7 % and 11.4 % and the daily power conversion efficiency at 6.3 %. Thermal and electrical performance of semi-transparent PV modules in buildings has been analyzed (Park et. al., 2010). They found that a clear day temperature of the PV modules placed on the building can reach 55^{o} C which decreases the power output of the photovoltaic cells. The behavior of semi-transparent photovoltaics in residential applications has been studied (Wong et. al., 2008). They found that semi-transparent PV modules placed on buildings result in power generation, increased heating during the winter, increased indoor daylighting, but also in summer overheating due to solar irradiance transmittance. Various characteristics of semi-transparent polycrystalline modules available on the market are presented in Table 1.

Table 1. Characteristics of various semi-transparent polycrystalline modules

Nominal power per module	141-250 Wp
Area per module	0.71-2.22 m^2
Weight	14.5-33.9 kg/m^2
Power per m^2	85-100 Wp/m^2
Efficiency	14-18 %
Transparency	16-37 %
Price	1-2.7 €/ Wp [142.4-282 €/m^2]

*Source: prices of various companies during 2015(BIC, ACROPOL, VIDURSOLAR, ONYX). Prices depend on size and quantity ordered.

Various characteristics of semi-transparent thin film modules available on the market are presented in Table 2.

Table 2. Characteristics of various semi-transparent thin film modules

Nominal power per module	31.68-102 Wp
Area per module	0.72-2.30 m^2
Weight	16.2-37.5 kg/m^2
Power per m^2	44-63 Wp/m^2
Efficiency	7-8 %
Transparency	10-14 %
Price	1-4.4 €/ Wp [45-193.6 €/m^2]

*Source: prices of various companies during 2015 (BIC, ACROPOL, ONYX), Prices depend on size and quantity ordered.

3. Use of Semi-Transparent Photovoltaic Modules in Agricultural Greenhouses

Semi-transparent photovoltaics can be used in greenhouses in order to generate electricity for covering their energy needs including electricity, heat and cooling and selling the surplus into the grid. Since semi-transparent PV cells placed on the roof reduce the solar irradiance incoming into the greenhouse, they also reduce the cooling load particularly in Mediterranean greenhouses which have high cooling needs during the summer. For obtaining higher energy efficiencies, it is preferable to place the PV modules on the rooftops in south orientation. Since the use of the abovementioned semi-transparent PV modules on the top of greenhouses will reduce the incoming solar radiation, it is better to cover only part of their upper surface allowing enough irradiance to reach to the crop. Therefore, the use of semi-transparent photovoltaic modules for covering rooftops of greenhouses may result in many benefits including:

1. Generation of electricity in order to meet their energy needs.
2. Generation of surplus electricity which can be sold to the grid offering an additional income to the farmers. In order to do so, the legal framework for selling solar-PV electricity to the grid must exist.
3. Reduction of the cooling load during the summer since semi-transparent photovoltaics reduce the incoming solar irradiance into the greenhouse
4. Decrease or zeroing CO_2 emissions from the greenhouse due to energy use in it.

The use of semi-transparent photovoltaics is of particular interest for modern highly automated Mediterranean greenhouses (like hydroponics) growing crops which require heating and cooling, therefore consuming a lot of energy. High annual solar irradiance in Mediterranean region allows the generation of large electricity amounts from PVs which can cover the greenhouse energy requirements selling at the same time the excess electricity to the grid.

4. Energy Needs of Greenhouses

Agricultural greenhouses consume energy for heating, cooling, lighting, and operation of various electric devices. Energy consumption depends mainly on the type of construction, local climate and the cultivated crop. In Mediterranean region greenhouses construction is light, climate is mild compared with central and northern Europe and their energy requirements are relatively low. In general, in Mediterranean region heating requirements are low, but cooling needs are higher compared with northern countries. Most of the energy used in them is consumed for heating while only a small percentage of it for lighting and operation of electric devices including cooling devices. Renewable energy sources including solar energy, solid biomass and geothermal energy are not often used in greenhouses, which are using mainly fossil fuels including heating oil and natural gas for heat generation and grid electricity for other operations. There are currently not many commercial greenhouses using solar thermal energy, geothermal energy and solid biomass for heat generation or solar PV and wind mills for power generation, although renewable energies can cover all the energy requirements of modern greenhouses (Vourdoubas, 2015). Energy requirements of a greenhouse with flowers cultivation have been estimated at 14 KWh/m^2 year for electricity and 220 KWh/ m^2 year for heating (Vourdoubas, 2015). Although typical light Mediterranean greenhouses used for vegetables production do not require a lot of energy, there are other types of greenhouses like hydroponics or those used for flowers cultivation which consume a lot of energy. Usually maintenance of indoor temperatures at desired levels with proper heating and cooling increases crops productivity, but also increases energy requirements and energy cost in them.

5. Use of semi-transparent photovoltaic cells in greenhouses

High energy consumption agricultural greenhouses can meet their energy requirements with semi-transparent photovoltaic cells covering partly their roofs as is shown in the following examples. Two cases of energy intensive greenhouses located in Crete-Greece will be examined. In the first, the greenhouse can cover its needs for lighting and operation of various electric devices with electricity and its heating and cooling needs with a high efficiency heat pump (which also consumes electricity). In the second case, the greenhouse can cover its heating requirements with solid biomass and its needs for lighting, operation of various electric devices and cooling with electricity. In the first case, the energy consumption of the abovementioned greenhouse located in Crete-Greece in an area of 1,000 m^2 is presented in Table 3.

Table 3. Energy consumption of an agricultural greenhouse using a heat pump for covering its heating and cooling requirements

Surface of the greenhouse	1 000 m^2
Electricity requirements excluding heat pump	14 000 KWh/year
Heating and cooling needs	220 000 KWh/year
Total energy consumption	234 000 KWh/year
Peak heating load	160 000 kcal/h
Efficiency of the heat pump	350 %
Power of the heat pump	53.1 KW
Electricity consumption of the heat pump	62 857 KWh/year
Total electricity consumption of the greenhouse	76 857 KWh/year

In the case that the semi-transparent photovoltaic cells will be placed on the roof of the greenhouse, they can cover 500 m^2 of its inclined surface (less than 50% of its horizontal surface) in order to allow enough solar radiation to be transmitted inside the greenhouse. Since crystalline photovoltaic cells have higher transmittance than the corresponding thin film cells, they will be preferred. Assuming that the nominal power of the semi-transparent PVs will be 85 Wp/m^2, it is concluded that the overall power of the modules covering partly the greenhouse will be 42.5 KWp. Taking into account that in Crete-Greece annual electricity generation from PVs is approximately 1,500 KWh/KWp, the electricity generated from the photovoltaic modules in the greenhouse will be 63,750 KWh/year. Therefore, the generated electricity can cover a large percentage of their annual energy requirements. Characteristics of the semi-transparent crystalline modules located on the roof of the greenhouse are presented in table 4.

