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# Evaluation of a hybrid system for a nearly zero energy greenhouse

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## ABSTRACT

Greenhouses are widely used in the World, especially in the Mediterranean climate, to provide suitable environment in cultivation of different agricultural crops. Significant amount of energy is necessary to produce, process and distribute these crops. Various systems, including steam or hot water radiation system and hot air heater system, are being used in greenhouse heating. A ground source heat pump system, generally seen as a favorable option since it can provide both heating and cooling energy, is considered for a greenhouse in this study. The aim of this study is to evaluate a renewable energy option for the required total energy need of a greenhouse. Grid connected solar photovoltaic panels are selected to assist a ground source heat pump, and generate sufficient electrical energy for lighting. In this way, a nearly zero energy greenhouse concept is foreseen for three different agricultural products. Monthly and annual heating, cooling and lighting energy load of the greenhouse for these agricultural products were computed. The monthly average electricity generation of 66 photovoltaic panels, which cover 50% of the southern face part of the asymmetric roof, was calculated. Annual photovoltaic electricity generation was found as 21510.4 kWh. It was observed that photovoltaic electricity generation can meet 33.2–67.2% of greenhouse demand in summer operation months. Nevertheless, the coverage ratio, calculated by dividing the photovoltaic panels electricity generation to the electricity demand of the greenhouse (heating, cooling and lighting) for each crop, were very high in winter operation months. Yearly coverage ratio values were 95.7% for tomato, 86.8% for cucumber and 104.5% for lettuce. These high coverage ratio values justify the nearly zero energy concept for the considered greenhouse. Economic and environmental evaluation of the considered system were also accomplished. A simple payback time of the crop cultivations was computed between 7.0 and 7.4 years. The energy payback time of the system was found to be 4.9 years and the greenhouse gas payback time value of 5.7 years and 2.6 years were calculated, based on natural gas and coal based electricity generation, respectively.

## 1. Introduction

Greenhouses make it possible to grow crops even in inappropriate climate conditions. They also provide an extended production season. According to reports of Food and Agriculture Organization of United Nations (FAO), worldwide total area of greenhouses is 1.2 million hectare [1]. Most of these greenhouses are in the Mediterranean basin. Greenhouses are widely used in Turkey, which is also located in the Mediterranean basin. The total greenhouse area of Turkey increased from 599,000 decare in 2011 to 649,118 decare in 2014 and the total yearly crop production in the same year reached 6.6 million tons with a half million tons increase compared to 2011 [1,2]. Indoor air conditions can be controlled and adjusted in greenhouses for the desired crops. This control makes a very suitable environment for the cultivated crop, but naturally requires an energy consumption. The control of the indoor conditions is another aspect of energy analysis. Graditi et al. [3] investigated the control logics for the electrical load and air conditioning systems. Siano et al. [4] proposed an innovative decision support and energy management system in terms of electricity supply continuity and economics. Providing adequate energy to a greenhouse results in achieving good quality and reduced cultivation time for products. Heating and cooling systems are needed for optimal temperature control according to the location of the greenhouse. Various systems, including steam or hot water radiation system and hot air heater system, are being used in greenhouse heating. Generally, fossil fuels are used in greenhouses for this purpose. Nevertheless, the geothermal renewable alternative is the best solution to provide sufficient heating to greenhouses. İzmir city has the largest greenhouse area of 1200 decare, which is heated with geothermal. This value represents 40% share in total 3000 decare geothermal heated greenhouse area of Turkey [1]. Additionally, especially in hot climates there may also be cooling requirement

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## Nomenclature

| | |
|---|---|
| $C_g$ | grid injection unit electricity price (Euro/kWh) |
| $C_{s\text{-}c}$ | self-consumption unit electricity price (Euro/kWh) |
| COP | coefficient of the performance (–) |
| $E_{BOS,E}$ | embodied energy of the BOS (kWh) |
| $E_{BOS,other}$ | embodied energy of other of BOS (kWh) |
| $E_{BOS,PI}$ | embodied energy of inverter production of BOS (kWh) |
| $E_{BOS,SS}$ | embodied energy of supporting structure of BOS (kWh) |
| $E_D$ | decommissioning and disposal or other end-of-life energy requirements of PV panels (kWh) |
| $E_F$ | embodied energy of PV module fabrication (kWh) |
| $E_g$ | annual electricity exported into the grid (kWh) |
| $\bar{E}_i$ | monthly average hourly electrical output (kWh) |
| $E_{output}$ | annual electricity generation of the PV system (kWh) |
| $E_P$ | embodied energy of silicon purification and processing (kWh) |
| $E_S$ | embodied energy of silicon ingot slicing (kWh) |
| $E_{s\text{-}c}$ | annual self-consumption electricity (kWh) |
| $E_{S,E}$ | embodied energy of the PV system (kWh) |
| $E_T$ | energy to transport PV modules from factory to installation site (kWh) |
| EER | energy efficiency ratio (Btu/kWh) |
| $G_{sc}$ | solar constant (W/m$^2$) |
| $GHG_{BOS}$ | embodied GHG of BOS (kg $CO_{2,eq}$) |
| $GHG_S$ | embodied GHG of PV system (kg $CO_{2,eq}$) |
| $GHG_{output}$ | annual GHG produced by the local power plant for the power generated by the PV system (kg $CO_{2,eq}$) |
| h | specific enthalpy (kJ/kg) |
| $\bar{H}$ | monthly average daily radiation incident on the PV panel (Wh/m$^2$) |
| $\frac{\bar{H}_d}{\bar{H}}$ | monthly fraction that is diffuse (–) |
| $\bar{H}_o$ | monthly mean daily extraterrestrial radiation (Wh/m$^2$) |
| I | annual insurance cost of the PV system (Euro) |
| $\bar{I}_T$ | monthly average hourly radiation incident on the tilted PV panel (W/m$^2$) |
| k | Ross coefficient (Km$^2$/W) |
| $\bar{K}_T$ | monthly average clearness index (–) |
| n | representative day number for the relevant month (–) |
| O&M | annual operation and maintenance cost of the PV system (Euro) |

