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Application of Distributed Electricity Generation Systems in Agricultural Greenhouses

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Abstract

Use of distributed electricity generation systems is currently increasing due to their economic and environmental benefits. Agricultural greenhouses require heat and electricity for covering their energy needs while their annual energy requirements vary significantly. Aim of the current work is the investigation of applying various distributed electricity generation systems in greenhouses. A review of different distributed generation systems currently used in various sectors as well as in greenhouses has been implemented. Various technologies are examined utilizing either renewable energies or fossil fuels in very efficient energy systems. Most of them are mature and cost-effective having lower environmental impacts compared with traditional centralized electricity generation technologies. Their use in greenhouses results in many benefits including the creation of an additional income for the farmer, reduction of carbon emissions into the atmosphere and increasing stability of the electric grid. It is suggested that distributed electricity generation systems should be used more in greenhouses when the necessary conditions are favorable.

Keywords: Agricultural greenhouses; Electricity; Distributed electricity generation systems; Renewable energies; High efficiency energy technologies; Co-generation systems.

1. Introduction

Distributed electricity generation (DEG) systems are currently expanding worldwide due to their benefits compared to traditional centralized generation systems. They often utilize either locally available renewable energies (RE) or conventional fuels in very efficient energy technologies. Their integration into the grid increases its stability while the use of RE reduces the consumption of fossil fuels and the greenhouse gas (GHG) emissions into the atmosphere as well as the grid's self-sufficiency. Current work investigates the use of various distributed electricity generation (DEG) systems in agricultural greenhouses which, in that case, could co-produce energy and food. DEG and co-generation of heat and power (CHP) could cover the electricity and heating needs of greenhouses while any surplus electricity could be sold into the grid with the net-metering regulations or with pre-agreed feed-in tariffs. DEG systems could be used in small size greenhouses, at 0.2-1 ha, with solar photovoltaic (solar-PV) technologies and in larger greenhouses, at 5-20 ha, with CHP systems. Our work indicates the way that greenhouse owners could achieve an additional income to traditional food production utilizing mature, reliable and cost-effective sustainable energy technologies to generate energy in their installations contributing in the global effort to climate change mitigation.

2. Literature Survey

2.1. Energy Consumption in Agricultural Greenhouses

Hatirli, *et al.* [1], have estimated the energy input in greenhouse tomato production in Antalya, Turkey. Their calculations were based on face to face surveys with growers. The authors mentioned that the electricity consumption in the greenhouses was at 4.75 KWh/m^2. Canakci and Akinci [2], have studied the energy use in greenhouse's vegetable production in 101 greenhouse farms located in Antalya, Turkey. The authors mentioned that their annual electricity consumption varied between 0.35 KWh/m^2 to 0.47 KWh/m^2 for different cultivated vegetables (tomato, cucumbers, eggplants and peppers). Yildirim and Bilir [3], have evaluated a hybrid energy system, consisted of a solar-PV system generating electricity and a ground source heat pump producing heat and cooling for an agricultural greenhouse used for tomato, cucumber and lettuce cultivation located in Izmir Turkey. The authors mentioned that the annual electricity consumption in the greenhouse was 8.96 KWh/m^2 while its needs for heating and cooling were between 128.33 KWh/m^2 and 156.33 KWh/m^2. Hassanien, *et al.* [4], have investigated the solar energy applications in greenhouses. The authors reviewed the use of solar thermal energy and solar-PV energy in covering their needs in heating, cooling and electricity. They mentioned that according to published research the annual energy consumption in greenhouses for heating, cooling, lighting and operation of electric devices in various countries varies between 0.1 KWh/m^2 and 528 KWh/m^2. Vourdoubas [5], has studied the use of REs for heating agricultural greenhouses with reference a greenhouse cultivated with flowers in the island of Crete, Greece. The author mentioned that the heating energy had a high share in the total energy consumption at 95.31% while solid biomass (olive kernel wood) was used as heating fuel. He also stated that the indoor temperature in the greenhouse was kept at approximately 20^{o}C all over the year while its annual total specific energy consumption was 328 KWh/m^2.

2.2. Distributed Electricity Generation Technologies

Hidayatullah, *et al.* [6], have studied the influence of DEG systems and smart grid technologies (SGTs) in future changes of the electricity sector. The authors mentioned that new challenges have appeared concerning climate change, increasing energy prices, energy security and energy efficiency changing the way that energy is produced, delivered and utilized. In the new emerging scenery DG systems and SGTs, they stated, are going to have an important role. Ali, *et al.* [7], have overviewed the current micro-grid policies in EU, USA and China. The authors mentioned that DG systems using REs combined with smart distribution grids result in many benefits regarding the current environmental, technical, social and economic problems and challenges. They stated that appropriate micro-grid policies and incentives are needed for the promotion of DG systems using locally available REs. Lahoud, *et al.* [8] have reviewed the co-generation and tri-generation systems. The authors stated that these systems can contribute to the reduction of primary energy consumption and greenhouse gas emissions. They also mentioned that tri-generation systems are characterized by very high energy efficiency, at 80-90%, while they have positive technical and environmental impacts. Colantoni, *et al.* [9], have analyzed a small scale Organic Rankine Cycle tri-generation system powered by biomass located in Central Italy. The authors mentioned that olive pomace was a satisfactory fuel for the abovementioned energy system generating electricity, heat and cooling while its electrical efficiency varied from 12.7% to 19.4%. Huang, *et al.* [10], have overviewed the fuel cell (FC) technology for DG. The authors stated that FCs are attracting more attention due to their high efficiency and low environmental impacts. They also mentioned that they will play an important role in DG in the future provided that their current high capital costs will be reduced. Moroni, *et al.* [11] have studied the concepts of local energy communities and distributed energy generation. The authors stated that these two concepts have created a global consensus among scholars and politicians. However, they mentioned, there are profound differences in the interpretation and evaluation of these two issues which should be taken into account in the creation of new policies fostering both of them. Suberu, *et al.* [12], have studied the application of REs, DG and micro-grids in rural electrification. The authors mentioned that the use of distributed energy generation using locally available REs could assist in the sustainable electrification of rural areas in developing countries which lack access to grid electricity**.** Hansen and Bower [13]**,** have evaluated the small-scale DEG technologies. The authors mentioned that numerous renewable and small scale DG technologies are currently economically and technically viable. These technologies could be used providing electricity in rural areas in developing countries where many people are without access to grid-connected power. Paliwal, *et al.* [14]**,** have reviewed the technology, objectives and techniques of grid integrated distributed generators. The authors stated that the world faces the transition from the current centralized electricity generation paradigm to a new model characterized from higher share of DG. They mentioned that DG planning is mainly based on conventional fuels use rather than on REs. Integration of REs in DG should take into account their stochastic nature. Purchala, *et al.* [15], have studied the integration of DG into the grid. The authors stated that DG is often used to depict a small-scale electricity generation while it is perceived as a technology with environmental, economic and energy security benefits. They also mentioned that DG in Europe consists mainly of wind power and CHP systems. Chow, *et al.* [16], have reviewed the solar-PV and thermal power generation. The authors stated that hybrid photovoltaic/thermal (PV/T) collector systems have been studied in depth during the past decades. They also mentioned that despite the increase of research and development activities commercial products and real system applications are still limited.