Table 4. Characteristics of semi-transparent crystalline photovoltaic modules which can be placed on the roof of a greenhouse in Crete-Greece using heat pumps for heating and cooling

Surface of the greenhouse	1 000 m^2
Surface of PV modules	500 m^2
Power of PV modules	42.5 KWp
Annual electricity generation from the PV modules	63 750 KWh

Annual electricity consumption of the greenhouse	76 857 KWh
Annual electricity consumption from the grid	13 107 KWh
Percentage of total electricity consumption which is covered from the electricity generated from the PV modules	82.95 %

The proposed semi-transparent PV modules placed on the top of the greenhouse covers less than 50% of its horizontal surface and it can generate enough electricity in order to cover more than 80% of total electricity needs of the abovementioned greenhouse which uses heat pumps for its space heating and cooling. Therefore, a large part of its energy needs will be covered with solar-PV energy reducing significantly its CO_2 emissions due to energy use. In the case that a higher percentage of its roof is covered with the PV modules, all its energy requirements can be met with the generated solar electricity, but in this case less solar irradiance will be transmitted inside the greenhouse. Also, in the case that the greenhouse is less energy intensive with lower energy requirements, these can be fully covered with the abovementioned semi-transparent photovoltaic modules.

In the second case where solid biomass is used for heating, the energy consumption of the greenhouse is presented in table 5.

Table 5. Energy consumption of the greenhouse using solid biomass for heating and electricity for lighting, cooling and operation of various electric devices.

Surface of the greenhouse	1 000 m^2
Electricity requirements	18 000 KWh/year
Heating requirements	216 000 KWh/year
Total energy consumption	234 000 KWh/year

Characteristics of the semi-transparent PV modules placed on the roof of the greenhouse are presented in table 6.

Table 6. Characteristics of semi-transparent crystalline photovoltaic modules which can be placed on the roof of a greenhouse in Crete-Greece using solid biomass for heating.

Surface of the greenhouse	1 000 m^2
Surface of the PV modules	500 m^2
Nominal power of PV modules	42.5 KWp

Annual electricity generation from the PV modules	63 750 KWh
Annual electricity consumption of the greenhouse	18 000 KWh/year
Electricity surplus which can be sold to the grid	45 750 KWh/year
Percentage of total electricity generation which can be sold to the grid	71.76 %

Therefore, in the case that the abovementioned energy intensive greenhouse will cover all its high heating requirements with solid biomass, the semi-transparent PV modules covering partly its roof will generate more electricity than it needs and the surplus can be sold to the grid, generating an extra income to the farmer. In this case the greenhouse will cover all its energy requirements with renewable energies, solar energy and solid biomass and it will generate also surplus electricity for the grid. Therefore, it will have negative CO_2 emissions to the atmosphere due to energy use in it.

6. Economic and environmental considerations

Current costs of crystalline and thin film semi-transparent photovoltaics are high and the total cost of their installation including cells, inverters, cabling, controllers, labour and metal infrastructure varies between 4-5 € per Wp. Therefore, the overall cost of installing semi-transparent PV modules with nominal power 42.5 KWp on the roof of the greenhouse will be 170,000-212,500 Euros. Due to their high investment costs, the price of solar generated electricity is higher than the price of grid electricity. Therefore, future use of semi-transparent PV cells in greenhouses needs a financial support from the governments in the framework of renewable energies promotion in agriculture. On the medium and long term their prices are expected to decrease due to higher production and technological improvements. Two other factors should be assessed for the use of semi-transparent photovoltaics in greenhouses together with the cost of generated electricity. : The first is related with reduction of the cooling loads during the summer, which results in energy saving in the greenhouse; the second is related with the reduction of CO_2 emissions in the greenhouse due to energy use in it. Use of semi-transparent PV cells in greenhouses will result in the reduction of CO_2 emissions due to energy use in them and, depending on the specific case; it could result in zero or negative CO_2 emissions. In the two abovementioned cases the use of crystalline PV modules will result in the reduction of 63,049 kg of CO_2 emissions provided that 1 KWh of grid electricity corresponds to 0.989 kg CO_2.

7. Conclusions

Crystalline semi-transparent photovoltaic cells with high transmittance can be placed on the rooftops of agricultural greenhouses in a way that they will not affect the growth of the cultivated crops. Since they generate electricity, they can cover their energy requirements and the surplus can be sold to the grid. They can also contribute in energy saving since they reduce the cooling load during the summer. Therefore, the farmers can have an income additional to the cultivated crop decreasing also CO_2 emissions due to energy use in the greenhouses. Crystalline PV cells have higher transmittance than thin films and their use is preferable on the rooftop of greenhouses. In Mediterranean region greenhouses do not require a lot of energy due to their light construction and the mild climate. However, high solar irradiance in the region allows the generation of high amounts of electricity from the PV cells. The possibility of installing semi-transparent modules in two energy intensive greenhouses located in Crete-Greece has been investigated and various estimations have been made. In the first which uses heat pumps for its heating and cooling, PV modules of a surface of 500 m^2 can be placed on the rooftop of the greenhouse with an area of 1,000 m^2.The nominal power of the PV modules is estimated at 42.5 KWp and their annual generated electricity can cover more than 80 % of its total energy needs. In the second greenhouse which uses solid biomass for its heating, the same PV modules can cover all its energy needs, generating a surplus which corresponds to 71.76 % of its annual electricity generation and it can be sold to the grid. The overall investment cost of the crystalline PV modules is estimated at 170,000-212,500 €. Therefore, current cost of semi-transparent PVs is still high and without subsidies it is not expected to generate profits to the farmers. Further work is needed in order to estimate the rooftop area in the greenhouses which can be covered with either crystalline or thin film semi-transparent PV modules without affecting the growth of the crops and the maximum temperatures reached in the cells which adversely affects energy generation. More experimental data are also needed in order to estimate better the annual generated electricity, as well as the effect of the semi-transparent PVs in greenhouse cooling.

