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Application of basket geothermal heat exchangers for sustainable greenhouse cultivation

Barbaresi A.[1*], Maioli V.[1], Bovo M.[1], Tinti F.[2], Torreggiani D.[1], Tassinari P.[1]
[1]Department of Agricultural and Food Sciences, University of Bologna, Italy
[2]Department of Civil, Chemical, Environmental and Materials Engineering, University of Bologna, Italy

ABSTRACT
The residential building sector is recently experiencing a large reduction of energy demand for conditioning, nevertheless, the use of energy in agro-industrial productions is constantly growing and the research of alternative and more sustainable sources has become necessary. In the greenhouses production, the energy problem is relevant since high demand is required, even for long periods with considerable peak requests and the use of renewable energy sources in such productions can allow a significant reduction of fossil fuel consumptions, greenhouse gas emissions and running costs.
In this context, this paper analyses the performance of a low-enthalpy geothermal system, consisting of basket geothermal heat exchangers with a ground source heat pump, specifically studied to provide the base load for winter heating demand of a greenhouse. Due to the large thermal demand requested by the greenhouse, the existent pressurized gas boiler and two existent air source heat pumps, now also converted to work in heating mode, cover the remnant demand. Based on the thermo-hygrometric data, collected during an experimental campaign carried out on a case study farm, the study evaluates the performance of the geothermal system prescribing the optimal thermo-hygrometric conditions requested for the production of three different protected crops. The shallow geothermal field operates mainly during the night-time, allowing the thermal recover of the ground during the daytime. The results provide an assessment of the performances of the hybrid system in terms of primary energy needs, running costs and CO_2 with respect to the existent system.

Highlights:
BGHE used in hybrid configuration can improve greenhouse cultivation sustainability
The performance of the shallow geothermal field is evaluated and discussed
The numerical results are obtained from experimental data
Hybrid system allows primary energy savings from 20% to 40%
GHG emissions and running costs can be reduced from 10% to 30%

Keywords: greenhouse design; protected crop; renewable energy; basket geothermal heat exchanger; shallow geothermal energy

Word count: 9345

*= Corresponding Author: Alberto Barbaresi, viale Giuseppe Fanin, 48 – 40127 Bologna (Italy).
Tel: +39 051 2096197 email: alberto.barbaresi@unibo.it

List of abbreviations

Abbreviation	Description
RE	Renewable Energy
RES	Renewable Energy Sources
SGHE	Shallow Geothermal Heat Exchangers
BGHE	Basket Geothermal Heat Exchangers
GSHP	Ground Source Heat Pump
PGB	Pressurized Gas Boiler
ASHP	Air Source Heat Pumps
TRT	Thermal Response Test
SPF	Seasonal Performance Factor
PEN_{exi}	Primary ENergy consumptions of the existent system
PEN_{des}	Primary ENergy consumptions of the designed system
COP	Coefficient Of Performance
COP_{aux}	COP considering the auxiliary devices
C_{exi}	operating heating Costs of the existent system
C_{des}	operating heating Costs of the designed system
EMI_{exi}	equivalent EMIssions of the existent system
EMI_{des}	equivalent EMIssions of the designed system
EN	Energy Need
S_E	Primary energy saving
S_C	Operating cost savings for heating
S_{GHG}	GHG emission saving
EP_{tot}	Energy performance
$EP_{pr.en}$	Primary energy performance
EP_{basket}	Contribution of basket in primary energy performance

1. Introduction

It is well known that the emissions of the agricultural sector are relevant and comparable to those of the transport and residential sectors [1] and various countries have stipulated agreements and signed treaties in order to face the climate change issues also deriving by the high worldwide energy demand. This aspect was highlighted since 2015 Climate Change Conference [2] where the role of agriculture for climate change mitigation was discussed, being one of the most polluting sectors. The European Commission is encouraging and funding new projects improving knowledge, development, production and distribution of Renewable Energy (RE) and facilitate investments in the green industry [3]. In this context, the geothermal energy development can quickly accelerate the conversion of the existing farms towards the use of green energy sources and speed up the decarbonisation of the agriculture also in the European area [4,5]. Among the various crop production, the protected crops represent one of the most energy-demanding sectors and literature reports just few data related to the consumptions. In the 2014, in Italy, the surface covered by greenhouses exceeds 42 000 hectares, 37 000 of which dedicated to horticultural crops and more than 5 000 for floricultural crops. During the cold season the energy necessary for greenhouse heating can entail remarkable costs in terms of fossil fuel, representing on average, more than 25% of the overall energy consumption of the whole process related to protected crops productions [6]. Furthermore, the energy production sector is the main source of emissions in Italy with a share of more than 80%, including fugitive emissions, for many pollutants (SO_X 89%; NO_X 92%; CO 94%; PM2.5 88%; BC 92%; Cd 83% as reported in ISPRA [7]) so reducing the energy use indirectly contributes to decrease pollutant emissions.