2.3. Applications of Distributed Electricity Generation Technologies in Greenhouses

Tataraki, *et al.* [17], have studied the CHP economics for greenhouses in Europe. The authors mentioned that co-generation is a cost-effective technology and modern greenhouses are considered one of the best applications for it due to their high energy intensity. They also stated that the most favorable conditions for CHP were found in Italy and in U.K. while it is an attractive technology option for Mediterranean greenhouses. Shahbazi, *et al.* [18], have investigated the use of wind turbines for covering the electricity requirements in greenhouses with reference Tehran province, Iran. The authors stated that Firoozkouh region had the highest energy density at 142.51 KW/m^2, while the power requirements in greenhouses were 11 KW/ha. They concluded that wind energy could cover part or all of the electricity requirements in greenhouses. Vourdoubas [19], has studied the use of FCs for energy generation in greenhouses with reference the island of Crete, Greece. The energy system was consisted of a FC powered by H_2 produced with water electrolysis and the use of solar-PV electricity. The author estimated that the overall energy efficiency of the hybrid system was low at 11.11% concluding that it is not appropriate for commercial greenhouses but probably only for stand-alone greenhouses located in areas without electric grid infrastructure. Ganguly, *et al.* [20], have analyzed the use of a hybrid energy system in a floriculture greenhouse located in Kolkata, India. The energy system was consisted of a solar-PV system, a water electrolyzer and a polymer electrolyte membrane FC. The authors concluded that this system could support the energy requirements of grid independent stand-alone greenhouses. Aschilean, *et al.* [21], have studied an energy system based on REs for covering the electricity and heat requirements in agricultural greenhouses. The hybrid energy system was consisted of solar-PV panels, a water electrolyzer unit and a PEM FC. The greenhouse was heated with solar thermal energy and solid biomass. The authors mentioned that the use of green energy, which is currently underexploited, would result in the increase of greenhouses' sustainability. Acosta-Silva, *et al.* [22], have studied the applications of solar and wind energy in agriculture. The authors mentioned that energy is one of the largest overhead costs in the production of greenhouse crops. They also stated that the use of solar and wind energy systems reduces the fuel consumption and enhances the sustainability of greenhouse production. Liu, *et al.* [23], have studied the use of clean energy for electricity generation in agriculture. The authors analyzed the feasibility and the advantages of coupling clean energy with agriculture. They stated that excess clean energy, including solar electricity, could be utilized in agriculture reducing environmental pollution and improving energy efficiency. Tataraki, *et al.* [24], have studied the use of CHP systems for covering the energy needs in greenhouses. The authors stated that the combined use of a cooling, heating and electricity generation system with a gas boiler for heating is profitable for tomato cultivation. They estimated that the return of the energy investments in tomato' greenhouses located in North, Central and South Greece was 23%, 28% and 27% respectively. Wonder-plant Company is producing tomato in hydroponic greenhouses located in Northern Greece. The greenhouse's covered area is 15 ha and it is heated with heat produced by the CHP system while the co-generated electricity is partly used in the greenhouse and the excess is sold into the grid. Vourdoubas [25], has investigated the co-production of vegetables and electricity in agricultural greenhouses located in Crete, Greece. The author estimated that semi-transparent solar-PV panels covering 15% of the rooftop surface of the greenhouse could generate 16.8 KWh/m^2, while their installation cost is at 25 $€/m^2$. He also mentioned that the levelized cost of solar electricity generated is 0.082 €/KWh. Moretti and Marucci [26] have investigated the optimization of agricultural and energy production in a photovoltaic greenhouse. The authors used a mobile regulated solar-PV system placed on the rooftop of the greenhouse in order to control the indoor solar radiation according to climate conditions achieving optimum agricultural production and electricity generation. Wang, *et al.* [27], have studied the integration of solar technology to modern greenhouses in China. The authors stated that the annual energy consumption in Chinese greenhouses varies between 1.5 KWh/m^2 to 235.6 KWh/m^2. They also mentioned that solar integration to modern agricultural greenhouses is a promising prospect in China achieving satisfactory technical performance and attractive payback periods of less than nine years. Anton, *et al.* [28], have assessed the environmental impacts of Dutch tomato production in glass greenhouses. The authors stated that the annual energy consumption in greenhouses has been reported at 695 KWh/m^2 in Germany and at 526 KWh/m^2 in United Kingdom. In Mediterranean countries, with mild climate, the specific energy consumption is lower at 39 KWh/m^2 for tomato production in unheated greenhouses and hydroponic crops and at 3.3 KWh/m^2 for unheated greenhouses and tomato grown in soil. They also mentioned that energy consumption in Dutch greenhouses was the main cause of negative environmental impacts. However the use of CHP systems, consuming natural gas, compensates the negative impacts due to the large amounts of co-generated electricity sent into the grid. Aroca-Delgado, *et al.* [29], have studied the compatibility between crops and solar panels regarding the shading effect. The authors reviewed the existing literature stating that the countries having the highest number of publications concerning solar panels and crops were Italy, Spain and Japan. They concluded that further technological development of solar-PV systems is required in order to make their use in greenhouses more economically viable.

Aim of the current work is the review of various distributed electricity generation systems which could be used in agricultural greenhouses.

Initially the existing literature is surveyed followed by an estimation of energy consumption, for heat, cooling and electricity, in greenhouses. After that the main DG and CHP systems are presented and the possibility of using them in greenhouses is investigated. The findings of the work are discussed followed by the presentation of the conclusions drawn and some proposals for further research.

3. Energy Consumption in Agricultural Greenhouses

Agricultural greenhouses require energy for covering their energy needs in heating, cooling, lighting and operation of various electric devices and machinery. Operational energy consumption depends on the cultivated crop, the local climate and the type of greenhouse construction. Therefore the annual energy consumption in greenhouses varies significantly [4, 27, 28]. Existing studies indicate that their requirements for heating and cooling are significantly higher than their needs for electricity [3, 5]. In various areas including the Mediterranean basin cultivation of various vegetables in traditional low-tech greenhouses do not require heating due to the mild local climate. The most common energy and fuels currently used are grid electricity (for lighting, cooling and operation of electric machinery) and heating oil or natural gas (for heating). Use of various renewable energy sources in greenhouses is limited so far. Energy consumption in greenhouses is presented in Table 1.

Table-1. Energy consumption in greenhouses

Author, year, country	Annual electricity consumption (KWh/m^2)	Annual energy consumption for heating and cooling (KWh/m^2)	Total annual energy consumption (KWh/m^2)
Hassanien, *et al.* [4], various countries			0.1 - 528
Wang, *et al.* [27], China			1.5 – 235.6
Vourdoubas [5], Greece			328
Yildirim and Bilir [3], Turkey	8.96	128.33 – 156.33	137.26 – 165.29
Anton, *et al.* [28], Germany			695
Anton, *et al.* [28], U.K.			526
Anton, *et al.* [28], Mediterranean countries	3.3 - 39		
Hatirli, *et al.* [1], Turkey	0.475		
Canakci and Akinci [2], Turkey	0.35 – 0.47		6.6-7.8

Source: Various authors

4. Distributed Electricity Generation Technologies which Could be used in Greenhouses

Various DEG technologies are currently used either for electricity generation or for co-generation of heat and power. Generated electricity could be used in the greenhouse or it could be sold into the electric grid according to net-metering regulations. These technologies utilize either REs or fossil fuels including:

4.1. Solar Photovoltaic Systems

Solar-PV systems are currently used for electricity generation. Depending on the intensity of the solar irradiance these systems are more or less attractive while they could generate part or all of the annual electricity requirements of the grid connected consumer. In many countries it is allowed, according to net-metering regulations, to store the electricity into the grid if the consumer does not need it when it is generated. They are intermittent energy generation systems while their cost has been substantially reduced during the last 15 years. Their average energy efficiency varies between 14-18%. In many areas with high solar irradiance solar-PV systems are cheaper than conventional electricity generation systems using fossil fuels.

4.2. Heat and Power Co-generation Systems

Co-generation systems generate both heat and electricity from the same machine. Their energy efficiency is high at approximately 80-90% while the most often used fuel is natural gas. They are cost-effective and they are currently used in industry, in buildings and in agriculture achieving continuous energy generation. Due to their high energy efficiency and the low carbon fuel used their CO_2 emissions into the atmosphere are low compared with other electricity generation technologies and other fuels used. Alternatively, tri-generation systems use the same technology with co-generation systems but during the summer the co-generated heat is utilized by thermal chillers for cooling production resulting in electricity, heat and cooling generation.

4.3. Fuel Cells

FCs are modern energy generation systems utilizing H_2 or some compounds containing H_2, like CH_3OH or CH_4, for electricity generation with electrochemical processes. They can simultaneously co-generate heat achieving power efficiencies at 40-50% and heat efficiencies at 30-40%. Therefore their overall energy efficiency is very high. Their commercial applications are rather limited due to their high initial cost while in some countries their installation cost is subsidized by the government. The main fuel used is natural gas resulting in low CO_2 emissions into the atmosphere. Alternatively hydrogen can be also utilized in FCs. In the case that the H_2 used is produced with water electrolysis from REs, like solar and wind energy, the carbon emissions during energy generation in the FC are zero.

4.4. Wind Turbines

Wind turbines can be used for electricity generation. Necessary pre-condition for that is the high annual average wind speed at the site of installation. They can generate part or all the electricity requirements in greenhouses. Electricity generated can be sold into the electric grid, according to net-metering regulations, if it is not needed in the greenhouse when it is produced. Wind turbines require more maintenance than solar-PVs and their applications in greenhouses are still limited.

4.5. Solid Biomass and Biogas use

Biogas, like natural gas, can be used for electricity generation in greenhouses while the co-produced heat can be also used for covering part of their heating needs. Biogas production by anaerobic digestion of organic wastes is currently technically and economically feasible and this fuel is currently used for energy generation or CHP. Additionally solid biomass could be used for CHP in greenhouses although its applications are limited so far. Various characteristics of distributed electricity generation technologies which could be used in greenhouses are presented in Table 2.

Table-2. Characteristics of the abovementioned distributed electricity generation systems

Technology used	Total energy efficiency	CO_2 emissions	Existing commercial applications in various sectors	Existing commercial applications in greenhouses
Photovoltaic panels	14-18%	zero	Yes	Yes, few
Wind turbines	Low depending on the average annual wind speed	zero	Yes	No
Biogas or solid biomass burning and steam to power engines	70-80%	zero	Yes	No
Electrochemical generation-fuel cells	70-80%	Low or zero (if H_2 is used)	Only few	No
Gas engines or other CHP technologies	80-90%	Low	Yes	Yes, many