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Overview of the Use of Sustainable Energies in Agricultural Greenhouses

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Abstract

Global concern on environmental problems like climate changes has altered our energy patterns promoting non-polluting renewable energies instead of fossil fuels. Technological advances in sustainable energy technologies allow their increasing use in all sectors of everyday life. Agricultural greenhouses utilize energy for heating, cooling and operation of various electric devices. The highest amount of energy used in greenhouses is consumed in heating them. Controlling crops growth conditions including temperature results in higher productivity and in better economic results. Various sustainable energies including renewable energies and high efficiency and low carbon energy technologies have been used in commercial scale and the technical and economic viability of others has been investigated in experimental scale. Among renewable energies solar energy, biomass and geothermal energy can be used in order to cover part or all of the energy requirements for heating, cooling and power generation of greenhouses. Energy efficient and low carbon technologies like co-generation of heat and power, heat pumps, fuel cells but also waste heat can be used also for energy generation in them. Governmental energy incentives for the promotion of sustainable energies like feed-in tariffs or net-metering allow the use of the abovementioned energy technologies for electricity generation in greenhouses offering additional economic benefits to the farmers. Use of the sustainable energies which are mature, reliable and cost effective in greenhouses results in mitigation of climate changes, use of local renewable energy resources instead of fossil fuels and better profitability of the cultivated crop.

Keywords: agricultural greenhouses, cooling, electricity, energy efficient technologies, heat, renewable energies, sustainable energies

1. Introduction

The necessity to cope with the severe problems of climate changes and the raise of the concentration of greenhouse gases in the atmosphere have increased the use of sustainable energy technologies in various sectors of daily activities. Low or zero carbon energy technologies for generation of power, heat, cooling and vehicle fuels include the use of various renewable energies as well as high efficiency energy technologies like cogeneration of heat and power, heat pumps and waste heat reuse. The majority of these technologies are currently mature, reliable and cost effective since technological innovations have reduced their cost and increased their economic attractiveness. Sustainable energies can find applications for energy generation in greenhouses covering part or all of their energy needs including electricity, heat and cooling. Usually greenhouses use grid electricity for lighting and operation of various electric devices and heating oil, fuel oil or gas for heating, contributing in CO_2 emissions in the atmosphere. Depending on the location and the type of the greenhouse, energy consumption may contribute more or less to the production cost of the crop, influencing the energy use in it. Mediterranean greenhouses are light structures with low energy consumption and low contribution of the energy cost to the final crop production cost. Governmental policies and various incentives play an important role in the promotion of sustainable energies use in agricultural greenhouses. Among renewable energies solar energy, solid biomass and geothermal energy have been used already in them. In some areas with high wind velocities, wind energy can be also used for power generation. Solar energy, wind energy and geothermal energy are site dependent and solid biomass should be produced nearby the greenhouse location, in order to minimize its transportation costs. Among energy efficient technologies cogeneration of heat and power, heat pumps, as well as waste heat recycle have been used in greenhouses and the emerging technology of fuel cells can be probably used in the near future. Successful incentives like feed-in tariffs and net-metering can promote the use of solar-PV energy, wind energy, and co-generation of heat and power in greenhouses offering the opportunity to the farmer to co-generate electricity additionally to crop production and to reduce or zero its electricity consumption cost. However, in some cases, the use of sustainable energies in greenhouses may require additional capital for the investments, which might not be available to the farmer and this fact limits the application of these technologies in them.

2. Solar Thermal Energy

Solar thermal energy can be easily used for heating greenhouses with various ways using active or passive solar heating systems. Solar heating of a greenhouse depends on its location and the climate conditions, the solar irradiance and its heating needs, but in general solar energy cannot cover all the heating needs of a greenhouse in a cost effective way. A survey of thermal performances of a solar system used for heating greenhouses in Morocco has been presented (Bargach et al., 2000). Solar flat plate collectors were used in order to heat water which afterwards was heating the greenhouse. Experimental results verified theoretical model simulation, obtaining satisfactory system efficiency. Worldwide evaluation of solar energy passive technologies used for heating greenhouses has been reported (Santamouris et al., 1994). They have classified the passive solar agricultural greenhouses in different categories like a) Passive solar using water storage, b) Passive solar with latent heat storage materials, c) Passive solar with buried pipes storage materials, d) passive solar with rock bed storage and e) Passive solar with other types of heat storage. They concluded that passive solar systems can be integrated into agricultural greenhouses in order to reduce their energy consumption for heating. In general these systems can increase the indoor temperature of the greenhouse at 2-12 °C compared with the minimum outdoor temperature. Design and operation of a low energy consumption passive solar agricultural greenhouse in Greece has been presented (Santamouris et al., 2004). They have constructed a 1 000 m^2 passive solar greenhouse with a mass storage wall located on the north side and a network of earth to air heat exchangers buried in the greenhouse. Operation for two years of the system has shown a 35% decrease of its heating requirements and an important reduction of its cooling needs during the summer. A survey and evaluation of various greenhouses heating technologies including solar flat plate collectors, ground source heat pumps and shallow solar ponds has been made (Setni & Sharma, 2008). They have concluded that performance of each system depends on the location, climate conditions and size of the greenhouse. Each heating system has advantages and limitations which should be taken into account. A review of energy storage applications in greenhouses by means of phase change materials has been presented (Kurklu, 1998). According to his findings, the most used phase change materials are based on salts hydrates, paraffins and polyethylene glycol.

3. Solar Photovoltaic Energy

Solar photovoltaic cells can be used for electricity generation in greenhouses covering part or all of their power needs and selling the excess electricity to the grid. Current decrease of photovoltaics prices has increased the attractiveness of solar-PV energy use in agricultural greenhouses. Use of semi-transparent photovoltaic films for Mediterranean greenhouses (simple structures covered with plastic films) as a sustainable technology has been reported (Marucci et al., 2012). The possibility of using semi-transparent PVs, which allow part of solar radiation to pass through them, in greenhouses in Crete-Greece has been examined (Vourdoubas et al., 2015). Their use can be combined with power generation in the greenhouse and the possibility of selling electricity to the grid. At the same time cooling requirements in the greenhouse are decreased. Use of solar PV cell assisted earth to air heat exchanger system for solar greenhouse has been reported (Yildiz et al., 2011). Assessment of the Italian energy policy through the study of a photovoltaic investment on greenhouse has been presented (Tudisca et al., 2013). The authors have analyzed a case study on a farm that has realized a grid-connected photovoltaic system on a greenhouse. They have reported that there are greenhouses in Italy which have invested in PV systems, taking advantage of the high feed in-tariffs offered by the government. However, these high feed-in tariffs have been reduced recently and with net-metering initiative farmers can use PVs in their greenhouses in order to save energy through self-consumption of the generated electricity. Feed-in tariffs and net-metering initiatives allow the farmers to become energy producers in their greenhouses having an additional income from energy generation. A network of small electricity producers can be created promoting distributed power generation. Future expectations of solar-PV use in greenhouses are high due to the decrease of their prices and the increase of the electricity prices.

