IX International Scientific Symposium
"Farm Machinery and Processes Management in Sustainable Agriculture", Lublin, Poland, 2017
DOI: 10.24326/fmpmsa.2017.8

STAND-ALONE PHOTOVOLTAIC AND HYDROGEN PLANT COUPLED WITH A GAS HEAT PUMP FOR GREENHOUSE HEATING

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Keywords: Ground source gas heat pump, photovoltaic-hydrogen plant, Greenhouse heating.

ABSTRACT

In recent years, the increasing interest in energy production from renewable energy sources has led to stand-alone renewable energy plant being developed in agricultural land. In particular, for greenhouses heating, diesel, LPG and natural gas are the main energy sources used. Alternative solutions are represented by the integration of renewable energy plants in off grid configurations. The aims of this research is to analyzed the energy performance of a photovoltaic, hydrogen and ground source gas heat pump integrated stand-alone system during the winter season. The results showed that the system had a total energy efficiency to 13%. The performance of the system was low because the efficiency of the photovoltaic panels was the bottleneck. In fact, starting from the energy available from the PV, the system has an efficiency of 96% if the COP of the heat pump is equal to 4. Finally, the heating system increased the greenhouse air temperature about 8°C respect to the external air temperature.

INTRODUCTION

Nowadays, several research attempts are focus on the micro-generation systems based on renewable energy sources in according with the Near Zero Energy Building (NZEB) concept and the new European Directive 2010/31/CE. However, in agricultural sector, in case biomasses are not available, some attractive solutions are represented by the geothermal heating systems (Anifantis et al., 2016) and stand-alone hydrogen plant (Anifantis et al., 2017). Transforming the solar radiation surplus into electrical energy is of extreme interest due to its double benefit: it solves the problem of excess solar radiation in the greenhouse and produces electricity from renewable sources without negative environmental effects (Marucci et al., 2017). Unfortunately, the energy production and consumption of solar energy for greenhouse requests are non-simultaneity and the electric energy produced during the daylight hours must be stored and reuse in the night. Then, the surplus electricity from wind farms or solar PV farms if not used can be stored using batteries. However, the uncertainties in the cost of batteries are rather wide, even larger than difference in costs between different technologies (Zakeri & Syri, 2015). Alternatively, the electricity can be stored in the form of hydrogen gas, the surplus electricity is used for water electrolysis to generate hydrogen gas that can stored and when electricity is needed, then this hydrogen gas can be used as feedstock for the PEM fuel cells to produce electricity or can be burned in internal combustion engines (ICE) to generate mechanical or electrical energy. Other interesting technologies for energy storage are hydropower generation, flywheels and compressed air energy storage (CAES) (Ghoniem, 2011). In this paper, a photovoltaic and hydrogen stand-alone systems integrated with a ground source gas heat pump (GSGHP) for greenhouse heating was studied. The GSGHP is composed by an internal combustion engine drive shaft connected to a compressor of a geothermal heat pump. The engine was feed by the hydrogen produced by an PEM electrolyzer during the daylight hours. A performance analysis was conducted in order to define the total efficiency and the power production of the integrated system.

MATERIALS AND METHODS

The only behavior of the gas heat pump was mathematical modeled using the technical manuals provided by the manufacturer AISIN (TOYOTA group). Instead the rest of the system components have been analyzed using the data of an hydrogen plant implemented at the experimental farm of the University of Bari, located in Valenzano, Italy. In particularly, the electricity generated by 56 m^2 (A_{PV}) of polycrystalline photovoltaic panels (PV), during day time from 08:30 to 17:30, fed a electrolyzer which produces hydrogen by water electrolysis. The hydrogen was stored in a pressure tank at 30 bar. The ground source gas heat pump heated an air-inflated, double layer polyethylene film tunnel greenhouse of 106 m^2 of cover surface (A_{cf}) and 48 m^2 of area. The diagram of the plant is shown in Fig. 1 and the specifications of the plants are reported in Tab. 1. The experimental test was carried out in a winter day of February.

Table 1. Specifications of two renewable energy hydrogen plant.

Components	Specifications
Photovoltaic array	BYD 240P6-30, 34 module, 8.2 kW peak
Electrolyser	Monopolar alkaline electrolyzer 2.5 kW, 0.4 Nm^3/h – H_2Nitidor S.r.l.
H_2 storage	30 bar, 0.5 m^3
Gas heat pump	Model AXGP224E1 8HP, Aisin (TOYOTA)
Geothermal borehole	120 m vertical double U-bend ground heat exchanger
Fan-coil unit	Carisma CRC53MV, Heating capacities: 3.59 kW; air flow rate 495 m^3/h
Greenhouse	Air inflated, double layer polyethylene film tunnel greenhouse

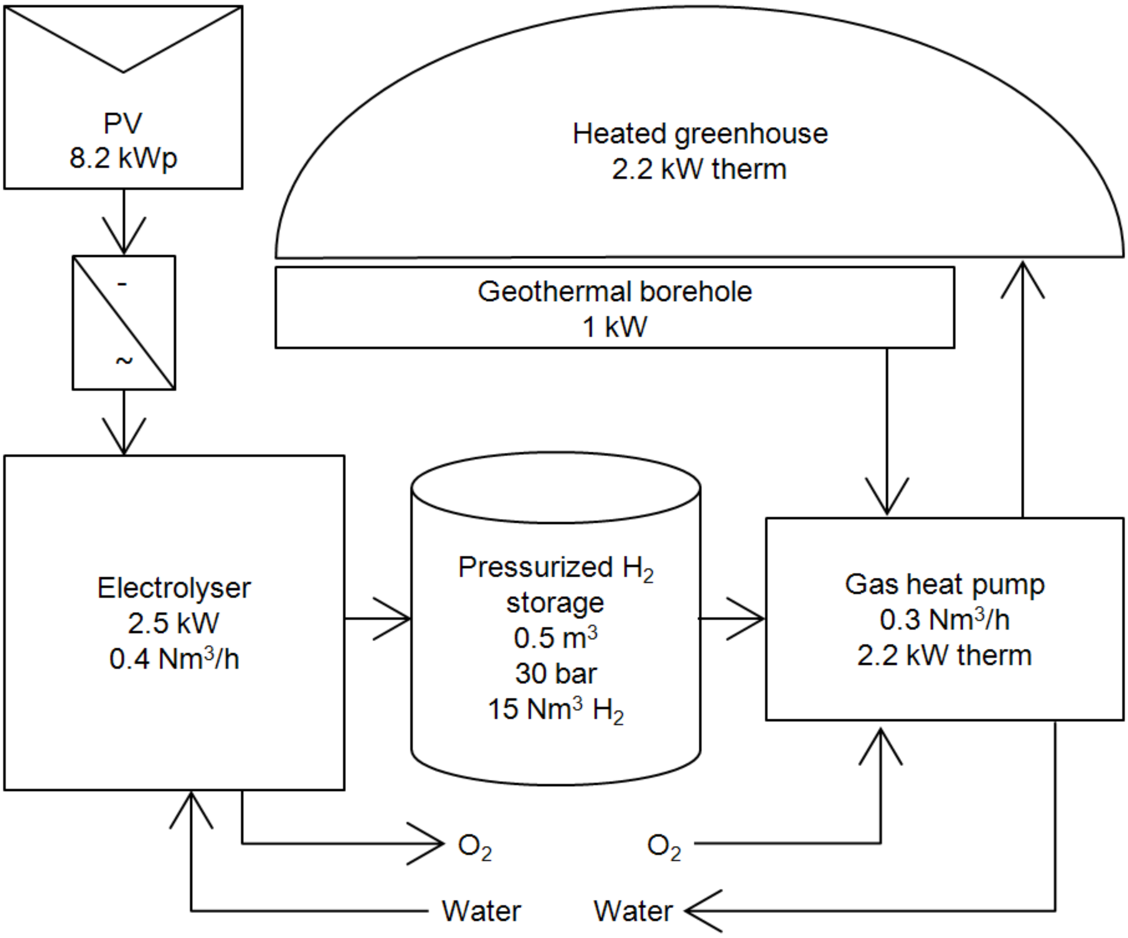

Figure 1. PV and GSGHP in a stand-alone hydrogen system for greenhouse heating.

Considering a clear day, the fraction of the instantaneous PV array power output used through electrolyzer input (P_{el}) is given by (Anifantis et al., 2017):

$$P_{el} = \Phi \eta_{vr} A_{PV}\, I_T \eta_r [1 - B(T_c - T_r)] \tag{1}$$

where η_r(=0.15) is the efficiency of the solar cell at a referenced solar radiation, T_c(~35°C) the solar cell temperature, T_r(=25°C) the referenced temperature of the cell and B(=0.005°C^{-1}) the temperature coefficient of a solar cell, A_{PV} the PV array surface, I_T the solar radiation, η_{vr}(=0.97) the DC/AC converter efficiency and Φ the solar radiation usability. Φ was necessary because the peak power of the PV array should be increased to assure enough available power to cover the needs of the electrolyzer.

Instead, the energy efficiency of the electrolysis reaction η_{el} is given in terms of the lower heating value of hydrogen (LHV_{H2}=119.96 [MJ kg^{-1}]), the overall hydrogen production rate $q_{el,H2}$ [=0.00011 Nm^3 s^{-1}] and the hydrogen density at standard condition (δ_{H2}=0.09 [kg Nm^{-3}]) by the expression (Calderóna et al, 2011):

$$\eta_{el} = \frac{\delta_{H_2} \cdot q_{el,H_2} \cdot LHV_{H_2}}{P_{el}} \tag{2}$$

Gas driven heat pumps performance was calculated by using the Gas Utilization Efficiency (GUE) given by the manufacturer (TecnoCasa Climatizzazione Sole European Distributor AISIN, 2017):

$$\mathrm{GUE} = 0.64 + 0.32 \cdot \mathrm{COP} \tag{3}$$

$$Q_1 = \mathrm{GUE} \cdot Q_{1\_burner} \tag{4}$$

where, considering the overall hydrogen consumption rate of the GSGHP $q_{GSGHP,H2}$, the equivalent thermal power supplies by an ideal hydrogen burner Q_{1_burner} is given by:

$$Q_{1\_burner} = \delta_{H_2} \cdot q_{GSGHP,H_2} \cdot LHV_{H_2} \tag{5}$$

Thanks to the Q_{1_burner} is possible to calculate the thermal power supplies by the heat pump to the thermal hating system inside the greenhouse (Q_1) that is equal to the thermal power demand of the greenhouse.

The ground source gas heat pump (GSGHP) has the same coefficient of performance (COP) of a common ground source heat pump (GSHP):

$$\mathrm{COP} = \frac{Q_1}{Q_1 - Q_2} \tag{6}$$

where Q_2 is the heat power extracted from the ground through the borehole-probe heat exchanger. Q_2 is given by:

$$Q_2 = q_r \cdot l_t \tag{7}$$

where q_r is the heat exchange rate and l_t is the total active length of the borehole. Considering the steady state and the overnight winter conditions, the thermal power demand of the greenhouse was assessed with the equation (Ozgener & Hepbasli, 2005):

$$Q_1 = \left[\frac{A_{cf}}{R}\right](f_w)(f_c)(f_s)(T_i - T_a) \tag{8}$$

Assuming 1, 0.9 and 1 for the wind factor (f_w), construction type factor (f_c) and system factor (f_s), respectively and 0.28 m^2 °C/W for the greenhouse thermal resistance (R).

RESULTS AND DISCUSSION

The results show that the use of a ground source gas heat pump unit integrated with a photovoltaic stand-alone hydrogen system allows to have a total energy efficiency of 13%, starting from the sun to the GSGHP. The major limitation to the performance of the whole system was represented by the performance of photovoltaic, in fact, starting from the energy available from the PV, the system has a 96% efficiency with a heat pump COP of 4. The heating system increasing the greenhouse temperature by about 8°C compared with the ambient conditions in a representative winter day of February.

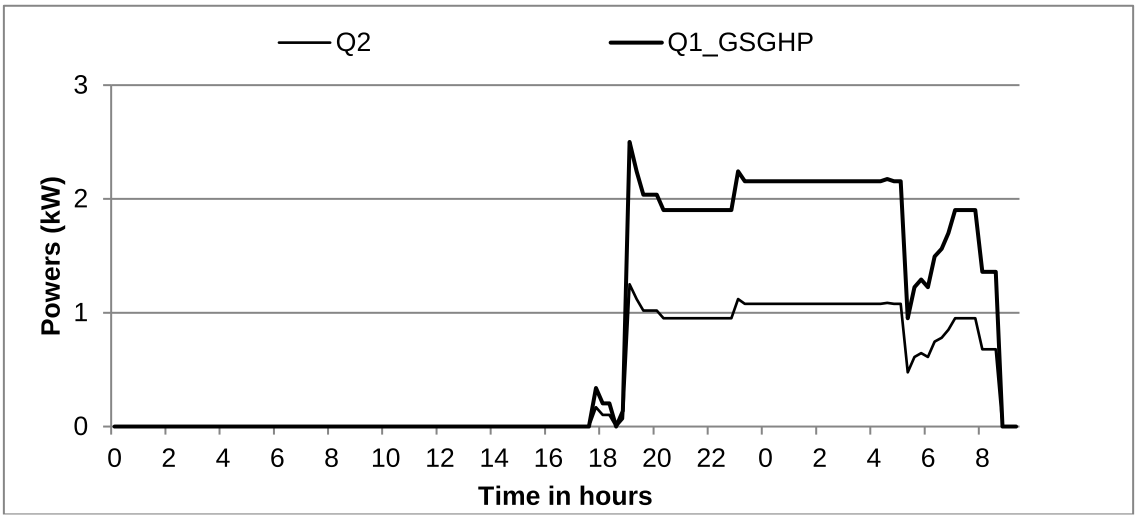

Figure 2. Equivalent thermal power supplies by the hydrogen burner (Q1_burner) and heat power extracted from the ground (Q2) during a winter day.