| | |
|---|---|
| q | unit heat (kJ/kg) |
| $Q_{cooling,i}$ | cooling demand of the greenhouse for month i (kWh) |
| $Q_{heating,i}$ | heating demand of the greenhouse for month i (kWh) |
| $R_b$ | the ratio of beam radiation on the tilted surface to that on a horizontal surface for a collector directed to south (–) |
| $r_d$ | the ratio of hourly diffuse to daily diffuse radiation (–) |
| $r_t$ | ratio of hourly total to daily total radiation (–) |
| SCOP | seasonal coefficient of performance (–) |
| SEER | seasonal efficiency ratio (Btu/kWh) |
| $T_a$ | ambient temperature (°C) |
| $\bar{T}_a$ | monthly average hourly outdoor temperature (°C) |
| $T_c$ | cell temperature (°C) |
| $T_{ref}$ | reference temperature (°C) |
| $W_{overall-c,i}$ | electricity consumption of GSHP system in cooling mode for month i (kWh) |
| $W_{overall-h,i}$ | electricity consumption of GSHP system in heating mode for month i (kWh) |

*Greek letters*

| | |
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| $\beta$ | slope angle of the PV panel (°) |
| $\delta$ | declination angle (°) |
| $\eta_e$ | efficiency of any power-conditioning equipment (%) |
| $\bar{\eta}_i$ | the monthly average PV efficiency for the hour i (%) |
| $\mu_{mp}$ | temperature coefficient of maximum power point efficiency (%/°C) |
| $\eta_{mp,ref}$ | reference maximum power efficiency (%) |
| $\rho_g$ | ground reflectivity (–) |
| $\phi$ | latitude (°) |
| $w$ | hour angle (°), unit compressor work (kJ/kg) |
| $w_s$ | sunset hour angle (°) |

*Abbreviations*

| | |
|---|---|
| ac | air change |
| BOS | balance of system |
| comp | compressor |
| cond | condenser |
| elec | electric |
| evap | evaporator |

for the optimum indoor thermal conditions for the considered products. Ground source heat pump (GSHP) systems are generally seen as a favorable option since they can provide both heating and cooling energy. Several studies indicate that about 60–70% of the energy supplied by a GSHP is extracted from the ground. The use of a heat pump instead of a conventional system can provide a 20–50% energy saving [5]. The use of renewable sources for the energy need of greenhouses is obviously advantageous for environment and they are less costly compared to fossil fuels in most cases. Photovoltaic panels (PVs) are very adequate in supplying electricity to greenhouses using solar energy. This electrical energy can be used to operate a heat pump to supply the required heating or cooling during a year. The use of PVs are very widespread in net zero energy building (NZEB) concept. Li et al. [6] made a review about zero energy buildings and the use of renewables, including PVs and heat pumps for buildings was evaluated. Scognamiglio et al. [7] investigated the use of PVs for net zero energy buildings and clusters. Deng et al. [8] performed also a review for the performance evaluation of NZEBs. They considered renewable source heat pump option among other energy efficient measures for NZEBs. In this study, the evaluated greenhouse was tried to become nearly zero energy building by the use of a hybrid system consisting of PVs and a GSHP. The use of greenhouses for the cultivation of various crops is widespread in many countries and there are many studies investigating their energy need as well as the use of renewables to meet their energy requirement. Al-Ibrahim et al. [9] took into consideration a 14.72 kW photovoltaic system to be used in meeting the cooling and pumping energy need of a 350 m$^2$ greenhouse in Saudi Arabia. They reported that the system met the required electrical energy need of the greenhouse satisfactorily. Nayak and Tiwari [10] evaluated a system consisting of PV/T and an earth air heat exchanger for a greenhouse in New Delhi, India. They reported that when PV/T system is operated during daytime and coupled with earth air heat exchanger at night, the air temperature inside the greenhouse can be heated about 7–8 °C. Three different shaped greenhouses were taken into consideration and a software, which calculates their dynamic loads, was developed by Rodriguez et al. [11]. The software can simulate a great number of scenarios and demonstrate the behavior of a greenhouse for four different locations and four seasons. Sanchez et al. [12] analyzed tomato cultivation inside a greenhouse with roof-mounted flexible PVs in Almeida, Spain. They compared the quality of tomato production for two different PV arrangements. They stated that different PV arrangement did not affect negatively