4. Wind Energy

Many agricultural greenhouses are located in areas with high annual wind velocities where wind turbines can be installed generating electricity in a cost effective way. When the greenhouse is not connected to the grid, the generated electricity must be stored in batteries in order to be used effectively. In the case of grid connected greenhouses, generated electricity from the wind mill can cover various power needs of them. A greenhouse in Turkey which was heated with a hybrid system consisted of a solar assisted geothermal heat pump and a small wind turbine installed separately has been reported (Ozgener, 2010). Electricity generated by the wind turbine was covering though a small part of the annual electricity needs of the greenhouse. Therefore, in areas with high wind energy resources, wind turbines can cover part of the annual electricity requirements of agricultural greenhouses. However, the economic attractiveness of these systems should be investigated and proved for each case. An experimental installation of a small wind turbine in a greenhouse in Italy has been reported (Vox et al., 2008). The annual wind velocity in the installation site was low and the efficiency of the small wind mill was also low.

5. Solid Biomass

Various types of agricultural and forest residues and wastes can be used for heating agricultural greenhouses. Usually solid biomass is cheaper than fossil fuels and the heating system can cover all the heating requirements of a modern greenhouse. Solid biomass should be produced nearby the greenhouse location in order to avoid its transportation in long distance which usually is costly. A greenhouse located in Crete, Greece used for flowers cultivation which covers all its heating needs with olive Kernel wood, a locally produced byproduct of the olive oil producing industry has been reported (Vourdoubas, 2015). During its heating hot water of 50-55 °C was produced which was circulating inside plastic pipes placed on the ground of the greenhouse. The low price of olive kernel wood (approx. 0.1 €/kg) compared with its heating value (approx. 4 051 Kcal/kg) makes it very attractive compared with fossil fuels like fuel and heating oil. Its granular form facilitates its transportation and handling and it can be easily burnt in a proper heating system. Apart from olive kernel wood other types of solid biomass like the Kernels of various fruits including peaches or apricots can be used as an energy source for heating greenhouses. Solid biomass heating systems in greenhouses require proper treatment of the burnt gases, regular cleaning of the heat exchanger and disposal of the ash produced during burning. However, these problems are easily solvable. An economic and environmental assessment of the use of various renewable energies for heating greenhouses has been made (Vourdoubas, 2015). It is concluded that use of solid biomass and geothermal energy are very attractive and profitable options for heating greenhouses.

6. Biogas

Biogas which is generated in landfills, in municipal garbage processing plants or in sewage treatment plants can be used for energy generation in nearby located agricultural greenhouses. It is worth mentioning that CO_2 generated during biogas burning after its purification can be used for the enrichment of the greenhouse atmosphere in order to increase crops productivity. A soilless greenhouse with roses cultivation which used biogas produced in a nearby landfill for heat generation in order to cover the greenhouse heating requirements has been reported (Jaffrin et al., 2003). CO_2 produced during burning after proper purification can be supplemented inside the greenhouse. Application in two 300 m^2 plastic greenhouses has proved the technical feasibility of this technology. The authors have reported that the benefits due to the increased productivity of the crop because of the enrichment of the atmosphere with CO_2, are higher than the benefits obtained because of the cost reduction due to replacement of the fossil fuels used with biogas. An experimental greenhouse in Turkey which is heated with biogas produced with anaerobic digestion of dairy cow manure has been described (Esen & Yuksel, 2013). Temperature inside digestor was kept at 27 °C and the burnt biogas was heating the greenhouse keeping the indoor temperature at 23 °C. Biogas used as fuel in greenhouses can cover all their heating requirements.

7. Direct Geothermal Energy Heating

Geothermal energy is used today in agricultural greenhouses in order to heat them. Low enthalpy geothermal energy consists of a cheap and renewable energy source which can be used for heating greenhouses with rather simple technologies. The use of low enthalpy geothermal source in Northern Greece to heat a greenhouse with roses cultivation has been described (Bakos et al., 1999). Geothermal fluid temperature was 95 °C and the heating system was able to maintain an indoor temperature at 20 °C when the outdoor was 7 °C. In a second experimental greenhouse geothermal fluid temperature was lower, at 50 °C, maintaining an indoor temperature at 15 °C. Space heating was achieved with plastic tubes placed on the ground of the greenhouse where hot water was circulated inside them. Various cost effective renewable energy technologies for energy generation in greenhouses, like solar energy, solid biomass and geothermal energy have been presented (Campiotti et al., 2010). According to them direct geothermal energy heating technology is mature, site-dependent with a current installation cost 1 500-2 000 €/KWth (compared to 1 000 €/KWth for oil). CO_2 emissions are less than 0.1 gr/KWh. Mathematical modeling of geothermal energy heating in a greenhouse equiped also with a thermal curtain for energy saving has been presented (Ghosal & Tiwari, 2004). According to them indoor temperatures of 14-23 °C could be obtained using thermal curtain and flowing geothermal hot water through polyethylene tubes placed on the ground of the greenhouse.

8. Geothermal Cooling

Low enthalpy geothermal energy can be used for cooling greenhouses with earth to air heat exchangers. Soil temperatures few meters below the ground are almost constant all over the year and equal with the annual average air temperatures. During the summer when air temperatures can exceed 40-45 °C, temperatures below the ground are significant lower. A fiberglass greenhouse of 1 000 m^2 located in Greece where plastic buried pipes were placed underneath the greenhouse has been described (Santamouris et al., 1995). A ventilator was used to circulate the air from the upper part of the greenhouse to the air pipes and back again. During the summer when the ambient temperature was much higher than the soil temperature, the ventilator forced the hot air from inside the greenhouse to pass through the buried pipes, where it was partly cooled, and then to return inside the greenhouse with lower temperature. The opposite can happen during the winter, when this underground earth to air heat exchanger can rise the indoor temperature of the greenhouse. Authors have reported that this cooling and heating system can obtain lower and higher air temperatures of 3-5 °C compared to ambient, during summer and winter correspondingly.

9. Geothermal Heat Pumps

Heat pumps are very efficient energy devices which are used broadly in heating and cooling. Their coefficient of performance (C.O.P.) is high in the range of 2-4. That means that they produce 2 to 4 times more energy than the consumed electricity. Ground source heat pumps have higher C.O.Ps due to the fact that they operate more efficiently because of the almost constant temperature few meters below the ground. Use of heat pumps in an experimental greenhouse in Japan has been reported (Tong et al., 2010) and the authors have estimated C.O.Ps values between 3.3 and 5.8. Evaluation of a heat pump system for greenhouse heating in Australia has been reported (Aye et al., 2010). An air to water heat pump was used in a 4 000 m^2 greenhouse and the payback period of the system was estimated approx. to 6 years. This payback period was lower than those reported in previous evaluations. A ground-source heat pump combined with latent heat storage system for heating a greenhouse in Turkey has been evaluated (Benli & Durmus, 2009). Average heating C.O.Ps between 2-3.8 was obtained. The authors found that during January with ambient temperatures between -5 °C and -20 °C, ground temperatures were 5-7 °C making the operation of the heat pump more efficient. An experimental evaluation of using various renewable energy sources for heating a greenhouse in Turkey has been presented (Esen & Yuksel, 2013), including a ground source heat pump combined with a biogas system, concluding that heat pumps can have a leading role in Turkey in the future.

