PERFORMANCE COMPARISON BETWEEN FUEL CELL COUPLED WITH GEOTHERMAL SOURCE HEAT PUMP AND GEOTHERMAL SOURCE GAS ENGINE HEAT PUMP SYSTEM FOR GREENHOUSE HEATING: A MATHEMATICAL STUDY

Alexandros Sotirios Anifantis, Simone Pascuzzi, Francesco Santoro
University of Bari Aldo Moro, Italy
alexandrossotirios.anifantis@uniba.it, simone.pascuzzi@uniba.it, francesco.santoro@uniba.it

Abstract. LPG, diesel and natural gas are generally used for greenhouse conditioning. Alternative technologies should be developed to increase the productivity of the protected environments. Innovative solutions are represented by photovoltaic, geothermal, wind and solar thermal integrated in a stand-alone system in agriculture land. The present paper compares the performances of two renewable energy systems for greenhouse heating based on geothermal and hydrogen technologies. The first integrated system is composed by a photovoltaic array, an electrolyzer, a hydrogen storage tank, a fuel cell and a ground source heat pump connected to a geothermal borehole. The second system, instead, is composed by a photovoltaic array, an electrolyzer, a hydrogen storage tank and a gas engine heat pump connected to a geothermal borehole. In order to compare the two systems, both heat pumps produced the same greenhouse heating power input. The results show a difference between the internal and external greenhouse air temperature from 7 to 15 ºC in winter, considering a deep insulating greenhouse cover material. As regarding the first system, the following energy efficiency has been calculated, photovoltaic arrays 13 %, electrolyzer 50 %, fuel cell 40 % and the ground source heat pump coefficient of performance 400 %. Than the total energy efficiency of the first system is 10.4 %. Instead, the overall efficiency of the second system is 11.9 % considering the same performance of the photovoltaic arrays and the electrolyzer of the first system and the ground source gas engine heat pump's primary energy ratio of 181 %. The primary energy ratio of the ground source gas engine heat pump seems to be low and not competitive respect to the coefficient of performance of a ground source heat pump, but considering the overall efficiencies of the both systems the performances are reversed. Furthermore, the first system is more complex than the second one.

Keywords: greenhouses, geothermal, hydrogen, gas engine.

Introduction

Greenhouses are essential in those regions with unfavourable environmental temperatures. However, the energy consumption of the greenhouse conditioning systems can overtake the 70 % of the production costs. For these reasons, the use of renewable energy resources for greenhouse heating can be a solution [1]. Furthermore, low enthalpy geothermal sources are becoming usual for greenhouse heating [2-5], especially for economical and installation reasons [6; 7]. In addition, the solar energy usage for greenhouse heating could be an environmental friendly and economically sustainable solution [8]. Unfortunately, the solar energy is non-stable and the electric energy coming out from the PV panels highly depends on the weather conditions. Hydrogen gas from water electrolysis is a vector with high energy density that can be used to storage the electric energy coming from the PV panels [9]. In the paper, the comparison of the energy efficiencies of two stand-alone geothermal and hydrogen systems integrated for greenhouse heating is studied by a mathematical model. The research is focused on two different geothermal energy systems, a geothermal source heat pump (GSHP) and a geothermal source gas engine heat pump (GSGEHP).

Materials and Methods

The first system is composed by a photovoltaic arrays connected to an electrolyzer, a hydrogen storage tank, a fuel cell and a GSHP (system 1). The second system, like the first one, starts with a PV, hydrogen electrolyzer and storage tank, but instead of the fuel cell and the GSHP a GSGEHP is implemented for greenhouse heating (system 2). The specifications are reported in Tab. 1. The principle behind the operation of the system is that the electric energy coming from the PV provides power for the electrolyzer, then the hydrogen is accumulated in a tank and, during the night, the tank provides hydrogen for the fuel cell coupled with the GSHP or for the GSGEHP. Both power systems have been calculated for supplying the hot water demanded for heating a greenhouse of 468 m^2 of area and 983 m^2 of cover surface (A_{cf}). The greenhouse structure is composed by tubular steel. The cover material used is a polyethylene film with a thickness of 200 µm, in order to increase the isolation propriety of the greenhouse cover film, a double layer with an air inflated gap of four centimetres is considered. Then the thermal resistance value (R) of the greenhouse covering system is 0.3 $m^2 \cdot {}^\circ C \cdot W^{-1}$ [10]. The hot sides condensing temperatures of both heat pumps are about 40-45 ºC, while the evaporating temperatures of the cool sides are 7-12 ºC.