Despite the funding and subsides, provided in the last decades at European [8] and local [9] levels, the problem of a sustainable rural development is still existing and improvements should be done [10].

In the recent years, different RES (Renewable Energy Sources), currently adopted in residential buildings, were firstly investigated and then applied to the agricultural and industrial production context [11–15], greenhouses included [16–19]. To date, one of the most promising RES for farm facilities is represented by shallow geothermal energy [20] already widely used for residential conditioning [21].

Among the variety of geothermal solutions, a prominent role is taken by the geothermal heat pump or ground source heat pump (GSHP) systems. A GSHP is a heating and cooling system able to transfer heat to or from the ground [22]. In its most simplistic version, it is composed by geothermal heat exchangers (GHEs), buried underground, and by a heat pump, generally working with electricity-fed compression and, to a lesser extent, with gas absorption [23]. Reaching high efficiency levels of GSHP, with subsequent low electricity consumption, depends on keeping circulating fluid temperature in the GHEs as close as possible to the terminals' working temperature [24]. This is assured, specific for each project, by a combination of: stable underground temperature, high ground thermal conductivity, low GHEs thermal resistance, sufficient number of GHEs composing the geothermal field [25].

As supported by some recent research works, application of geothermal heat pump is raising a growing interest also in the agricultural field, since they could be a sustainable solution allowing for the reduction of both energy costs and CO_2 emissions [26]. For example, one application can be found in wineries, where the cooling need represents a high percentage of total energy consumption [27,28]. More specifically in the greenhouse sector, Sethi and Sharma [29] studied an aquifer coupled cavity flow heat exchanger system (ACCFHES), designed using underground water for heating and cooling a composite-climate greenhouse. Benli et Durmus [30] studied a combined ground source heat pump phase-change-material latent heat storage system, developed to use the natural energy for greenhouse thermal control. More recently, Anifantis et al. [31] performed an experimental work on a real case study greenhouse, aiming to the evaluation of the suitability of low enthalpy geothermal heat source for heating. These recent outcomes proved that the usage of ground as the natural source of heat pumps is effective, efficient and environmentally sustainable if applied to agricultural sector as well. Moreover, a reduction of the construction costs could furtherly facilitate the diffusion of geothermal technologies in the agricultural field and this may be obtained for example by considering simple geothermal systems easy to be implemented by the farmers themselves [32].

On one hand, since greenhouses are high-energy demanding structures, if compared to residential buildings with the same area, especially for crops particularly sensitive to changes in the environmental conditions, the adoption of renewable energy sources can provide a considerable reduction of the energy need for heating. On the other hand, given the typical low capacity provided by single geothermal heat exchangers [33], and the need of proper greenhouse insulation for the heat pumps to work at decent yield [34], their use requires a specific design of the farm building, being building envelope and conditioning system optimization strictly correlated (see for example Fabrizio [35] and Djevic et al. [36]).

Several authors carried out theoretical studies and experimental tests on the application of geothermal systems to greenhouse heating, with regard to both open-loop and closed-loop systems [29]. With reference to closed-loop system technology, they focused on different aspects: Fuji et al. [37] studied the efficiency of heat capture systems considering different configurations of heat exchangers, while Benli and Durmus [30] analysed the efficiency in extracted heat exploitation. Moreover, in the recent years, a significant progress was achieved in the development of shallow geothermal heat exchangers (SGHE), which can exploit the insulation potential of surface ground layers from weather temperature. Florides et al. [38] analysed SGHE, showing that for suitable geometric configurations the energy efficiency of shallower systems can result equal or higher than systems with deep vertical probes. Even though their performances were not investigated thoroughly so far, basket geothermal heat exchangers (BGHE) represent an effective compromise between horizontal and vertical probes. On one hand, working at around a depth from 0.5m to 2-3m below the ground level, they require lower initial excavation costs compared to vertical probes, which entail higher drilling costs. On the other hand, BGHEs require smaller extensions compared to horizontal probes, due to their conical or cylindrical configuration [39–42]. Other studies demonstrated that the ground volume involved by the BGHE is affected by seasonal climate variations, meaning that the ground does not reach the "neutral zone", at constant temperature, usually found at depths of 10 m and more, varying based on hydrogeological conditions [43–46]. Therefore, the adoption of BGHE prevents the rapid heat reintegration after thermal exchange between the probes and the ground, thus decreasing the geothermal system performance [47]. This aspect is an important issue when exchangers are used steadily and for long periods [48,49]. For this reason, more than other alternative heating and cooling systems, BGHE systems need a proper design in order to maximize the system efficiency. The most important input information come from quantification of ground thermal exchange potential, which is generally based on preliminary experimental tests [50]. To this regard, accurate field data, collected for a sufficient period and close to the site installation, must be available to get reliable design parameters.