10. Co-Generation of Heat and Power

Cogeneration of heat and power is a very efficient energy generation technology obtaining an overall energy efficiency 75-90%. Different technological systems like gas turbines, steam turbines and diesel engines have been used for that. Since it is a low carbon energy technology which uses fossil fuels but generates low emissions of greenhouse gases, it is promoted in various sectors from E.U. policies (Directive 2008/8/EC). It is currently used in greenhouses for covering their heating needs, part of their power needs and selling the excess electricity to the grid. Various countries offer currently attractive feed-in tariffs for the electricity derived from CHP systems and sold to the grid. Cogeneration systems used in greenhouses are more attractive in northern European countries where greenhouses need heating almost all the year, than in warmer climate like Mediterranean countries (Garcia et al., 1998). Natural gas is the most popular fuel used in cogeneration systems and heat storage can improve the economics of such a system. Various cogeneration systems applications in greenhouses have been reported (Compernoll et al., 2011). They have implemented two case studies which prove the profitability of C.H.P. systems resulting also in positive environmental impacts. A C.H.P. in a greenhouse can 1) generate electricity which can be used in the greenhouse and the excess sold to the grid, 2) produce heat covering its heating needs, 3) Produce cooling with absorption cooling systems when the greenhouse needs cooling instead of heating and 4) Enrich the greenhouse atmosphere with purified CO_2 from the exit gases resulting in increasing productivity of the crop and improving its economics.

11. Waste Heat Recovery

Power plants as well as various other plants reject cooling water at temperatures which can be effectively reused for various heating purposes. Low enthalpy cooling water can be used for heating greenhouses covering all their heating requirements. Use of the water from the cooling towers of the large power plant in NiederauBen, Germany for heating commercial greenhouses has been reported (Bredenbeck, 1992). An area of 53 000 m^2 of greenhouses was heated with warm water at 30 °C during the winter, keeping the indoor temperature at 22 °C with ambient temperature at -14 °C. The heating system was using water to air heat exchangers with forced ventilation, properly controlled. The ratio of electricity used to gained heat energy varies from approx. 1:20 to 1:30 depending on temperatures of the cooling water, as well as the indoor and outdoor temperatures. Authors concluded that the use of waste heat for heating greenhouses is not so simple as it seems due to various financial and organizational problems. The possibility of using the cooling water of the power plant in Heraklion, Crete, Greece for heating nearby greenhouses used for cultivation of various vegetables like tomatoes, cucumbers, green papers and egg-plants has been presented (Vourdoubas et al, 1998). Maximum cooling water temperatures vary from 25 °C in the winter to 31 °C in the summer and the required minimum indoor temperatures in the greenhouses vary from 10°C-14 °C during day time and 8 °C-13 °C during the night.

12. Fuel Cells

Fuel cells can be used for cogeneration of heat and power in order to cover the energy requirements of agricultural greenhouses. Electricity generation efficiency of the fuel cells is approx. 50% and the overall efficiency including heat production is 80-90%. Modeling of a floriculture greenhouse in India equipped with solar- PV cells, an electrolyzer and a PEM fuel cell has been reported (Ganguly et al., 2010). Excess electricity generated from solar-PVs during peak hours after meeting the requirements of the greenhouse, can be used for hydrogen production with water electrolysis, which is consumed from the PEM fuel cell for electricity generation to cover electricity needs of the greenhouse during the low sunshine hours. This study has shown that such an integrated power system provides a viable option for powering stand-alone greenhouses in a self-sustained manner. The possibility of using fuel cells for providing energy in commercial greenhouses has been reported (Mulloney, 1993). According to him the benefits which are resulted from this application include a) Generation of electricity which can cover the greenhouse requirements and the rest can be sold to the grid if this is allowed. b) Heating the greenhouse as well as cooling it during the summer with absorption cooling systems c) Exhaust gases from the fuel cell can be used directly to greenhouse both for heating and for enriching the atmosphere with CO_2 in order to increase crop productivity. Renewable energies which can be used for energy generation in greenhouses are presented in Table 1 and low carbon technologies which can also be used for that are presented in Table 2.

Table 1. Renewable energies which can be used for energy generation in greenhouses

Energy source	*Generated energy*
Solar thermal	Heat
Solar- PV	Electricity
Solid biomass	Heat
Biogas	Heat
Direct geothermal	Heat
Ground heat (heat exchanger)	Heat and cooling
Wind	Electricity

Table 2. Low carbon energy technologies which can be used for energy generation in greenhouses

Technology	*Generated energy*
Cogeneration of heat and power	Heat and electricity
Fuel cells	Heat and electricity
Waste heat recycle	Heat

13. Benefits from the Use of Sustainable Energies in Greenhouses

The use of sustainable energies in agricultural greenhouses results in many environmental, social and economic benefits including:

a) Reduction of CO_2 emissions to the atmosphere due to the use of fossil fuels or to low efficiency energy technologies.

b) Increasing use of local renewable energy resources instead of fossil fuels which in many cases are imported.

c) Economic benefits to the farmers in the case that sustainable energies used are cost effective and reduce the production cost of the crop.

d) Possibility of creation of an additional income to the farmer in the case of using solar-PV energy or C.H.P. systems in the greenhouse and selling the electricity to the grid.

e) Increase of the employability and the local income from the exploitation of local resources like biomass and the operation of local companies installing and maintaining sustainable energy systems.

14. Conclusions

The effort to cope with global environmental challenges and climate changes has increased the use of non polluting energy resources including renewable energies and low carbon energy technologies. Recent improvements and innovations in these energy technologies have increased their reliability, maturity and their cost effectiveness. Therefore they can be used broadly for power generation as well as for heating and cooling. Modern agricultural greenhouses require energy in various operations and traditionally they use fossil fuels. However they can be replaced with sustainable energies, including solar energy, biomass, geothermal energy, heat pumps, cogeneration systems and reuse of waste heat. Depending on the case they can cover part or all of their energy needs in heating, cooling and electricity consumption. There are currently worldwide various commercial greenhouses using renewable energies and low carbon energy technologies. The technological viability of some others has been investigated and proved in experimental installations. Use of solar-PV cells or C.H.P. systems in grid connected greenhouses is combined with selling the electricity to the grid with attractive feed-in tariffs resulting in additional income to the farmers. The benefits of replacing conventional fuels in greenhouses with sustainable energies result in many environmental and economic benefits to the farmer and to the local society.

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Possibilities of Using Landfill Biogas for Heating Agricultural Greenhouses in Crete-Greece

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Abstract

Biogas is currently produced in Crete-Greece from the two existing landfills in the island, as well as from the sewage treatment plants in Chania and Heraklion. Biogas produced in the two treatment plants is already used for co-generation of heat and power. However, since the quantities of landfills biogas and its energy content are significant, it can be used in the future either for heat production or for heat and power generation. Generated power can be fed into the grid and the produced heat can be used from a heat consumer. Since large heat consumers are not located nearby the existing landfills, there is the possibility for the creation of agricultural greenhouses in the surrounding agricultural areas which can utilize the generated heat. Landfill in Heraklion has an average biogas production of $1.43x10^7$ NM^3/year, almost five times higher than the landfill in Chania and the totally recoverable biogas from the two landfills can generate 16.73 GWh/year of electricity, in the case of a CHP plant, and enough heat for heating 15.4 hectares of modern greenhouses. In the case of direct heat generation, recoverable landfill biogas can heat 24.41 hectares of modern greenhouses. Since the global warming potential of methane is much higher than CO_2, energy exploitation of landfills biogas in Crete will result in environmental benefits compared with its direct emission to the atmosphere.

Keywords: Biogas, co-generation, Crete, greenhouses, heat, landfill, methane, power

1. Introduction

Biogas constitutes a renewable fuel produced mainly from organic wastes which are anaerobically digested with bacteria. Since its heating value is not negligible and its global warming potential high, its use for heat and power generation is considered as a good option for its utilization. Currently, biogas in Crete-Greece is produced from the two landfills in Chania and Heraklion and from the two sewage treatment plants which operate in the same cities. Biogas from those treatment plants is currently utilized for heat and power generation. An assessment of the pollutants from the Akrotiri landfill site in Chania-Western Crete has been presented (Chalvatzaki et al, 2009, Chalvatzaki et al, 2010). The landfill consists of two cells: the first with capacity of 440,000 M^3, operated during the period 2003-2007 with annual acceptance of wastes 80,000 tn/year and the second with capacity of 660,000 M^3, operated from 2007 until 2015 with annual acceptance rate of 85,000 tn/year. Three different landfill gas emissions models have been used for the assessment of the gas emissions rates. The authors have predicted a rather constant biogas production rate over the period 2008-2025 using the reliable Land GEM model. They have estimated an average biogas emission rate of $1.1x10^6$ NM^3/year for cell A and 1.8 x 10^6 NM^3/year for cell B. A report on the management of olive mill wastes in Greece has been presented (Chartzoulakis, 2014). Among different treatment methods, anaerobic biological processing mostly driven by bacteria with biogas production has a high construction and operation cost and it is not affordable from small-size, family-based olive mills. A report on current situation and perspectives of biogas production in Greece has been published (Zafiris, 2007). According to him, biogas production in sewage treatment plant in Chania is 1,085 NM^3/day and in the respective plant in Heraklion 3,200 NM^3/day. Investigation of biogas produced in the landfill of Heraklion Crete for power generation has been presented (Tsave et al, 2008, Karapidakis et al, 2010). An average biogas production from the landfill over the period 2006-2026 of 1,636.68 NM^3/h has been estimated and assuming that 75% of the produced biogas can be recovered, its energy content is 55.95 GWh/year. Assuming that the power generation efficiency is 25%, the average electric power generation from this landfill gas (LFG) is estimated at 13.99 GWh/year. The power plant capacity for generation of 13.99 GWh/year has been estimated at 1.6 MW. An evaluation of biogas utilization for energy generation from the sewage treatment plant in Heraklion, Crete has been presented (Tsagarakis et al, 2006). An average biogas production of 2,040 NM^3/day over a period of 5.5 years has been found. The average electricity generation from the biogas was 2,039.3 KWh/day. Generated power corresponds to 15.9 % of the consumed electricity of the sewage treatment plant, but the authors believe that with proper process optimization it could reach at 39 %. An experimental application of LFG for heating a greenhouse with roses cultivation in France has been reported (Jaffrin et al, 2003). In an experimental greenhouse of 300 M^2, they have used LFG to heat the space and the purified burnt gases were enriching the greenhouse atmosphere. They have reported that crop productivity increases due to CO_2 enrichment, are more important to greenhouse economics, compared to the benefit resulting from the reduction of heating costs due to the use of LFG. The authors have underlined the potential for developing greenhouses located nearby landfill sites. The possibility of power generation from LFG using traditional and innovative technologies have been presented (Bove et al, 2006). They have compared traditional technologies like internal combustion engine, gas turbine, plant with organic Rankine cycle and Stirling engine with innovative technologies like molten carbonate fuel cell and solid oxide fuel cell. They have concluded that, although internal combustion engines have the poorest environmental performance, they are the most widely technology used due to economic reasons. A technical, economic, and environmental analysis of biogas utilization has been reported (Murphy et al, 2004). They have investigated the possibilities of using LFG for CHP production and for transport fuel production in Ireland. The authors have concluded that the production of transport fuel is more economic than the utilization of biogas in a CHP plant depending on transport fuel taxes. They have reported also that the conversion of LFG to carbon dioxide through direct burning, significantly reduces greenhouse-gas production as compared with the emission of LFG to the atmosphere. Energy recovery combined with greenhouse effect reduction from landfills has been investigated (Lombardi et al, 2006). The authors have compared the traditional use of LFG for power generation with innovative technologies using its direct feeding to a fuel cell, the production of a hydrogen rich gas with steam reforming to feed a stationary fuel cell and to feed a vehicle fuel cell. They have concluded that steam reforming of LFG and subsequently use of the gas, reduces overall greenhouse gas emissions. A report on methane generation in landfills has been presented (Themelis et al, 2007). According to their findings an approximate production of 50 NM^3 of methane per ton of municipal solid wastes landfilled could be a conservative estimation. However, currently only 10 % of this methane potential worldwide is captured and utilized. In USA, 70 % of the captured LFG is currently utilized for generation of heat and power. The authors report that global generation of methane from landfills is estimated at 50 million tons and from them 45 million tons are emitted to the atmosphere, which approx. are equivalent to 1 billion tonnes of CO_2, since CH_4 has 23 times higher global warming potential than CO_2. Four different technologies which produce energy from municipal solid wastes including incineration, gasification, generation of biogas and utilization in a CHP plant and generation of biogas and conversion to transport fuel have been investigated (Murphy et al, 2004). Both biogas technologies require less investment costs than the thermal conversion technologies and have smaller gate fees but the transport technology is cheaper. Energy production from LFG in Central Italy has been reported (Caresana et al, 2011). The authors have investigated the profitability of five alternative configuration plants for power generation and for CHP. They have concluded that internal combustion engines is the most cost effective technology compared to other innovative technologies. In order to utilize the co-produced heat in industrial facilities and to profit from that, they have installed the CHP plant in some distance from the landfill, which results in additional costs. Environmental aspects of landfill gas utilization for power generation have been studied (Qin et al, 2001). The high concentration of CO_2 in LFG (typically 40-50 %) negatively impacts combustion efficiency and stability. Experimental and theoretical investigation has proved that CO_2 increases the NO emissions per gram of CH_4 consumed. The authors concluded that its combined use with natural gas will result in more efficient energy utilization and less emissions. The energy potential of the biogas produced by an urban waste landfill in Southern Spain has been investigated (Zamorano et al, 2007). In a sealed landfill in Granada, Spain, LFG yield was estimated at 250-550 NM^3/h, with CH_4 content of 45 %. The authors have found that its utilization for power generation with a 624 KW engine is profitable having a high internal recovery rate. The present study highlights the importance and the challenges of utilizing LFG in Crete-Greece for energy generation and the possibility of creating greenhouses nearby the existing landfills, in order to utilize the produced heat resulting in higher profitability of biogas exploitation for energy generation.