Table 1

System 1 and System 2 components

Components	System 1	System 2
PV array	BYD 240P6-30, 356 kW peak	BYD 240P6-30, 286 kW peak
Electrolyzer	43 stacks of an AEM electrolyzer 2.5 kW, 0.5 $Nm^3 \cdot h^{-1}$ – Heliocentris	35 stacks of an AEM electrolyzer 2.5 kW, 0.5 $Nm^3 \cdot h^{-1}$ – Heliocentris
H_2 cylinder	30 bar, 3.6 m^3	30 bar, 2.9 m^3
Fuel cell	6-7 modules of a 2 kW PEM Fuel Cell (T-2000TM), 24/48 V - ReliON	-
Battery	75 kWh	-
HP	Model NBW 207 H, Aermec, 48 kWth	-
GEHP	-	Model AWGP450E1 16 HP, Aisin-Toyota
Geothermal borehole	7 vertical double U-bend ground heat exchanger, 120 m deep	6 vertical double U-bend ground heat exchanger, 120 m deep
Fan-coil unit	14 fan-coils of CRC53MV - Carisma. Heating capacities: 3.6 kW; air flow rate 495 $m^3 \cdot h^{-1}$	14 fan-coils of CRC53MV - Carisma. Heating capacities: 3.6 kW; air flow rate 495 $m^3 \cdot h^{-1}$
Greenhouse	470 m^2	470 m^2

Regarding system 1, starting from the solar energy, the electrolyzer power input is a portion of the PV energy output [11] and it depends on several factors, such as the solar radiation, the performance of the solar cell and the solar radiation usability [12]. Furthermore, the electrolyzer energy efficiency η_{el} is given by the equation [13]:

$$\eta_{el} = (\delta_{H2}\, q_{H2,el}\, LHV_{H2})/P_{el}, \quad (1)$$

where δ_{H2} – hydrogen density at standard condition, 0.0899 $kg \cdot Nm^{-3}$ [11];
$q_{H2,el\_}$ – overall hydrogen production rate, $Nm^3 \cdot s^{-1}$;
LHV_{H2} – lower heating value of hydrogen, 119.96 $MJ \cdot kg^{-1}$ [11];
P_{el} – electrolyzer power input, W.

The energy efficiency of the PEM fuel cell is given by:

$$\eta_{fc} = P_{fc}/(\delta_{H2}\, q_{H2,fc}\, LHV_{H2}), \quad (2)$$

where P_{fc} – fuel cell power output, W [11];
$q_{H2,fc}$ – fuel cell hydrogen consumption rate, $Nm^3 \cdot s^{-1}$.

The COP of the GSHP is given by:

$$COP_{\_GSHP} = Q_{1\_GSHP} /(Q_{1\_GSHP} - Q_{2\_GSHP}) = Q_{1\_GSHP} /L_{\_GSHP}, \quad (3)$$

where Q_{1_GSHP} – heating power supplies by the heat pump, W;
Q_{2_GSHP} – heating power absorbed from the ground by the heat pump, W;
$L_{\_GSHP}$ – electrical power supply to the heat pump, W.

The heat power extracted from the ground (Q_2) is also given by:

$$Q_{2\_GSHP} = q_r\, l_t, \quad (4)$$

where q_r – heating exchange rate [14-16], $W \cdot m^{-1}$;
l_t – total active length of the borehole [11; 17-19], m.

At night, the greenhouse heating power demand can be calculated neglecting the transitory effects and considering the steady state conditions [20; 10]:

$$Q_{1\_GSHP} = [A_{cf}/R]\, (f_W)\, (f_C)\, (f_S)\, (T_i - T_a), \quad (5)$$

where f_W – wind factor, 1;

f_C – construction type factor, 0.9;
f_S – system factor, 1;
R – thermal resistances of the greenhouse covering material, 0.3 $m^2 \cdot C^o \cdot W^{-1}$.

Then, the heat transfer coefficient K is 3 $W \cdot m^{-2} \cdot {}^oC^{-1}$.

Regarding system 2, the equivalent thermal power supplies by the ICE (Q_{gas}) is given by [21]:

$$Q_{gas} = \delta_{H2}\, q_{H2,gas}\, LHV_{H2}, \tag{6}$$

where $q_{H2,gas}$ – ICE hydrogen consumption rate, $Nm^3 \cdot s^{-1}$.

The same efficiency is for the ICE powered by natural gas with hydrogen. In steady state conditions and with the optimum air/fuel equivalence ratio the efficiency (η_m) can be assumed equal to 0.39 [22]. Then the mechanical power supply to the heat pump by the ICE's shaft of the GSGEHP (L_{GSGEHP}) is given by:

$$L\_{GSGEHP} = \eta_m\, Q_{gas}. \tag{7}$$

The return water from the air conditioning system [23] of the GSGEHP firstly enters the condenser to absorb the condenser heat and then goes through the water-to-water heat exchanger and gas to water heat exchanger to recover the engine waste heat. Then the heated water again supplies the air conditioning system for space heating [23]. Therefore, the total heat gained ($Q_{1\_GSGEHP\_TOT}$) is given by [24]:

$$Q_{1\_GSGEHP\_TOT} = Q_{1\_GSGEHP} + Q_{recov}, \tag{8}$$

where Q_{1_GSGEHP} – heating power supplies by the only heat pump cycle of the GSGEHP, W;
Q_{recov} – engine waste heat recovered from the cylinder jacked and the exhaust gas, W.

Eq. 1, Eq. 3 and Eq. 4 can be used also for system 2 just changing the subscript from "GSHP" to "GSGEHP". Furthermore, the Eq. 5 can be used if instead of Q_{1_GSHP} is considered $Q_{1\_GSGEHP\_TOT}$.

The PER and the recovery efficiency (η_{recov}) given by the manufacturer are used to calculate the performance and Q_{recov} of the gas engine driven heat pumps [23; 25]:

$$Q_{recov} = \eta_{recov}\, Q_{gas}, \tag{9}$$

$$PER = Q_{1\_GSGEHP\_TOT} / Q_{gas} = \eta_m\, COP\_{GSGEHP} + \eta_{recov}, \tag{10}$$

Results and Discussion

At the experimental site latitude, the solar radiation peak ranged from 0.5 to 1 $kW \cdot m^{-2}$. Unfortunately, in winter, the cloudy day influenced the performance of the hydrogen system and the average clearness index can be considered equal to 0.2 [21]. In summer, when the cooling demand is very high, the cycle of the GSHP and the GSGEHP can be inverted, otherwise, natural or dynamic ventilation, operated by the fans, could be enough [26]. Fig.1. shows the power flow diagrams of the systems 1 and 2, in February, the coldest month of the year. In winter, in order to maximize the work time of the electrolyzer, the PV panels peaks (P_{PV}) should be increased by 3.3 times than the electrolyzer power input (P_{el}), then, P_{PV} is equal to 356 kWp and 286 kWp for the systems 1 and 2, respectively. Both GSHP and GSGEHP heating systems work during the night for ten hours, while the electrolyzer works only for five hours depending on the weather conditions, for this reason, the hydrogen production rate of the electrolyzer for both systems (q_{H2,el_GSHP} = 21.6 $Nm^3 \cdot h^{-1}$, $q_{H2,el\text{-}GSGEHP}$ = 17.4 $Nm^3 \cdot h^{-1}$) must be doubled compared to the fuel cell or GSGEHP hydrogen consumption rate ($q_{H2,fc}$ = 10.8 $Nm^3 \cdot h^{-1}$, $q_{H2,gas}$ = 8.7 $Nm^3 \cdot h^{-1}$). The monthly average electrolyzer electric power inputs (P_{el}) of the systems 1 and 2 ranged from 25 to 110 kW and from 20 to 90 kW, respectively and then the monthly average electrolyzer mass flow outputs ranged from 6 to 20 $Nl \cdot h^{-1}$ and from 5 to 15 $Nl \cdot h^{-1}$, respectively (Fig. 2). In summer, $q_{el,H2}$ increases, but the heating energy demand of the greenhouse decreases.

In winter, during the day, at Mediterranean latitude, the heating systems were turned off and the greenhouse effect was enough to high the greenhouse air temperatures. Then the averages working temperatures of the GSHP and the GSGEHP, and of the greenhouse internal air were analyzed from 18:00 to 8:00. In Fig. 3 the results of one year analysis as monthly average values were showed. The greenhouse thermal power demand (Q_{1_AV}) is equal to the monthly average heating power supplies by the GSHP (Q_{1_GSHP}) and the GSGEHP ($Q_{1\_GSGEHP\_TOT}$). Instead, the heating power absorbed from the ground by the GSHP (Q_{2_GSHP}) is smaller than the heat power absorbed by the GSGEHP (Q_{2_GSGEHP}) thanks to the Q_{recov}.