Summing up, solutions able to reduce the energy need in agricultural buildings (such as greenhouses) are more and more required. Nevertheless, facilities are often provided with existing heating systems. Besides, the shallow geothermal technology proved to be easily applicable in those structures due to both its compatibility and the availability of wide external space in rural areas. The present work proposes a methodology oriented to define the building characteristics and needs, to design a cost-effective geothermal system and to assess the results in terms of energy, cost and carbon savings.

Specifically, the methodology was applied to the existing greenhouse of the University of Bologna and selected as case study. The study focuses on the analysis of the expected performance of an energy retrofitting intervention applied to the existent heating system. The current configuration is composed by a pressurized gas boiler (PGB) for heating and two air source heat pumps (ASHP) used only for cooling. The retrofitting intervention provides for the addition of a BGHE coupled to a ground source heat pump (GSHP) to cover the base load in cold season and converts the two ASHPs in heating mode, thus transforming the system operational into hybrid. As far as the cold season only is concerned, no interventions on the cooling system were hypothesized for now, since, for the case study here investigated, the energy consumptions for cooling represent a negligible percentage of the yearly energy needs. In fact, the cooling system operates for a limited number of hours along the year seeing that important benefits are achieved with the natural ventilation of the building [51]. In particular, the study presents the system design, sizes the intervention based on thermal response test (TRT) field data [52] and assesses the gains in terms of energy needs, running costs and CO_2 emissions reductions, which can be achieved by installing the new equipment.

Mostly differently from previous works cited and known literature, attention was specifically paid on understanding the differential behaviour of BGHEs throughout the year, subjected to natural weather and climate variations. A second innovation aspect resides in the optimization attempt of the integrated system (PGB-GSHP-ASHP), allowing the BGHEs working in the best possible conditions (mostly covering the base load), without ground heat overexploitation and at the same time reducing the BGHEs field dimension and related installation costs.

By comparing the energy needs for the two configurations (i.e. existent and design), the performances of the BGHE-GSHP are evaluated on the basis of the real temperature and humidity conditions recorded inside the greenhouses for a four-year monitoring period (Scenario 1). Moreover, the performances of the retrofitted system were used for the assessment of the achievable savings with reference to three different optimal thermo-hygrometric conditions requested for the production of three different protected crops (Scenario 2).

2. Materials and Methods

The paper focuses on the feasibility study and performances evaluation of the new geothermal system used to cover the base load of a greenhouse structure. The work is mainly composed of three phases:

- acquisition of geometry of the building, energy needs, ground thermal behaviour and characterization, indoor and outdoor thermo-hygrometric conditions, climatic analysis of the surrounding area (input data);
- planning and design of the new geothermal heating system necessary to support the existent one;
- evaluation of the performances (output data) of the hybrid system, by comparing the current configuration and the design configuration, expressed in terms of energy needs, running costs and CO_2 emissions for two scenarios.

As better explained in the following sections, the present study is based on real data (monitored, collected and experimental). Specifically, the data monitored and collected in the greenhouse about environmental conditions, heating systems' performance and energy consumptions, allowed to precisely calibrate the energy model and define the conditions of Scenario 1.

The experiment carried out to test the geothermal exchangers (TRT test), returned accurate data on the actual performance of the exchangers investigated in this work.

The scheme of the research has been reported in Figure 1.

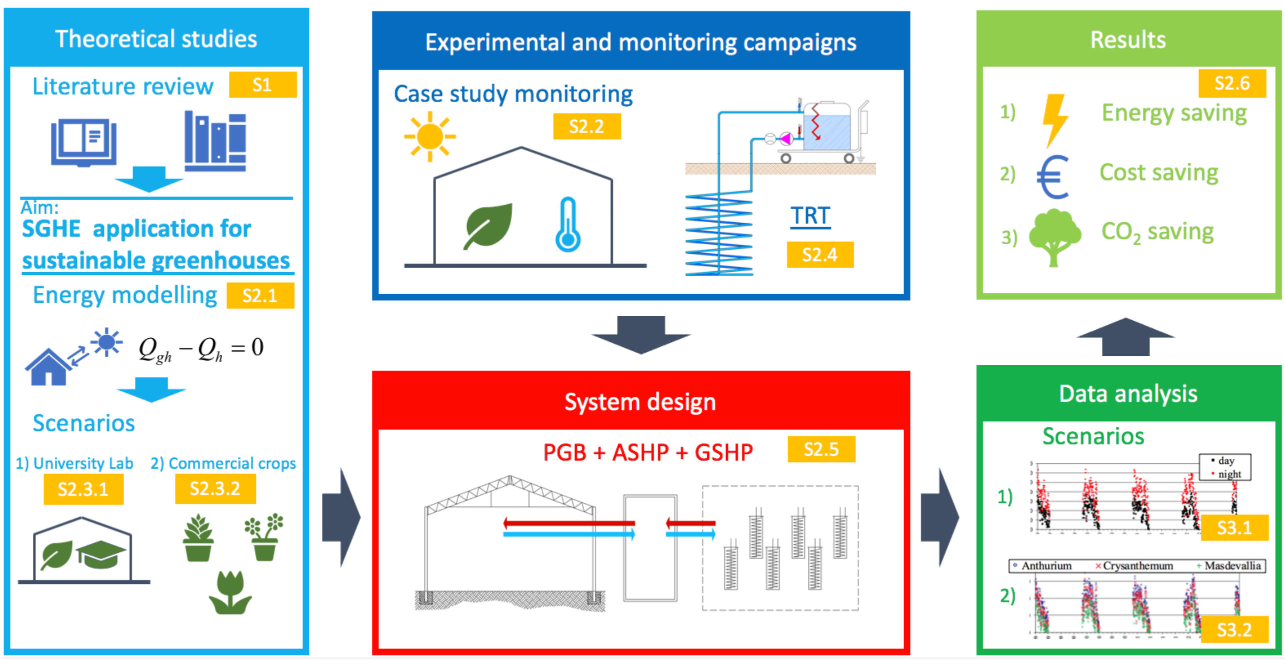


Figure 1. Scheme reporting a graphical explanation of the research process. The yellow rectangles refer to the sections in the present manuscript where S identifies the section.

2.1 Energy modelling

The hourly thermal energy balance for a greenhouse can be expressed, in general, according to the Eq. (1) provided by De Luca et al. [39]:

$$Q_{gh} - Q_h = 0 \tag{1}$$

where: Q_{gh} [W] is the heat dispersed from the greenhouse and Q_h [W] is the heat generated by the heating system. Then:

$$Q_{gh} = Q_c + (Q_{vs} + Q_{vl}) + Q_i - Q_s \tag{2}$$

where: Q_c [W] represents heat losses for conduction and convection through roof, lateral surface and ground; Q_{vs} [W] and Q_{vl} [W] are the sensible and the latent heat dispersed for ventilation by evaporation respectively; Q_i [W] is the net heat dispersed by radiation (difference between the radiation emitted from the greenhouse surface and the thermal radiation from the atmospheric air); Q_s [W] is the heat absorbed for solar radiation by the greenhouse (the term contributes to the greenhouse heating). Moreover, it is possible to evaluate each term in Eq. (2) as a function of greenhouse geometrical dimensions and materials characteristics, indoor/outdoor thermo-hygrometric conditions. So, we can express the various terms as follows:

$$Q_c = K_t \cdot A_r \cdot (T_{in} - T_{out}) + K_t \cdot A_w \cdot (T_{in} - T_{out}) + K_g \cdot A_c \cdot (T_{in} - T_g) \quad (3)$$

$$Q_{vs} = \dot{m}_a \cdot [c_{pa} \cdot (T_{in} - T_{out})] \quad (4)$$

$$Q_{vl} = \dot{m}_a \cdot [r_i \cdot X_{ai} - r_{out} \cdot X_{aout} + c_{ps} \cdot (X_{ai} \cdot T_{in} - X_{aout} \cdot T_{out})] \quad (5)$$

$$Q_i = \tau_{LW} \cdot \sigma \cdot (A_r + A_w) \cdot (\varepsilon_c \cdot T_{in}^4 - \varepsilon_v \cdot T_s^4) \quad (6)$$

$$Q_s = \alpha_s \cdot A_c \cdot R \quad (7)$$

The complete list of data, variables and parameters introduced from Eq. (3) to Eq. (7) is reported for the sake of clarity in Table 1.

The airflow $\dot{m}_a$ [kg s^{-1}] has been evaluated as follows:

$$\dot{m}_a = \frac{N}{3600} \cdot \rho_a \cdot V \quad (8)$$

For the case at hand, the roof and side vents are set to automatically open when the indoor air temperature T_{in} exceeds 26°C. Consequently, N has been set equal to 1 when vents are closed ($T_{in} \leq$ 26°C) and the airflow is driven by natural air infiltration, door openings and work operations inside the greenhouse (this allows to increase CO_2 concentration as reported in [53] while avoid an indoor air temperature reduction) and equal to 7 when vents are open (for $T_{in} >$ 26°C).

By the evaluation of each contribution from the expressions from Eq. (3) to Eq. (7) is possible to find the hourly heat dispersed from the greenhouse and consequently to obtain the necessary heat quantity that the heating system must provide to keep the prescribed thermo-hygrometric conditions. By the integrations of these hourly quantities is then possible to derive the daily or the interested period total amount. The thermal energy balance was introduced in a spreadsheet in order to quickly quantify the values of Q_h for different input conditions.

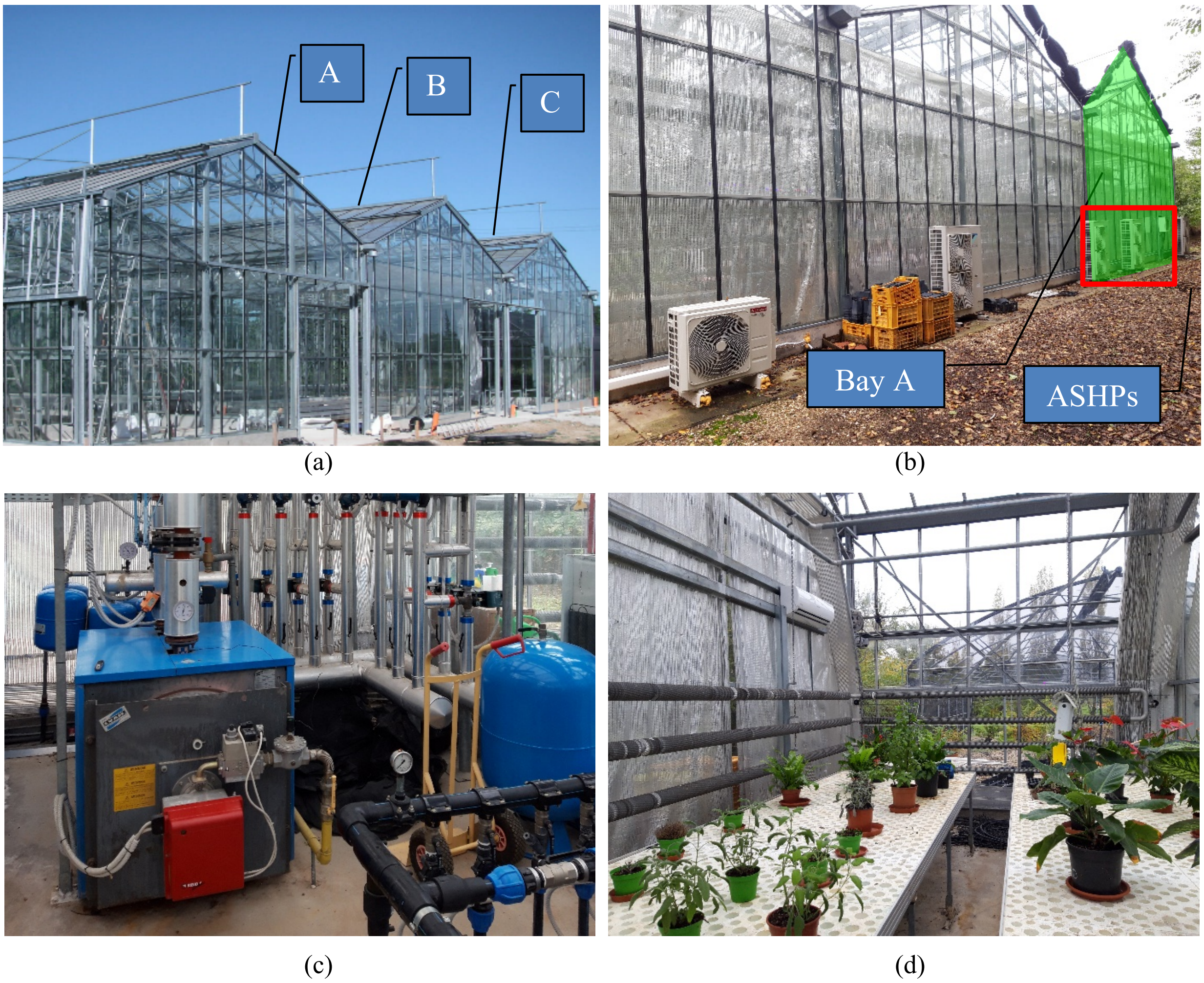
Table 1. List of geometrical greenhouse data, variables and parameters used in Eq. (3)-Eq. (7).

		Geometrical greenhouse data
A_c	[m^2]	*Area covered by the greenhouse (horizontal projection)*
A_r	[m^2]	*Area of the transparent roof surface*
A_w	[m^2]	*Area of the transparent lateral surface*
V	[m^3]	*Volume*
		Variables
T_{in}	[°C]	*Indoor air temperature*
T_{out}	[°C]	*Outdoor air temperature*
rH_{in}	[-]	*Indoor relative humidity*
rH_{out}	[-]	*Outdoor relative humidity*
$\dot{m}_a$	[$kg\ s^{-1}$]	*Airflow*
r_{in}	[$J\ kg^{-1}$]	*Specific latent heat of evaporation at the indoor temperature*
r_{out}	[$J\ kg^{-1}$]	*Specific latent heat of evaporation at the outdoor temperature*
$X_{a,in}$	[-]	*Humidity ratio of moist air at the indoor temperature*
$X_{a,out}$	[-]	*Humidity ratio of moist air at the outdoor temperature*
R	[$W\ m^{-2}$]	*Solar radiance*
		Parameters
α_s	[-]	*Solar radiation absorptivity of greenhouse material (i.e. glass)*
K_t	[$W\ m^{-2}\ °C^{-1}$]	*Thermal transmittance of roof and walls material (i.e. glass)*
K_g	[$W\ m^{-2}\ °C^{-1}$]	*Convective heat transfer coefficient*
ε_c	[-]	*Emissivity coefficient of roof and wall material (i.e. glass)*
ε_v	[-]	*Emissivity coefficient of the celestial vault*
T_s	[°C]	*Apparent sky temperature*
T_g	[°C]	*Groundwater temperature*
$N = 1$ if $T_{in} \leq 26°C$	[h^{-1}]	*Air changes per hour*
$N = 7$ if $T_{in} > 26°C$	[h^{-1}]	*Air changes per hour*
τ_{LW}	[-]	*Medium-long infrared transmission coefficient of greenhouse material (i.e. glass)*
c_{pa}	[$J\ kg^{-1}\ °C^{-1}$]	*Specific heat of moist air at a constant pressure*
c_{ps}	[$J\ kg^{-1}\ °C^{-1}$]	*Specific heat of steam at a constant pressure*
σ	[$W\ °C^{-4}\ m^{-2}$]	*Stefan–Boltzmann constant*
ρ_w	[$kg\ m^{-3}$]	*Water density*
ρ_a	[$kg\ m^{-3}$]	*Moist air density*

2.2 *Description of the case study*

The structure selected as case study in this work is an experimental three-bay greenhouse of the University of Bologna, located in Imola (in the Northeast of Italy, 40 km from Bologna). This building is representative of the majority of greenhouses located in the Central Italy, in terms of dimensions, materials, shape and orientation, moreover, is equipped with precise environmental condition monitoring systems and energy consumption data are constantly recorded. These characteristics allow accurate calibration for this work.

Every bay of the building is realized with a steel structure covered by 4mm clear tempered glass. Views of the greenhouse are reported in Figure 2.



(a) (b) (c) (d)

Figure 2. Pictures of the greenhouse selected as case study. (a) External frontal view; (b) External back view with details of the bay "A" object of the study (green shaded) and the two ASHPs external machine currently used for cooling (red rectangle); (c) Detail of the gas boiler used for heating; (d) Internal view with particular of the perimeter iron radiators.

Each bay has in plan dimension of 8.0m×12.7m (width × length) and the total building is about 24.0m×12.7m. The layout of the greenhouse area is showed in Figure 3a whereas the plan view of the building is detailed in Figure 3b. In particular, the work focuses on one of the three bays, labelled A in Figure 3, Bay A is divided into two different volumes: the technical room A1, about 4.7m×8.0m, unheated, containing the equipment used for the experimental activities and the actual heating system, and the growing room A2, about 8.0m×8.0m with an area of 64 m^2, used for crops production. Three sliding doors, made of aluminium and glass, connect respectively technical and growing room (door dimension 1.7m×2.8m), the outdoor area (door dimension 2.4m×3.2m) and the adjacent bay (door dimension 1.7m×2.8m). Each bay has eave height of 4.0m and ridge height of 5.5m. The greenhouse is remarkably higher than similar one due to the University experiment needs. The roof pitch is around 38% (see Figure 3c).

The structure has two roof vents 1.5m wide, positioned symmetrically with respect to the ridge line and a lateral vertical vent, high 1.5m and starting from 2.5m from the ground level (i.e. until the eave). Both the roof and lateral vents run for the whole length of the building and are automatically open if the indoor temperature overpass 26°C allowing the natural ventilation of the two rooms.

The actual 3-span greenhouse heating equipment consists of a pressurized gas boiler (PGB) with furnace thermal capacity of 211 kW and a nominal thermal capacity of 192 kW (Figure 2c) and iron cast radiators positioned along two sides of the growing room (Figure 2d). Two reversible Air Source Heat Pumps (ASHP) are installed for summer cooling with nominal thermal capacity of 11.2kW each one (Figure 2b). In the existent configuration, the PGB provides the heating in the cold season whereas the ASHP is responsible of the cooling during the hot period.

In addition to the greenhouse, the University of Bologna has the availability of a limited external area surrounding the building. This area, currently free of obstacles and constraints, is about 460m^2 (grey hatched in Figure 3a). The design of the new geothermal system of BGHE is based to fit with this available area.