2. Heating requirements of agricultural greenhouses

Modern greenhouses require energy for heating, cooling, lighting, and operation of various electric devices. Most of the energy used is consumed for their heating, which can reach at 95,31 % of the total energy used (Vourdoubas, 2015). Heating requirements of greenhouses depend on the climate, the construction type and the cultivated crops. Northern European greenhouses, which are heavy constructions, need more energy for their heating than Mediterranean greenhouses, which are simple constructions and the climate is mild. The most common fuels currently used for heating them include fuel oil, heating oil and natural gas and only a small percentage of them utilize renewable energies or low carbon energy technologies for their heating although some of them are cost effective (Vourdoubas, 2015). Greenhouse heating can increase crops productivity, improve the quality of the products and increase profitability. Heating cost constitutes a significant part of the total crops production cost in the greenhouses and the selection of the suitable fuel as well as the proper heating technology can influence their profitability. Although the heating requirements of a greenhouse vary depending on many factors, for a modern and well equipped greenhouse of 1,000 M^2 located in Chania-Crete-Greece and in order to control the indoor temperature at 20-22 ℃ during the winter and at 26-27 ^oC during the summer, heating needs have been estimated at 220,000 KWh/year and the peak heating load at 185.8 KW (Vourdoubas, 2015).

3. Use of renewable energies for heating greenhouses

Various renewable energy sources have been used for heating greenhouses including solar energy, geothermal energy and biomass. Low carbon and high efficiency energy technologies like heat pumps and co-generation systems have been also used including waste heat reuse for that. Many of these technologies are cost effective and their use results in the decrease of heating costs in agricultural greenhouses. Use of renewable energies and high efficiency energy technologies in heating them, results in many environmental and social benefits, including the mitigation of greenhouse gas emissions in the atmosphere and the use of local renewable energy resources instead of imported fossil fuels. Renewable energies can either cover part or all of the heating requirements of modern greenhouses without requiring additional fuels. Solar energy can cover part of the heating and cooling requirements and it is occasionally used in commercial greenhouses. Biomass and direct geothermal heating are currently used for covering all their heating needs. Co-generation systems and waste heat reuse have been also used commercially. However, although many sustainable energy technologies are currently mature, reliable and cost effective, their use in greenhouses should be propagated more. In order to increase their use, governmental support including awareness raising, training and technical support as well as financial incentives among the farmers should be offered. Various renewable energies are site depended and this limits their use for energy generation to nearby located greenhouses.

4. Biogas production n Crete

Biogas is currently produced in Crete from the existing landfills in Heraklion (Tsave et al, 2008, Karapidakis et al, 2010) and in Chania (Chalvatzaki et al, 2009, Chalvatzaki et al, 2010). It is also produced in the sewage treatment plants in the same cities. Various studies have proved the technical viability of the production of biogas from olive mills liquid wastes in Crete. However, although these wastes are highly polluted having very high BOD_5 and COD values, their anaerobic digestion for biogas production is not cost effective and they are not processed in this way in Crete. Biogas produced from the sewage treatment plants in Chania and Heraklion is currently used for co-generation of heat and power. Power is sold to the grid and the heat is used for heating the sludge digestors, in order to keep the sludge in the desired temperatures. However, LFG is not currently utilized for heat or power generation or for co-generation of heat and power since the co-produced heat cannot be utilized in the landfills or nearby, since they are located in remote areas away from urban or industrial activities. However due to high global warming potential of biogas, it must be burnt instead of being emitted to the atmosphere (EU directive 1999/31/EC). The existence of available agricultural land nearby the landfills and the mild climate of Crete, offer the opportunity to create greenhouses which can be heated with the biogas produced in the landfills. In that case LFG can be used either directly for heating greenhouses or it can be used for co-generation of heat and power. Generating only power from the LFG and feeding it to the grid is not economically attractive, if heat is not co-generated. However, if the generated power can be sold to the grid and heat is co-produced, which is used for heating greenhouses, the co-generation option is more profitable. The combination of biogas production from wastes, biogas utilization for CHP and the use of the generated heat and power in different applications, promotes recycling economy, industrial ecology and overall sustainability. Biogas produced from the landfills in Chania and Heraklion as well as from the sewage treatment plants in these cities is presented in table 1.

Table 1: Biogas production in Crete from two landfills and two sewage treatment plants located in Chania and Heraklion Prefectures

Source of biogas production	Biogas production (NM^3/year)	Energy content of the produced biogas (Kcal/year)	Biogas which can be recovered (NM^3/year)	Energy content of the recovered biogas (Kcal/year)	% of total in Crete
Landfill in Chania, cell 1[3]	1.1×10^6	4.9×10^9	8.25×10^5	3.7×10^9	5.87
Landfill in Chania, cell 2[3]	1.8×10^6	8.1×10^9	1.35×10^6	6×10^9	9.55
Landfill in Heraklion[2]	1.43×10^7	6.4×10^{10}	1.08×10^7	4.8×10^{10}	76.21
Sewage treatment plant in Chania[1]	3.96×10^5	1.77×10^9	2.97×10^5	1.33×10^9	2.12

Sewage treatment plant in Heraklion[1]	1.17 x 10^6	5.24 x10^9	8.77x10^5	3.93x10^9	6.25
Total	1.88 x10^7	8.4x10^{10}	1.41x10^7	6.3x10^{10}	100

[1]data from Zafiris, [2]data from Tsave et al., [3]data from Chalvatzaki et al., Biogas energy content 4,475 Kcal/NM^3,Biogas recovery rate 75 %

5. Co-generation of heat and power from LFG

LFG can be used for co-generation of heat and power having high overall efficiencies in the order of 70-80 %. Electric efficiency of 25 % and heat efficiency of 50 % can be easily achieved. The generated electricity can be fed into the grid and the co-generated heat can be sold to a heat consumer located nearby the landfill. However this is not always possible since landfills are located in remote areas without many activities nearby. The economics of power generation from LFG are considerably improved in the case that power and heat are co-produced. Current feed-in tariffs for power generated from LFG and fed into the grid in Crete is at 0.09945 €/KWh_{el}. Current price for heat is estimated in Crete at 0.06 €/KWh_{th}. Since the landfills in the island are located in surrounding areas suitable for the creation of greenhouses, they can profit from their operation since they will have access to a rather cheap heat source. Various technologies which can be used for power generation from LFG are presented in table 2.

