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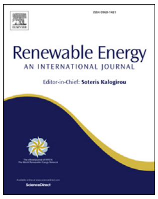

Thermal energy assessment of a small scale photovoltaic, hydrogen and geothermal stand-alone system for greenhouse heating

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ABSTRACT

This experimental study shows the results of an analysis of the performance of a stand-alone renewable energy system for greenhouse heating on a winter day. The systems consist of photovoltaic panels connected to an electrolyzer which during daylight hours produce hydrogen by electrolysis and then store it in a pressure tank. During the night, thanks to a fuel cell, the hydrogen is converted into electricity in order to feed a ground source geothermal heat pump to heat a tunnel greenhouse. The procedure for estimating hourly solar radiation, hydrogen production and consumption for short-term energy storage on a partly cloudy day is also given. The solar energy usability concept, the capacity of energy storage systems and the thermal energy load govern the effective energy management of the system. This performance analysis is necessary to determine the actual total efficiency of integrated photovoltaic, geothermal and hydrogen renewable energy systems and their contribution to the load. The overall system efficiency obtained, starting from the amount of solar energy available during daylight hours until it is used as thermal energy at night, was 11%.

1. Introduction

The current rise of floricultural and horticultural crops in a protected environment, mainly due to market factors and to increased demand for organic products, is the basis of the significant increase of energy consumption for greenhouse climate control [26]. Diesel, LPG and natural gas are generally used as fuel in heating greenhouses and, though the use of renewable energy can improve the sustainability of crops in a protected environment, these still play a niche role in the energy panorama due to the non-simultaneity of energy production during daylight hours compared to the energy required by night [8]. The scientific community is testing new energy storage technologies, such as new batteries with very high efficiency, re-pumping water into elevated water storage systems, boilers powered by solar thermal systems, underground heat storage techniques, hybrid PV/T collectors and systems, phase change material [11], and energy-efficient heat pumps coupled with geothermal boreholes [4]. An interesting solution consists in the conversion of solar energy into hydrogen in order to implement a totally renewable and stand-alone system for greenhouse heating [6,22,23,25,27]. In this respect, geothermal heating systems are economically advantageous, as they have a lower environmental impact in the agricultural sector especially for greenhouse heating [21]. Different processes can generate hydrogen, but hydrogen is produced worldwide from fossil sources employing coal gasification or natural gas reforming process. Water electrolysis is the only method without carbon dioxide emissions into the atmosphere and generates “zero emissions” if the electricity necessary for electrolysis is produced from renewable sources. The incorporation of an efficient and suitable vector as a secondary power supply also means reducing consumption of imported liquid fossil fuels and therefore a reduction of environmental pollution [5,24].

We present an hourly model that we have implemented to analyze the performance of a photovoltaic array connected to an electrolyzer that during daylight hours produces hydrogen by electrolysis and then stores it in a pressure tank. At night, thanks to a fuel cell, the hydrogen is converted into electricity to feed a ground source heat pump (GSHP) with vertical geothermal borehole for heating a tunnel greenhouse. In such a system, performance depends heavily on how weather conditions influence energy production from PV and the energy demand of the greenhouse. The photovoltaic array is highly intermittent on cloudy days

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and features high seasonal variations, thus strongly affecting the work-time of the electrolyzer. The electrolyzer will start and stop its operation depending on the time profile of the energy available from the solar energy sources. Differently, the fuel-cell generator stops as the specific energy level of the batteries is reached. The energy level of batteries depends on the energy demand of the GSHP and therefore on the thermal energy available from the ground and the energy required by the load. As in the case of solar energy for the electrolyzer, the load profile affects the COP of the GSHP, and it, in turn, depends on the weather conditions and temperatures. This study shows that the solar and geothermal energy source performances for stand-alone systems depend on meteorological data, type of electrolyzer and load profile.

2. Materials and methods

The study was carried out at the experimental farm of the University of Bari located in Valenzano, Bari, Italy, where an air-inflated, double layer polyethylene film tunnel greenhouse of 32 m^2 of cover surface (A_{cf})and 16 m^2 of area was heated by a ground source heat pump (GSHP). The electricity generated by 56 m^2 (A_{PV}) of polycrystalline photovoltaic panels (PV), during day time from 08:00 to 18:00, feeds the electrolyzer which, in turn, produces hydrogen gas by water electrolysis. The hydrogen is stored in a pressure tank (Fig. 1) and, when the photovoltaic source is not operating, at night from 19:15 to 07:50, it is used by a fuel cell system that generates electricity for a GSHP to meet the greenhouse heating energy demands when the internal air temperature falls below 20 °C. In particular, the system was composed of polycrystalline photovoltaic panels with peak power of 8.16 kWp, an alkaline electrolyzer with 2.5 kW of electric power in absorption, hydrogen storage tanks with a capacity of 15 Nm^3 and operating pressure of 30 bars, a PEM fuel cell with 2 kWp of peak power, buffer gel batteries with a capacity of 10.8 kWh, a heat pump with thermal power of 0.8 kW and 0.16 kW of electric absorption and a vertical geothermal borehole 120 m deep. The diagram of the plant is shown in Fig. 1 and the specifications of the plant are reported in Table 1. The experimental test was carried out on 1–2 March 2015.