Source: Own estimations

5. Applications of Distributed Generation Technologies in Greenhouses

Various DEG systems based either in REs or in very efficient energy technologies could be used in greenhouses reducing their conventional energy and fuel consumption and their carbon footprint. Their use is desirable since they increase their energy security and self-sufficiency while they result in many benefits for the electric grid. Taking into account that greenhouses require large amounts of heat energy for space heating the use of CHP systems could cover a significant part of their heat and electricity requirements. For financing the required energy investments greenhouses could utilize new financial tools including third party financing and public private partnerships. An energy saving company (ESCO) could design, finance and implement the energy investments resulting in benefits both to the greenhouse owner and to the ESCO. The DEG systems which could be used in greenhouses depend on the availability of the energy source and the fuel, the maturity and the cost of the energy technologies and the possibility of achieving financial support by public subsidies. The sustainable energy systems which could be used in greenhouses include:

a) Renewable energy systems like solar-PV, small wind turbine systems and systems based in solid biomass and biogas burning, and
b) High efficiency energy systems like heat and power co-generation systems, heat, cooling and power tri-generation systems and fuel cells using conventional fuels like natural gas or even hydrogen. Their overall efficiency in heat and power generation is in the range of 80-90 %. The co-generated heat and cooling could be also used in the greenhouse.

The main factors which should be taken into account for the application of DG systems in greenhouses are:

1. Energy requirements (heat, cooling, electricity) in the greenhouse,
2. Availability of the energy source (solar energy, wind energy, biomass) or the fuel (natural gas, hydrogen) in the location of the greenhouse,
3. Legal regulations regarding the possibility of selling surplus electricity generated by the DEG system into the grid,
4. Financial support offered by the government for the promotion of some sustainable energy technologies, and
5. Possibility of having local technical support in the installation, operation and maintenance of the energy system.

The DG systems which could be used in greenhouses are presented in Table 3.

Table-3. Distributed generation technologies which could be used in greenhouses

Distributed electricity generation technology	Energy/fuel used	Generated energy	Technology efficiency	Continuous/Intermittent generation
Solar-PV	Solar	Electricity	15-18%	Intermittent
Wind turbine	Wind	Electricity	Depends on the wind speed	Intermittent
Solid biomass/biogas burning	Biomass	Electricity/heat	70-80%	Continuous
Fuel cell	Hydrogen, natural gas	Electricity/heat	80-85%	Continuous
Co-generation of heat and power	Natural gas	Electricity/heat	80-85%	Continuous

Source: Own estimations

6. Discussion

Our results indicate that various DEG technologies, using either REs or conventional fuels, could be used in agricultural greenhouses. Some of them are appropriate for small size greenhouses while others for larger size production systems. Their application depends on a) the local availability of the energy source (solar energy, wind energy, biomass) and the fuels, b) the greenhouse requirements in electricity and heat, c) the possibility of selling any surplus electricity into the grid according to the existing regulations, d) the possibility of co-producing heat and using it in the greenhouse, and e) the cost-effectiveness of the technology as well as the possibility of receiving financial support for the energy investment. Our results are useful for greenhouse owners since they indicate that they could have an additional income to the crop production due to energy generation in their greenhouses. They are also useful for local authorities since the use of sustainable energy technologies in DEG systems results in lower CO_2 emissions into the atmosphere, in increased utilization of local energy resources and in higher grid stability. The results do not indicate under which circumstances DEG technologies could be used in greenhouses. Farmers installing DEG systems in their greenhouses could participate in local energy communities and cooperatives promoting collectively with other professionals and households the exploitation of locally available renewable energy resources.

7. Conclusions

Greenhouses require energy for their heating, cooling, lighting and operation of electric machinery. The most of their annual energy consumption is related with their heating. Application of various DEG technologies in agricultural greenhouses has been investigated. These sustainable energy systems could cover the electricity requirements of greenhouses selling any surplus electricity into the grid according to the existing regulations. Use of co-generation technologies in greenhouses could additionally cover part or all of their heating needs. DEG technologies could utilize locally available REs or fossil fuels like natural gas. The most of them are mature, reliable and cost effective while others, like the FCs, need financial support for entering into the market. These energy technologies include solar-PV systems, wind turbines, solid biomass and biogas burning systems, various CHP systems and FCs. Some of them, like co-generation systems, are already used in greenhouses while others, like solar-PVs, are expected to have increasing applications in the future. Energy generation in greenhouses results in additional economic benefit for the growers. The use of locally available REs results in lower fossil fuel utilization as well as in less CO_2 emissions into the atmosphere. Use of DEG technologies in greenhouses reduces the carbon footprint of agriculture contributing in the global effort for climate change mitigation. At the same time the stability of the electric grid is increased. Further work should be focused in the implementation of various case studies regarding the use the abovementioned DEG technologies in greenhouses.

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