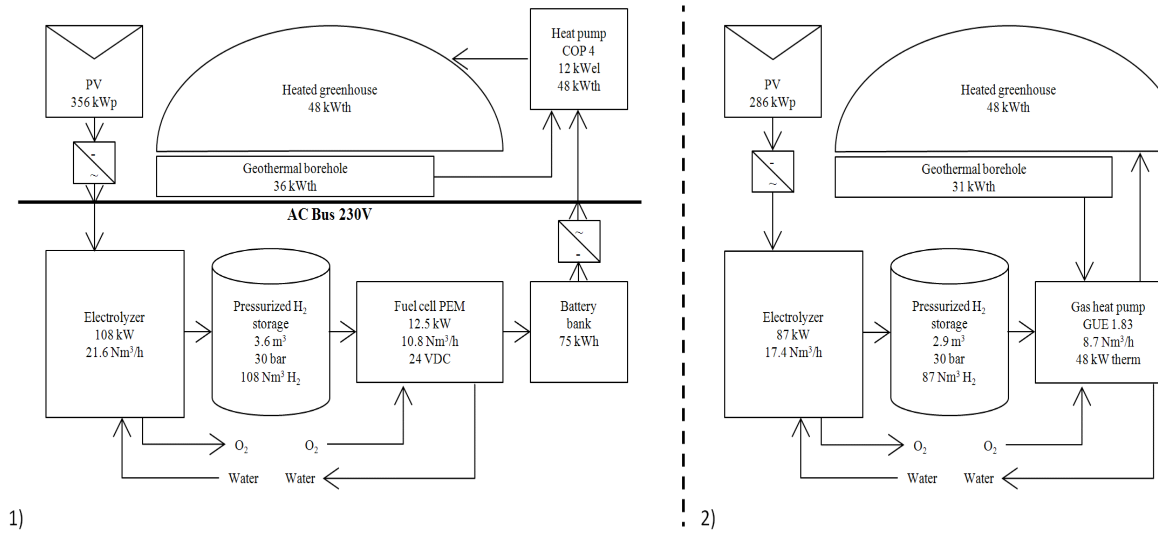

Fig. 1. **Comparison between (1) PV, electrolyzer, fuel cell and GSHP system and (2) PV, electrolyzer and GSGHP system in stand-alone applications for greenhouse heating**

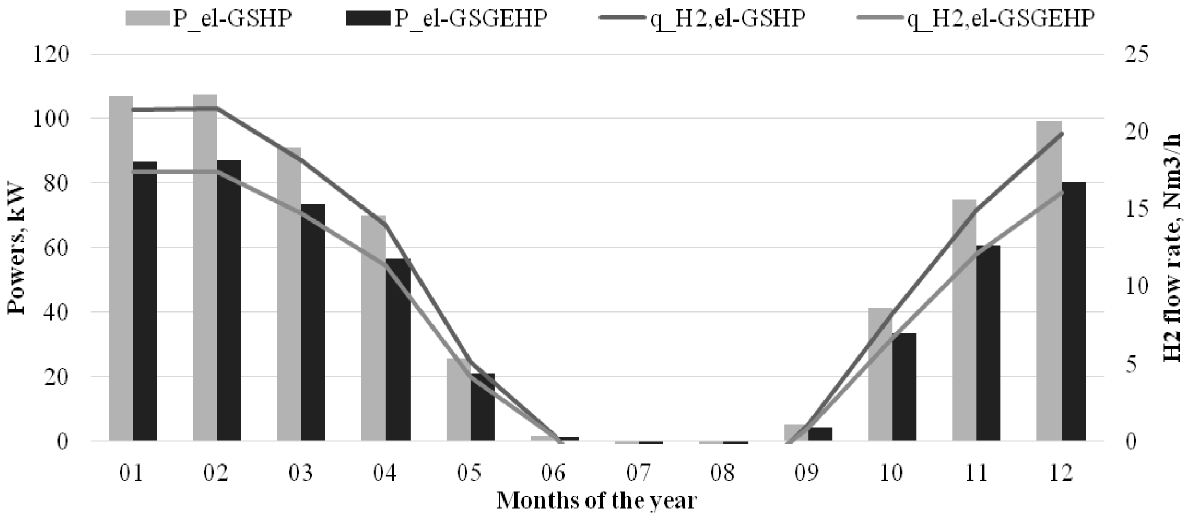

Fig. 2. **Monthly average electrolyzer power input and mass flow output for energy supply of GSHP and GSGEHP in 2015**