The batteries were used to meet the energy peaks required by the three-phase motor of the heat pump in the scroll start-up phase. The battery, therefore, did not serve for long-term energy storage, as this task was assigned only to the hydrogen storage tank.

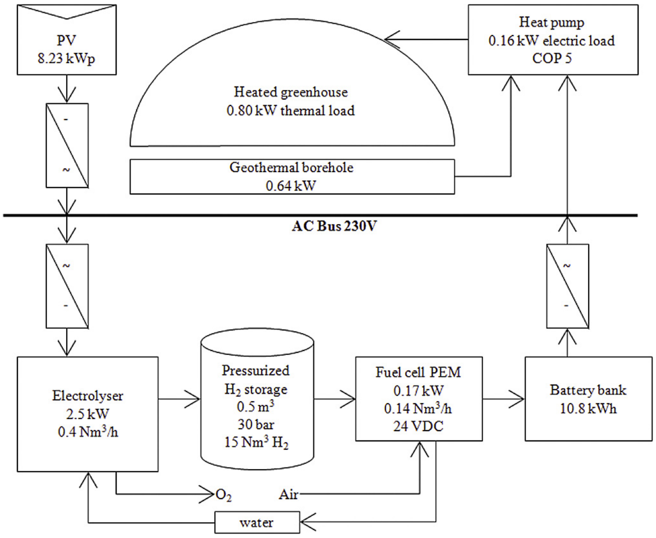

Fig. 1. Stand-alone PV and GSHP system with energy storage as hydrogen.

A nitrogen storage tank is necessary for safety reasons. It is used to wash the hydrogen system in case there is a failure or an emergency.

3. Modeling of the components

3.1. Solar radiation

The first step for assessing the performance of a tilted PV array is to determine solar radiation. Considering the Julian day of the year (j_d) and the time (t) expressed in hours, the hour angle (ω) and the declination angle (δ) in radians are defined as:

$$\omega = \pi \frac{12 - t}{12} \tag{1}$$

$$\delta = \frac{\pi}{180} 23.45 \sin\left[\frac{2\pi}{365}(284 + j_d)\right] \tag{2}$$

the tilt factors for the direct (R_b), diffuse (R_d) and reflected (R_r) part of the solar radiation are defined as Ref. [17]:

$$R_b = \frac{\sin\delta \sin(\phi - \beta) + \cos\delta \cos\omega \cos(\phi - \beta)}{\sin\delta \sin\phi + \cos\delta \cos\omega \cos\phi} \tag{3}$$

$$R_d = \frac{1 + \cos\beta}{2} \quad \textit{and} \quad R_r = \rho \frac{1 - \cos\beta}{2} \tag{4}$$

where φ is the local latitude, ρ the ground reflectivity and β the tilt angle of the PV.

The three components of solar radiation, in W m^{-2}, falling on a tilted array—direct normal solar radiation (I_b), diffuse solar radiation (I_d) and global solar radiation (I_g)—are calculated by the following set of equations:

$$I_0 = H_{sc}\left[1 + 0.033 \cos\left(\frac{2\pi j_d}{365}\right)\right](\sin\phi \sin\delta + \cos\phi \cos\delta \cos\omega) \tag{5}$$

$$k_t = \frac{I_g}{I_0} \quad \textit{and} \quad I_d = I_g(1 - 1.13k_t) \quad \textit{and} \quad I_g = I_b + I_d \tag{6}$$

where H_{sc} = 1367 W m^{-2} is the solar constant, I_0 the extra-terrestrial solar radiation on the horizontal surface and k_t the clearness index.

Finally, the total hourly solar radiation on the tilted PV array (I_T) can be calculated using the following equation:

$$I_T = I_b R_b + I_d R_d + I_g R_r \tag{7}$$

3.2. Photovoltaic array efficiency

The efficiency of the solar cell is defined as Ref. [17]:

$$\eta_{PV} = \eta_r[1 - B(T_c - T_r)] \tag{8}$$

where η_r is the efficiency of the solar cell at a referenced solar radiation (1000 W m^{-2}), T_r the referenced temperature of the cell, B the temperature coefficient of a solar cell, and T_c the solar cell temperature. If T_c is not available, it can be computed from the sum of the instantaneous ambient temperature and the effect of the PV array thermal loss [17]: