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Performance Assessment of Photovoltaic, Ground Source Heat Pump and Hydrogen Heat Generator in a Stand-Alone Systems for Greenhouse Heating

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The energy balance is one of the most important factors of the commercial greenhouses. Diesel, LPG and natural gas are generally used as fuel for greenhouses heating. A great amount of scientific research are focused on innovative renewable energy systems in the agricultural sector. The goal is to reduce the use of fossil sources and to change the energy mix of the traditional greenhouses heating system. However, the renewables energies sources and the micro-generation systems still play a niche role in the energy panorama, mainly due to the intermittence of the energy production. In particular, for the solar energy systems used for greenhouse heating applications, the energy produced must be storage and used at night. Stand-alone energy storage systems is necessary to overcome the discontinuity in the energy production and consumption. In this paper, the performance of the stand-alone renewable energy systems for greenhouse heating during the winter season was analyzed. The aims of this research is to compare the energies efficiency of two different stand-alone systems based on hydrogen. The first systems consist of a photovoltaic array connected to an hydrogen electrolyzer, a pressure tank, a fuel cell and a ground source geothermal heat pump. The second system is analogous to the first but a direct air hydrogen burner was used instead to the fuel cell and the heat pump. The second system was designed in order to shorten the energies chain and to simplify the plant. A performance analysis ware conduct in order to define the energy efficiency and the power productions of the both systems. The results show that the heating power produced by the first system is greater than 30% compared to the second one if the hydrogen production and consumption of the two solutions are the same and the coefficient of performance of the heat pump is 5. Furthermore, the first system increasing the greenhouse temperature by 6°C to 10°C compared with the ambient conditions, while the second system by 3°C to 7°C.
Keywords: Stand alone renewable energy system; Ground source heat pump; Hydrogen burner; Greenhouses heating.

1. Introduction

The changes exerted by agriculture on ecosystems are represented by the consumption of renewable and non-renewable natural resources (Russo et al., 2016). Unfortunately, the renewable energy source in agriculture still play a niche role due to the non-simultaneity of energy production and consumption(Blanco et al., 2013; Blanco et al., 2014). Furthermore, energy consumption for greenhouse climate control and irrigation are the principal costs production for the floricultural and horticultural crops in a protected environment (Russo et al., 2014; Anifantis et al., 2012; Vox et al., 2008). Some attractive solutions are represented by the renewable and hydrogen stand-alone systems for greenhouse heating (Pascuzzi et al., 2016[a]; Pascuzzi et al., 2016[b]). The geothermal heating systems are economically advantageous, especially for applications in agricultural sector (Anifantis, 2016). In this paper two different stand-alone renewable energy system based on hydrogen were studied. The first systems consist of a photovoltaic array connected to an hydrogen electrolyzer, a pressure tank, a fuel cell and a ground source geothermal heat pump. During the daylight hours the hydrogen produce by the electrolyzer was storage in a pressure tank. Instead, during the night, a fuel cell converted the hydrogen into electricity to feed a ground source geothermal heat pump (GSHP). The second system is similar to the first but a direct air hydrogen burner was used instead to the fuel cell and the GSHP. This solution allows to reduce the energy chain and simplify the plant. Both the solutions was implemented in order to heat a tunnel greenhouse in the winter. A performance analysis was conducted to define the total efficiency and the power production of the two systems.

2. Materials and Methods

The study was carried out at the experimental farm of the University of Bari, located in Valenzano, Italy. Two twin tunnel greenhouses of 106 m^2 of cover surface (A_{cf}) and 48 m^2 of area was installed. The first greenhouse was heated by a ground source heat pump and the other one by a hydrogen burner. From 08:30 AM to 5:30 PM, the electricity generated by 56 m^2 (A_{PV}) of polycrystalline photovoltaic panels fed a electrolyzer which produces hydrogen by water electrolysis .
The hydrogen was stored in a pressure tank at 30 bar. In the first systems, the hydrogen produced during the day fed a fuel cell that supplied electricity for a GSHP. Instead, in the second system, the hydrogen produced during the day fed a hydrogen burner. Both the greenhouse heating energy systems started when the internal air temperature falls below 10°C. In particular, the components of the plants was shown in Figure 1, Figure 2 and Table 1. The experimental test was carried out on 18-19 February 2016.

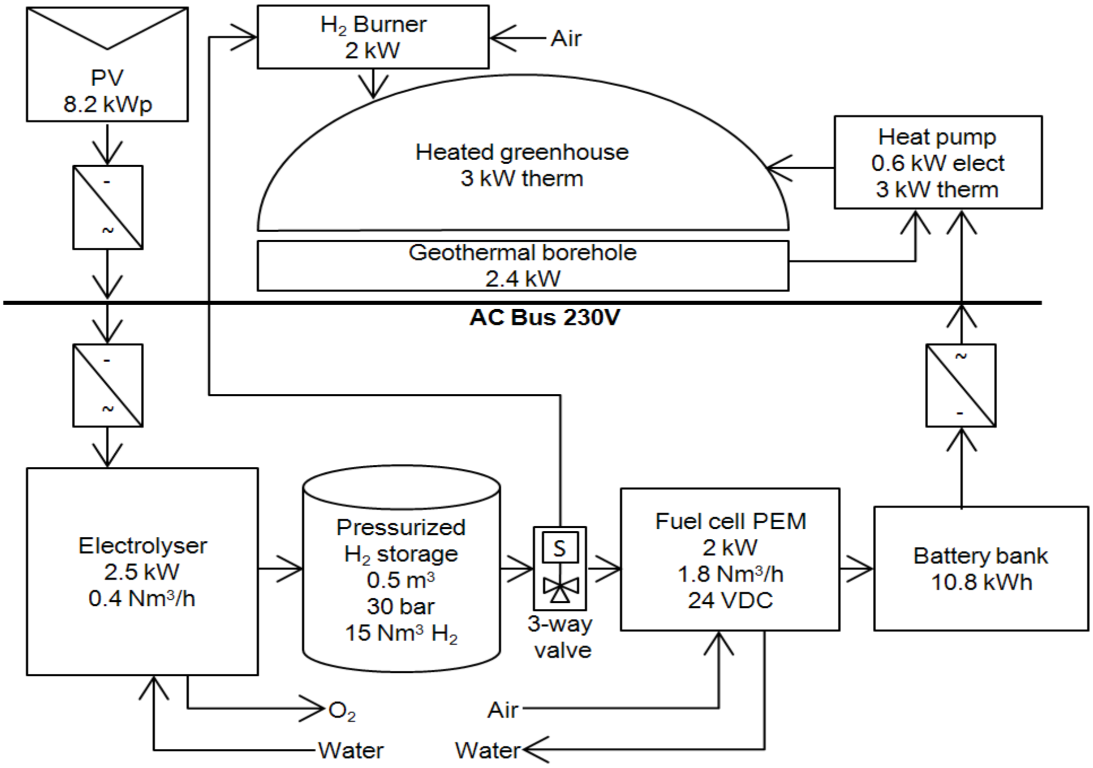

Figure 1: PV, GSHP and hydrogen heat generator in a stand-alone system for greenhouse heating.

Figure 2: Control system, electrolyzer internal stack and fuel cell of the stand-alone hydrogen plant.

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, 0.5 Nm^3/h – H_2Nitidor S.r.l.
Fuel cell	Proton exchange membrane Fuel Cell (T-2000TM), 2 kW, 24 or 48 V – ReliON
H_2 Burner	Hydrogen heat generator 2 kW
3-way valve	hydrogen settable 3-way valve
Battery	10.8 kWh
H_2 storage	30 bar, 0.6 m^3
Heat pump	Model RAA-EF, Riello, 3 kW thermal power with inverter controller
Geothermal borehole	120 m vertical double U-bend ground heat exchanger
Fan-coil unit	Carisma CRC53MV,Cooling/Heating capacities:2.28/3.59kW;air flow rate 495m^3/h
Greenhouse	Air inflated, double layer polyethylene film tunnel greenhouse

3. Modelling of the components

The performance of a tilted PV array highly depend to the solar radiation I_T and the clearness index. For a clear day the efficiency of the solar cell can be evaluated by (Kolhe et al., 2003):

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

where η_r(=0.15) is the efficiency of the solar cell at a referenced solar radiation, T_c(~35°C) is the solar cell temperature, T_r(=25°C) is the referenced temperature of the cell and B(=0.005°C^{-1}) is the temperature coefficient of a solar cell. Considering the PV array surface A_{PV}, the instantaneous PV array power output is defined as:

$$P_{PV} = A_{PV}\, I_T \eta_{PV} \tag{2}$$

The peak power of the PV array should be increased to assure enough available power to cover the needs of the electrolyzer; in fact, a small part of the power is lost due to DC/AC converter efficiency ($\eta_{vr}=0.97$), while, for stand-alone systems, a large part is lost due to solar radiation usability (Φ). The fraction of the instantaneous PV array power output used through electrolyzer input (P_{el}) is given by (Anifantis, 2017):

$$P_{el} = \Phi \eta_{vr} P_{PV} \tag{3}$$

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):

$$\eta_{el} = \frac{\delta_{H_2} \cdot q_{el,H_2} \cdot LHV_{H_2}}{P_{el}} \tag{4}$$

Similarly to the case of the electrolyzer, the PEM fuel cell stack efficiency (η_{fc}) is given by the ratio of the fuel cell power output (P_{fc}), the hydrogen density at standard condition, the overall hydrogen consumption rate $q_{fc,H2}$ [=0.00013 Nm^3 s^{-1}] and the lower heating value (LHV_{H2}) of hydrogen (Calderóna et al, 2011):

$$\eta_{fc} = \frac{P_{fc}}{\delta_{H_2} \cdot q_{fc,H_2} \cdot LHV_{H_2}} \tag{5}$$

Therefore, η_{fc} can be assumed to be 0.4, as most fuel cells operate in these conditions (Tingting et al, 2015). P_{fc} depends on the load demand which in this system is equal to the power demand of the GSHP (L). Furthermore, the GSHP has to meet the following system of linear equations:

$$COP = \frac{Q_{1\_GSHP}}{L} = \frac{Q_{1\_GSHP}}{Q_{1\_GSHP} - Q_2} \tag{6}$$

where Q_{1_GSHP} is the thermal power supplies by the heat pump, COP(~5) is the coefficient of performance, L(=P_{fc}) is the electric power required and Q_2 is the heat power extracted from the underground. On the cold side of the heat pump, Q_2 is the thermal power exchanged with the ground through the borehole-probe heat exchanger. Several technical aspects affect the performance of the borehole-probe-ground thermal system; therefore, the evaluation of Q_2 is very complex. A simple way consists in considering Q_2 as:

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

where q_r is the heat exchange rate and l_t(=120 m) is the total active length of the borehole. In order to simplify q_r assessment for a double U-bend pipe, the maximum value of 50 W m^{-1} was considered, this assumption is well-suited for the small plants analysed by the technical standard (VDI 4640, 2009).

Instead, the thermal power supplies by the hydrogen burner Q_{1_burner} is given by:

$$Q_{1\_burner} = \delta_{H_2} \cdot q_{fc,H_2} \cdot LHV_{H_2} \tag{8}$$

the burner efficiency is around 100% as the hydrogen is burned in air and so the humidity rises to 100%.
The thermal energy requirement of a greenhouse (Q_1) depends on many factors such as solar radiation, inside and outside air temperatures and so on. Considering the steady state and the overnight winter conditions, the heating power loss was assessed with the equation (Ozgener and Hepbasli, 2005):

$$Q_1 = \left[\frac{A_{cf}}{R}\right](f_w)(f_c)(f_s)(T_i - T_a) \tag{9}$$

Assuming, 1.0, 0.9 and 1.0 for the wind factor (f_w), construction type factor (f_c) and system factor (f_s), respectively, 0.28 m^2 °C/W for the thermal resistance of the greenhouse (R), and T_i as the nocturnal average temperature of the internal air of the greenhouse, T_a the nocturnal average low temperature of the external air.

4. Results and Discussion

The equations from 1 to 4 and the solar radiation bend (Figure 3) can be used to predicted the PV and electrolyzer efficiency. The PV efficiency (η_{PV}) is 13% thanks to the low temperature of the solar panel. Unfortunately, only a fraction of PV power output can be used to feed the electrolyzer, as a part is lost during the maximum solar radiation hours, because it exceeds the power input peak of the electrolyzer (Equation 3). The electrolyzer energy efficiency is on average 50%, the value varies widely and it is low due to the device power losses and also because the electrolyzer produces hydrogen directly at 30 bar of pressure.

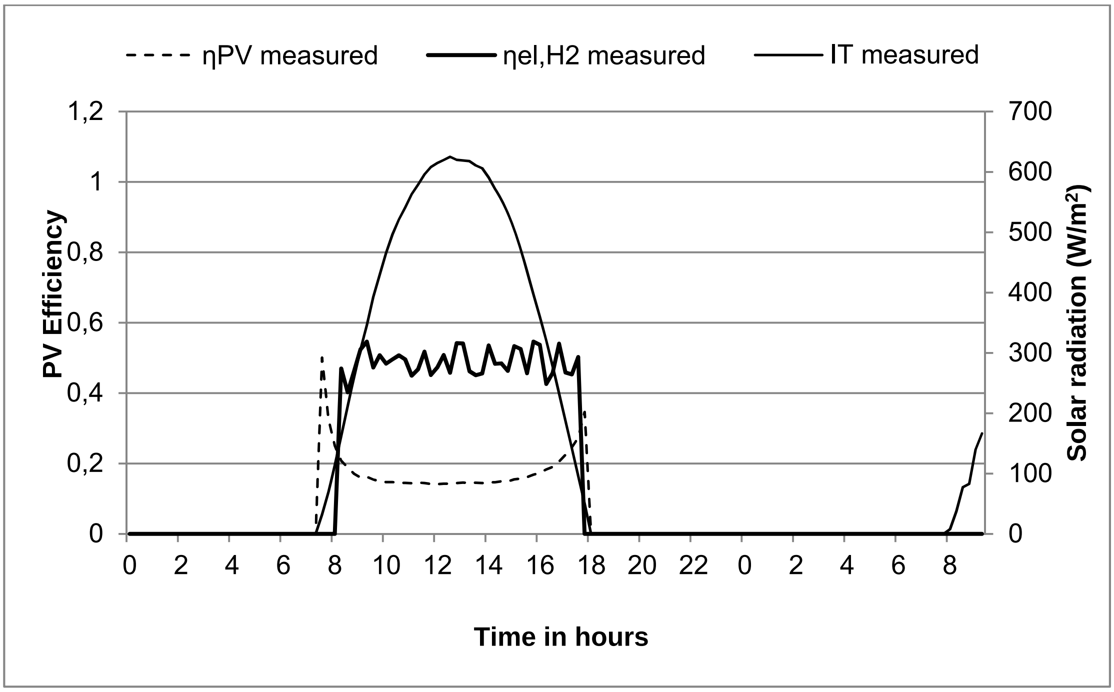

Figure 3: Solar radiation, PV and electrolyzer efficiency of the stand-alone hydrogen plant.

The Fuel cell efficiency is stable at 0.4. The fuel cell power output (P_{fc}) can be considered 0.6 kW and it is almost the heat pump power input (L) in steady state conditions. At night the fuel cell and the GSHP worked from 18:30 to 05:30 when the temperature decreased to 10°C. The COP of the GSHP is 5, the thermal power output of the GSHP (Q_{1_GSHP}) is 3 kW (Equation 6) and the thermal power input of the GSHP (Q_2) is 2.4 kW. The required heat exchange rate of the geothermal borehole (q_r) is 20 W m^{-1} for a double U-bend pipe. This value is lower than the maximum heat extraction rate of the borehole so the COP of the heat pump is quite high. The hydrogen burner was set-up to follow the same worked time and hydrogen consumption of the fuel cell connected to the GSHP. The Figure 4 shows the thermal power supplies by the hydrogen burner. The Q_{1_burner} is about 2 kW, 30% less than the heating power supply by the GSHP.

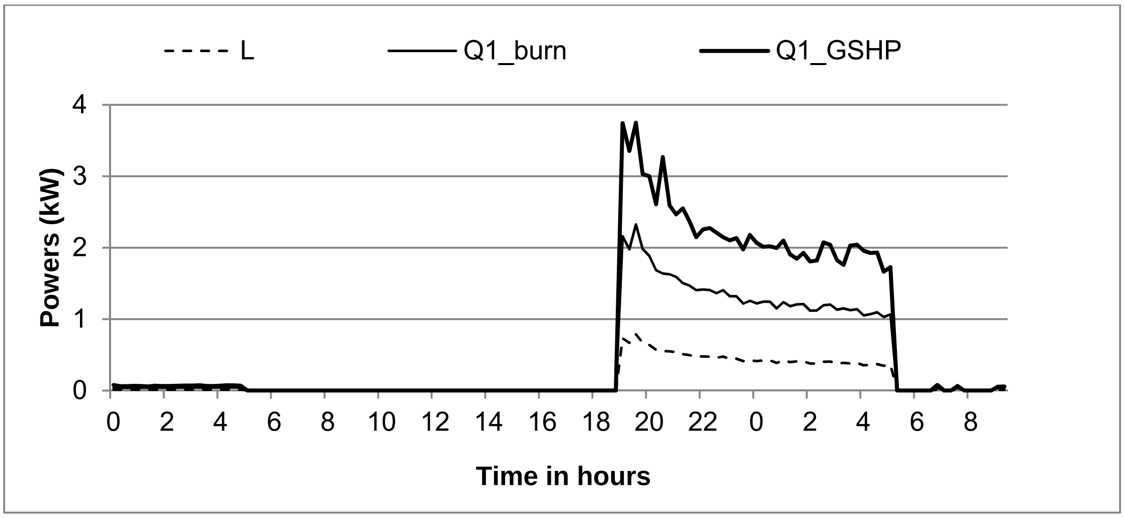

Figure 4: Fuel cell electric power, ground source heat pump and hydrogen burner heating powers.

The difference between the indoor and outdoor greenhouse temperatures (T_i-T_a) is 8°C and 5°C for the first and the second system respectively (Figure 5). The total thermal conductivity of the greenhouse is equal to 3.21 W/m^2 °C.

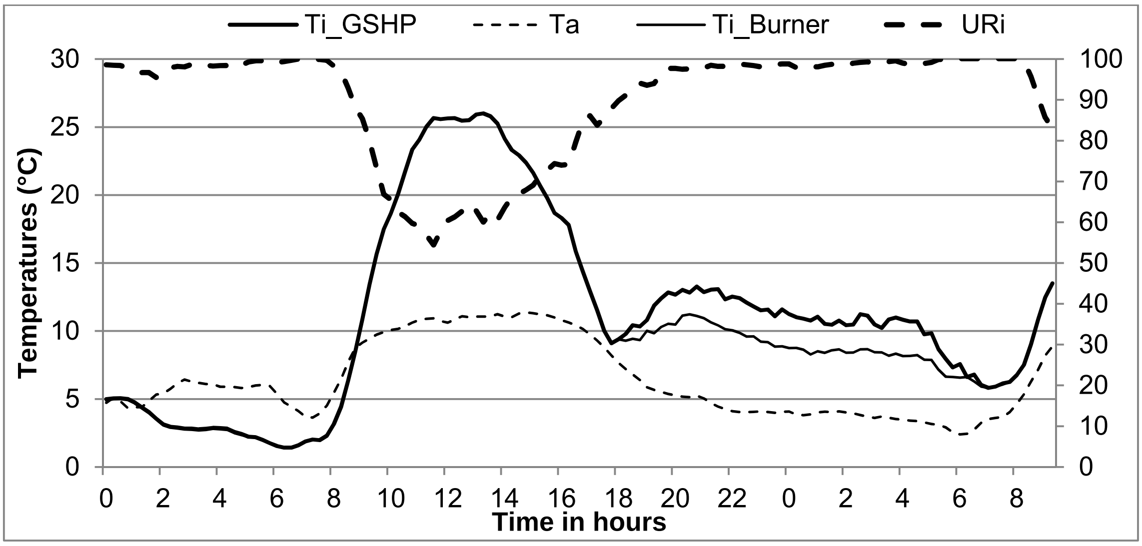

Figure 5: Ambient air temperature, internal air temperatures and humidity of the two twin greenhouses.

The installation cost of the hydrogen systems is ten times more than a system with lithium battery; however, the installation cost in €/kWh of the hydrogen systems is one thousand times lower than a system with lithium battery. Furthermore, the service life in years of the hydrogen plant is longer than lithium battery, so the system is more suitable for long-term applications (Anifantis, 2017).

5. Conclusion

In this paper a comparison between the overall performance efficiencies of a GSHP system and a hydrogen burner both coupled with a photovoltaic stand-alone hydrogen plant has been done. The energy efficiency of the plant is strongly affected by electrolyzer management. The energy efficiency of the photovoltaic panels is 13%, the electrolyzer energy efficiency is 50%, the fuel-cell energy efficiency is 40%, the COP of the GSHP is 5 and the hydrogen burner efficiency is about 100%, than the overall system efficiency of the first system is 13%, while for the second system is 7%. Furthermore, the first systems allows to have a power up to 30% compared with a hydrogen burner power if the hydrogen production and consumption of the two solutions are the same and the coefficient of performance of the heat pump is 5. On the other hand, the complexity introduced by the first systems is quite high. When the COP of the GSHP is lower than 3, the performance of the two systems are the same. The air temperatures reached in the first greenhouse exceeds the values of the second one. The greenhouse temperatures of hydrogen burner solution are 2-3°C less than the GSHP system. In conclusion, a combination of the solar thermal panels, the hydrogen burner and the GSHP in a stand-alone hydrogen system could be high the performance of the two systems, also through the increase of the hot water enthalpy of the heating system.

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