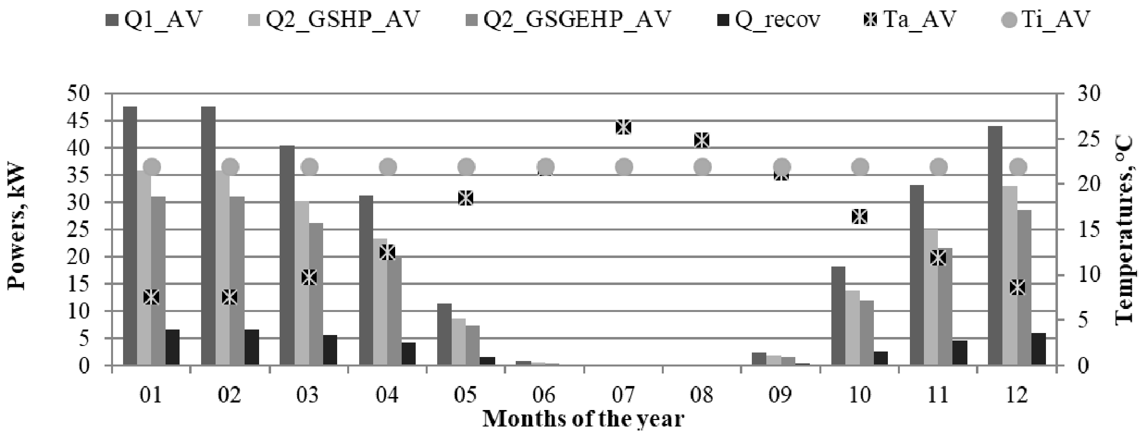

Fig. 3. **Monthly average internal and external greenhouse air temperatures, heating power supplies and extracted from ground by GSHP and GSGEHP in 2015**

In February (Fig. 1), Q_{1_AV} is 48 kW and Q_2 is 36 kW and 31 kW of the systems 1 and 2, respectively. The monthly average heating power supplies by the two systems decreased double from February to April because the average external air temperature (T_{a_AV}) hardly increased. The year average value of the PER of the GSGEHP was 181 % considering a η_m of 0.39, a COP_{GSGEHP} of 4 and a η_{recov} of 0.25. In addition, the COP_{GSHP} was considered equal to 4 in order to compare the performances of the two heating systems considering the same operation systems efficiencies. Furthermore, the same thermal power demand of the greenhouse and monthly average external (T_{a_AV}) and internal (T_{i_AV}) greenhouse air temperatures were considered for System 1 and System 2. The difference between T_{a_AV} and T_{i_AV} ranged from 15 to 7 ºC from February to April. The heating energies supplied by the two systems were high and the level of temperatures achieved by the internal greenhouse air justifies the investments.

Conclusions

The present paper calculated the performance efficiencies of GSHP and GSGEHP systems integrated with the hydrogen system fed by PV array for greenhouse heating.

The overall energy efficiency of the first system is 10.4 % considering the efficiency of the PV panels of 13 % the energy efficiency, if the electrolyzer equals to 50 %, the efficiency of the fuel cell equals to 40 % and the GSHP's COP of 4, respectively. The overall efficiency of the second system is 11.9 % considering the same energy efficiency of the photovoltaic panels and the electrolyzer of the first system and the GSGEHP's primary energy ratio (PER) of 1.81, respectively. The coefficiency of performance of the GSHP seems to be low and not competitive in respect to the PER of the GSGEHP, but considering the overall efficiencies of both systems the performances are reversed. The PER of the GSHP and GSGEHP highly depend on the coefficient of performance of the thermodynamic Carnot cycle achieved by the heat pump, the ground average annual temperature and the specific heat and exchange rate of the geothermal borehole.

In winter, taking in account a traditional greenhouse cover system, the system 1 and system 2 increase the greenhouse temperature from 7 to 15 ºC in respect to the external air. Furthermore, the first system is more complex than the second one.

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