ENERGY PERFORMANCE COMPARISON OF TWO SMALL SCALE COMBINED GEOTHERMAL HEATING PLANTS FOR GREENHOUSE HEATING

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Abstract. The focus of this paper is on the energy performance and thermo-economic assessment of small scale (50 kWth) heating plants to match a greenhouse (468 m^2) energy demand. The annual energy demand of an air inflated-double layer polyethylene film greenhouse located in Apulia region (South of Italy) is considered. Two different system configurations are designed to produce hot-water by using low enthalpy geothermal source and a natural gas engine. The systems analyzed are: i) a grid-connected and electricity-driven ground source heat pump, ii) a gas engine-driven ground source heat pump feed by natural gas. The heat pump Model NRW 127 HA (brand AERMEC), which uses R407c as a refrigerant fluid circulating inside its circuit, is the unit used in the i) system. Instead, the Model AWGP450E1 16HP manufactured by Aisin (TOYOTA) is the gas heat pump unit used in the ii). According to the technical data provided by the manufacturers, the GSHP and GSGHP output is 48 kW thermal power and the input is 36 kW. The GSHP and the GSGHP are equipped with ten geothermal closed-loop vertical boreholes 100 m deep and modelled assuming data from existing commercial plants. The global thermal resistance values of the covering material of the greenhouse were 0.13 $m^2 \cdot {}^{\circ}C \cdot W^{-1}$. The investment profitability is assessed in light of the Italian regulations. The coefficient of performance (COP) of the heat pumps is 4 for configuration i), while the gas utilization efficiency of the ii) systems is 1.6 and the heating consumption of methane is 2.2 $kg \cdot h^{-1}$. The heating system increased the greenhouse air temperatures by 10 ºC respect to the external air temperatures and climate conditions. Average hot water outlet temperatures between 35 ºC and 45 ºC are obtained over the considered range of the external operating parameters and this met the temperature demand of the greenhouse.

Keywords: renewable energy sources, gas heat pump, greenhouse heating systems.

Introduction

Nowadays, the main issues in agriculture are represented by the high cost of production, the safety of the operators [1; 2], the considerable use of pesticides [3; 4] and the consumption of primary energy necessary both for tractors and operating machines [5; 6], food processing [7-9] and conditioning.For these reasons, specialized operators are required in agriculture [10] able to combine the increase in quality standards required by the market [11-13] with the increasing challenges of the international regulationsmaintaining, at the same time, low production and energy costs.Furthermore, energy consumption is one of the main cost factors in commercial greenhouses, since high amounts of energy are used for greenhouse climate control to obtain good yields and high quality [14].

Greenhouses are one of the most modern expressions of recent agriculture and it is expected for them to increase numerically in the future, especially in those areas with hostile climatic conditions. However, the investment required for implementing a greenhouse environmental control system can be quite high and the energy costs for heating a greenhouse can reach 70 % of production costs. The changes exerted by agriculture on ecosystems are represented by the consumption of renewable and non-renewable natural resources.

Geothermal systems are a promising option to match the greenhouse energy demand [15; 16]. The geothermal system application is growing rapidly, because it consumes less conventional energy for operation, which, in turn, results in fewer CO_2 emissions [17; 18]. About 71 % of renewable energy can be provided by ground-source heat pumps [19].Another interesting technology is represented by biogas heating and cogeneration plants [20; 21].

The paper analyses the whole conversion process from electric energy and gas supply to heating, reporting energy balances and costs analysis. Two different system configurations are designed to produce hot-water by using low enthalpy geothermal source and a natural gas engine. i) a grid-connected and electricity-driven ground source heat pump (GSHP), ii) a gas engine-driven ground source heat pump (GSGHP) fed by natural gas.

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Materials and methods

The focus of this paper is on the energy performance and thermo-economic assessment of small scale (50 kW_{th}) heating plants to match a greenhouse energy demand covered by polyethylene material with a thickness of 0.15 mm and the total surface of 468 m^2. The research was carried out at the experimental centre "P. Martucci" of the University of Bari in Valenzano (Bari), Italy (41.025800 N, 16.907563 W, 140 m a.s.l.), where after an accurate evaluation, having esteemed the advantage and the disadvantage, the energy-producing capacity, the environmental impact, the economy, the installation and the maintenance of the most common renewable energy source, it opted for a "Closed-loop groundsource heat pumps (GSHP)". The reason for this choice sprang from the low depth of aquifer in Valenzano, measured around 120 m, and also from the warm water temperature, around 13 ºC. The main benefit of the heat pumps is the coefficient of performance (COP), thanks to this property, for example, the heat pump can transform 1kWh of electric energy in 4 kWh of heating energy, it mainly depends on the aquifer water temperature and the ambient temperature demand, other important factors are the heat pump characteristics, the real thermodynamic cycle and the heat pump system design and installation. Moreover, the same heat pumps can work both in cold and hot periods to produce warm water for the cold period or cold water for the hot period, that is the simple invert of the cycle heat pump. Instead, the main disadvantages are the initial high cost and the authority's trouble to obtain the authorization to use the aquifer water for heating.

A real fast germination chamber greenhouse was considered. The principle was based on atomize greenhouse split in four zones. Each zone has a different air and floor temperature, nutrient solution composition, light and carbon dioxide fertilization requirements. Also, the plant permanence time in each step is different according to the biological cycle. Normally in the greenhouse management, it must assure that each zone has the same air conditions thanks to use of high environmental control systems, and the total production time is the growth times sum for each step plus the handler times between two steps. All heating, hydroponic irrigation and control systems were located underground to optimize the greenhouse space occupation (Fig. 1).

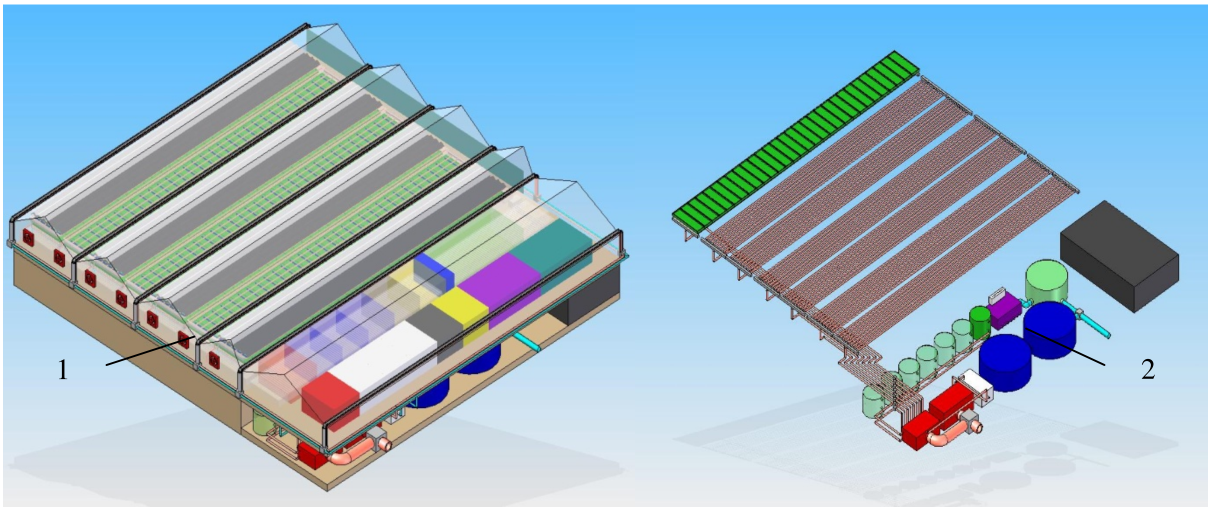

Fig. 1. **Greenhouse:** 1 – plant complex; 2 – floor heating system

The annual energy demand of an air inflated-double layer polyethylene film greenhouse located in Apulia region (South of Italy) is considered.The climatic data for the year 2018 were taken to carry out the analysis of the thermal levels, temperatures, powers and hours of heating of the greenhouse. The environmental data were stored by two data loggers, CR1000 and CR10X, Campbell, Logan, USA, and numerous sensors for climaticparameter acquisition. In general, all calculations were made with an accuracy of two and three significant digits.

Considering the steady-state and monthly average conditions, the greenhouse heat power loss was assessed with the equation [22]:

$$Q_1 = \left(\frac{A}{R}\right) \cdot f_w \cdot f_c \cdot f_s \cdot (T_{i\_av} - T_{a\_av}) \qquad (1)$$

where Q_1 – greenhouse heat power loss, W;
A – greenhousecover film surface, m^2;
R – thermal resistance of the greenhouse, m$^2\cdot$°C$\cdot$W^{-1};
f_w – wind factor;
f_c – construction type factor;
f_s – system factor;
T_{i_av} – monthlyfixed internal air temperature of the greenhouse, °C;
T_{a_av} – nocturnal monthly average external air temperature, °C.

Considering 1.0, 0.9 and 1.0 for f_w, f_c and f_s factors, respectively; 468 m^2 for A and 0.13 m$^2\cdot$°C$\cdot$W^{-1} for the global thermal resistance values [23] of the covering material of the greenhouse.

The monthly average heating greenhouse energy demand can be described by [24]:

$$E_1 = Q_1 \Delta t_n, \tag{2}$$

where E_1 – monthly average heating greenhouse energy demand, J;
Δt_n – monthly average time range of heating, s.

Furthermore, the heating system should be properly sized to meet the needs of the greenhouse under average extreme weather conditions. Two different system configurations are designed to produce hot-water by using low enthalpy geothermal source and a natural gas engine. i) a grid-connected and electricity-driven ground source heat pump (GSHP), ii) a gas engine-driven ground source heat pump (GSGHP) fed by natural gas. The heat pump Model NRW 127 HA (brand AERMEC), which uses R407c as a refrigerant fluid circulating inside its circuit, is the unit used in the i) system. Instead, the Model AWGP450E1 16HP manufactured by Aisin (TOYOTA) is the gas heat pump unit used in the ii) systems. Both the GSHP and GSGHP COPs are given by the formula:

$$COP = \frac{Q_1}{Q_1 - Q_2}, \tag{3}$$

where Q_1 – heat power supplied by the GSHP or the GSGHP, W;
Q_2 – heat power extracted from the ground, W.

The heat power supplied by the GSHP or the GSGHP is equal to the greenhouse heat power loss. For i) system Q_1 is given by the formula:

$$Q_1 = COP \cdot L \tag{4}$$

where L – electrical energy consumed by the GSHP, W.For ii) system Q_1 is given by the following set of formulas [25]:

$$GUE = 0.64 + 0.32 \cdot COP, \tag{5}$$

$$Q_1 = GUE \cdot Q_{1\_burner}, \tag{6}$$

$$Q_{1\_burner} = \delta_{CH4} \cdot q_{CH4} \cdot LHV_{CH4}, \tag{7}$$

where GUE – gas utilization efficiency of the GSGHP;
Q_{1_burner} – equivalent thermal power supplied by the natural gas burner, W;
δ_{CH4} – natural gas density at standard condition, kg$\cdot$m^{-3};
q_{CH4} – overall natural gas production rate, m$^3\cdot$s^{-1};
LHV_{CH4} – lower heating value of the natural gas, J$\cdot$kg^{-1}.

According to the technical data provided by the manufacturers, the GSHP and GSGHP output is 48 kW thermal power and the input is 36 kW. The GSHP and the GSGHP are equipped with ten geothermal closed-loop verticalborehole-probe heat exchanger100 m deep and it is modelled assuming data from existing commercial plants. The LHV$_{CH4}$ was equal to 52.2 MJ$\cdot$kg^{-1}, while δ_{CH4} was assumed equal to 0.77 kg$\cdot$m^{-3}. The investment profitability is assessed in light of the Italian regulations, which include feed-in-tariffs for electricity and thermal energy. For the electricity grid network, the cost was assumed equal to 0.22 EUR$\cdot$kWh^{-1}, while for natural gas the cost was assumedequal to 0.96 EUR$\cdot$kg^{-1}, these are the costs currently reported in [26].

Results and discussion

The coefficient of performance (COP) of the heat pumps is 4 for configuration i) while the gas utilization efficiency (GUE) of the ii) systems is 1.6 and the heating consumption of methane is 2.2 kgh^{-1}. The yearly $T_{i,av}$ air temperature inside the greenhouse is fixed around 22 ºC, while the monthly average nocturnal temperatureswere reported in Table 1 and Fig.2-a. The figures were calculated with an accuracy of three significant digits. The average temperature values have been reported in Table 1. The averages were calculated from 960 data for each month, one every 15 minutes during the night, and the corresponding standard deviations were also reported in Table 1.

Table 1

Monthly average nocturnal temperatures

Month	1	2	3	4	5	6	7	8	9	10	11	12
T_{a_AV}, ºC	7.5	7.5	9.7	12.5	18.5	21.8	26.3	24.9	21.3	16.4	11.9	8.6
T_{a_σ}, ºC	0.97	0.95	1.16	0.67	1.29	1.45	0.61	1.2	1.1	0.75	1.39	0.69

The greenhouse heat power loss and the heating hour are shown in Fig. 2-b. During summer the heating is not required and, on the contrary, for the Mediterranean latitudes, thermal cooling power is necessary. Most hours of heating are therefore concentrated in the four winter months from November to February. The consumption of electricity and natural gas is maximum in January and February and reaches the threshold of 4.5 GWh·month^{-1} for electricity and 2000 kg·month^{-1} for natural gas respectively. It must also be considered that the supply of methane is much easier to implement, while it is more difficult in terms of the way it is to obtain a supply of 50 kW of electric power (Fig. 2-c). For each month the cost of electricity for the GSHP is about 30 % greater than the cost of natural gas needed to achieve the same greenhouse heating effect given by GSGHP. Furthermore, the cost, if only electricity is needed for the operation of the GSHP, without considering the other management costs, reaches the threshold of 1000 EUR·month^{-1} during the coldest winter months, while the consumption of methane is about 780 EUR·month^{-1}, from a reduction of 870 EUR·year^{-1} (Fig. 2-d).