At night, the fuel cell and the GSHP worked from 18:30 to 08:30 and start when the temperature decreased to 10°C. The thermal power output (Q_1) and input (Q_2) of the GSGHP is 2 kW and 1 kW respectively (Fig. 2). The heat exchange rate of the geothermal borehole required (q_r) for a double U-bend pipe is 10 W m^{-1}. The difference between the indoor and outdoor greenhouse temperatures ($T_{i\ GSGHP}$-T_a) was 8°C (Fig. 3).

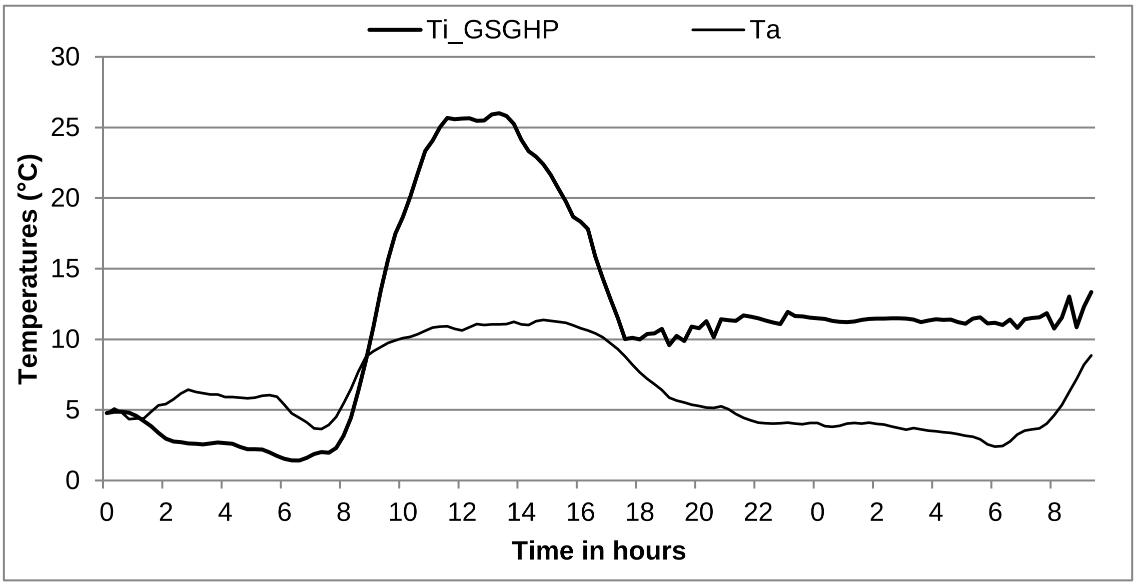

Figure 3. Internal and external greenhouse air temperature during a winter day.

CONCLUSION

The present paper analyzed the overall performance efficiency of a ground source gas heat pump integrated with a stand-alone renewable energy plant. The results obtained in these trials and the mathematical model implemented allow some remarks about the performance and efficiency of the water electrolyzer and the geothermal source gas hat pump (Aisin-TOYOTA). These trials give us a glimpse to its usage within a greenhouse-integrated heating system comprised of photovoltaic panels, alkaline barometric water electrolyzer, hydrogen storage and geothermal source gas heat pump even if experimental tests are required to better assess the GSGHP's achievement. The electrolyzer worked non-stop during the days characterized by clear skies but the electrical power supplied by the PV modules was greatly affected by the very unstable solar radiation during the partial cloudy day. In these cases, the electrolyzer overall operation was disjointed sometimes for many hours due to intemperate weather conditions in which the hydrogen production was cut off. The energy efficiency of the plant is strongly affected by electrolyzer and gas heat pump management. Considering the energy efficiency of photovoltaic panels of 13%, an electrolyzer energy efficiency equal to 50%, a ground source gas heat pump GUE of 192% respectively, the overall system efficiency is 13%. Finally, the heating system increasing the greenhouse temperature by about 8°C compared with the ambient conditions in a representative winter day of February.

ACKNOWLEDGMENTS

Funding source: Fondo di Sviluppo e Coesione 2007-2013 – APQ Ricerca Regione Puglia "Programma reg. a sostegno della specializzazione intelligente e della sostenibilità sociale ed ambientale-FutureInResearch".

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