Table 2: Different technologies for power generation or co-generation of heat and power from LFG

Technology type	**Use**
Internal combustion engine	Most common
Gas turbine	Common
Steam turbine	limited
Stirling engine	Very limited in commercial scale
Fuel cells	Very limited in commercial scale

6. Use of LFG for heating greenhouses in Crete-Greece

LFG can be used for heating greenhouses which could be created nearby the existing landfills since the surrounding land is suitable for these cultivations. In achieving that, biogas can either be used only for heating purposes or it can be used for CHP and the produced heat to be used for heating them. The economics and the technologies used in those two cases are different. Since a renewable fuel is generated from organic wastes and it is used afterwards for energy generation and crops production, it results in energy recycle in a sustainable way. Various different processes are interwoven including organic wastes digestion with biogas production, power and heat generation from the biogas, power fed to the grid and use of the produced heat for food or flowers production.

6.1 Use of LFG for heat generation and use of the produced heat in greenhouses

Direct burning of the LFG requires simple technology and the produced heat can be used for heating greenhouses. The burnt gases can also be reused after treatment for enriching the greenhouse atmosphere with CO_2 which will result in higher crops productivity. The area of the greenhouses which can be heated in this case is presented in table 3.

Table 3. Area of greenhouses which can be heated after LFG burning from the existing landfills in Crete

Landfill	Energy content of the recovered biogas (Kcal/year)	Usefull heat after burning of biogas (Kcal/year)	Heating needs of greenhouses (Kcal/hectare year)	Area of greenhouses which can be heated (Hectares)
Landfill in Heraklion	$4.8x10^{10}$	$3.84x10^{10}$	$1.89x10^{9}$	20.3
Landfill in Chania, cell 1	$3.7x10^{9}$	$2.96\ x10^{9}$	$1.89x10^{9}$	1.57
Landfill in Chania, cell 2	$6x10^{9}$	$4.8x10^{9}$	$1.89x10^{9}$	2.54
Total	$5.77x10^{10}$	$46.16\ x10^{10}$		24.41

Efficiency of biogas burning for direct heat production 80 %

6.2 Use of LFG for CHP and use of the produced heat in greenhouses

Co-generation of heat and power using LFG has the advantage that the generated electricity can be fed into the grid and the co-produced heat can be used for heating greenhouses which can be created nearby the landfills. Taking into account that the electric efficiency of the CHP plant will be 25 % and the heat efficiency 50 %, the area of the greenhouses which could be heated is presented in table 4.

Table 4. Area of greenhouses which can be heated with the heat produced in the CHP plants using LFG of the existing landfills in Crete

Landfill	Energy content of the recovered biogas (Kcal/year)	Generated heat from the CHP plant (Kcal/year) [1]	Generated electricity from the CHP plant (GWh/year)[2]	Heating needs of greenhouses (Kcal/hectare year)	Area of greenhouses which can be heated (Hectares)
Landfill in Heraklion	$4.8x10^{10}$	$2.4\ x10^{10}$	13.92	$1.89x10^{9}$	12.7
Landfill in Chania,	$3.7\ x10^{9}$	$1.85\ x10^{9}$	1.07	$1.89x10^{9}$	0.98

cell 1					
Landfill in Chania, cell 2	6 x10^9	3 x10^9	1.74	1.89x10^9	1.72
Total	5.77 x10^{10}	28.8x10^{10}	16.73		15.4

[1] Heat efficiency 50 %, [2] Power efficiency 25 %

7. Environmental considerations

It is estimated that methane landfills emissions correspond at 13 % of the total antropogenic methane emissions (Themelis et al, 2007). Since methane has 23 times the global warming potential of CO_2, it is concluded that the warming potential of biogas emitted from the existing landfills in Crete is significant. Assuming that the methane concentration in biogas is 50 % and the methane density is 0.714 kg/NM^3 it is concluded that methane production in the landfills in Crete is 5,033.7 tons/year and it has the global warming potential of 115,775 tons CO_2 annually.

8. Conclusions

Modern and well equipped greenhouses are energy intensive crops production systems. Use of renewable energy sources like solar energy, biomass and geothermal energy for heat and power generation in them can improve their sustainability and profitability as well. Various sustainable energy technologies are currently reliable, mature and cost effective and they can be used for energy generation in agricultural greenhouses. The existing two landfills in Crete, in Prefectures of Chania and Heraklion, produce biogas which is not currently used for energy generation although its value is relatively high. Both landfills produce approx. 92 % of the biogas production in Crete and the rest is produced in the two sewage treatment plants in Chania and Heraklio. LFG can be used for power generation which can be fed into the grid with attractive feed-in tariffs. However the possibility of CHP from LFG and the use of co-produced heat for heating greenhouses can improve the process economics compared with power generation only, provided that the heat can be consumed locally. Alternatively, LFG can be used for direct heat production, if a large heat consumer like a greenhouse located nearby the landfill could utilize the produced heat. Fortunately, both landfills in Crete are located in surrounding agricultural areas where greenhouses can be created. The landfill in Heraklion produces almost five times more biogas than the landfill in Chania and its direct heat production can be used for heating of 20.3 hectares of greenhouses. Biogas from the landfill in Chania can be used for heating of 4.11 hectares of greenhouses. In the case that LFG is used for CHP, Heraklion landfill can generate 13.92 GWh/year electricity and enough heat for heating 12.7 hectares of greenhouses. LFG from Chania s landfill can generate 2.81 GWh/year electricity and enough heat for heating 2.7 hectares of greenhouses. Recycle of the cleaned burnt gases in the greenhouse atmosphere will result in additional benefits due to higher crops productivity. Future use of LFG for energy generation in Crete apart from economic benefits will result in environmental benefits, since the global warming potential of CH_4 is much higher than CO_2.

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ANNEX 2: Additional published work by the author

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