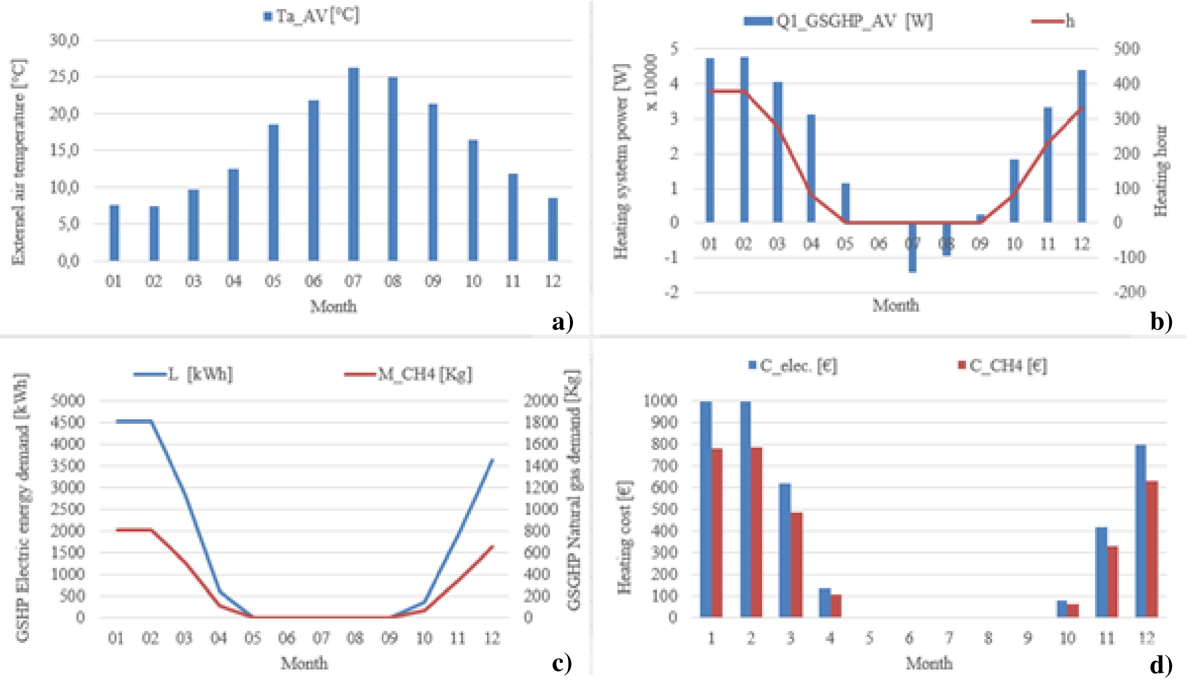

Fig. 2. **Greenhouse:** a – monthly average nocturnal temperaturesb) heat systems power and heating; c – GSHP electric energy demand and GSGHP natural gas demand; d – cost of electric energy and natural gas for heating

The heating system increased the greenhouse average air temperatures between 6 ºC and 15 ºC respect to the external air temperatures and climate conditions. Average hot water outlet temperatures between 40 ºC and 50 ºC are obtained over the considered range of the external operating parameters and this met the temperature demand of the greenhouse.

Conclusions

1. The experimental results showedthat both GSHP and GSGHP integration systems areeffective, efficient, ecological and sustainable for supply of the heating energy demand of the greenhouse.
2. The use of the GSGHP system allowed a cost saving of 30 % month^{-1}in comparison with the GSHP system and bothensure an increase of the internal greenhouse air temperature of 6-15 ºC respect to the outside air temperature.
3. GSGHP and GSHP systems arevery sustainable in the Mediterranean area, while for the regions of northern Europe they are suitable only if coupled with other traditional heating systems that raise the enthalpy of the water coming out from the heat pump. It must be considered that by raising the water temperature coming out to the heat pumpthe COP decreases [27-31].
4. Both experimental systems allow also to lowerthe emissions of CO_2 in comparison with other traditional systems. Future developments of the research will evaluate the life cycle assessment of the two solutions to investigate the overall sustainability.

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