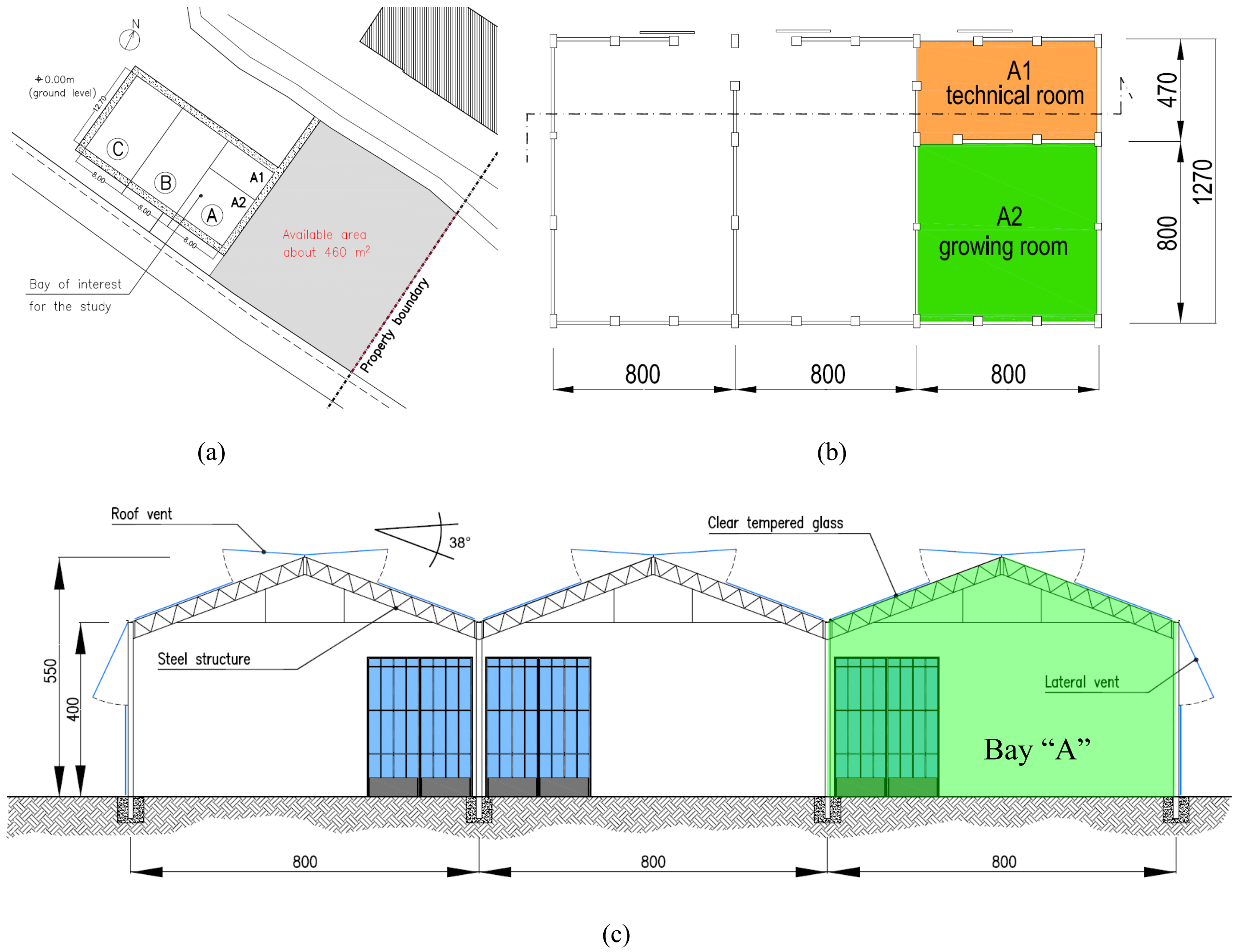


Figure 3. Layout of the greenhouse and surrounding area. (a) Plan view of the whole area. (b) Plan view of the building. (c) Vertical section of the building.

Being the greenhouse a university building, it is currently used as laboratory for different investigations and experiments on various crops species. However, the building technology and the data on energy consumptions are representative of several greenhouse establishments with productive use.

2.3 Indoor and outdoor thermo-hygrometric conditions

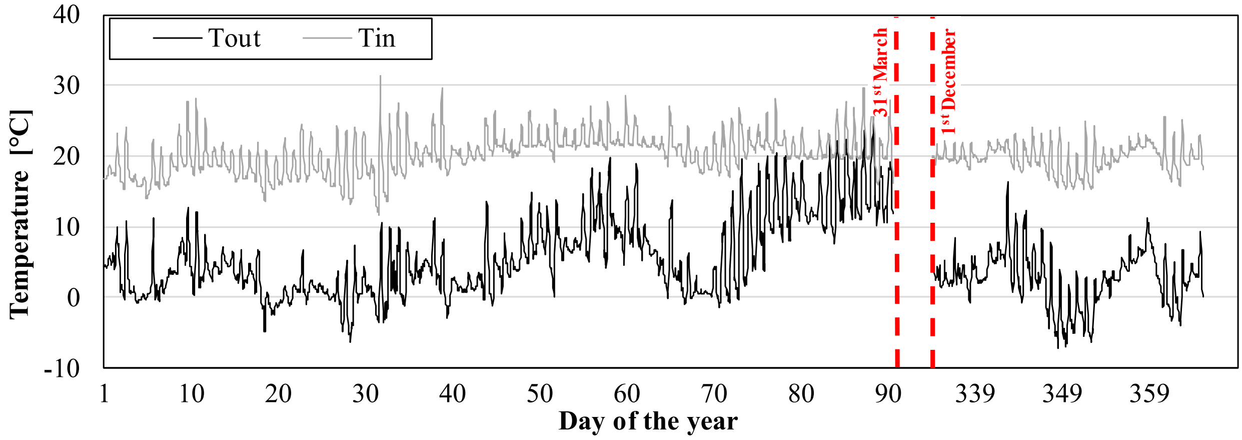
The indoor and outdoor thermo-hygrometric conditions define the greenhouse loads in cold and hot seasons. Therefore, the energy model adopted uses as input data the air temperature (T) and the relative humidity (rH), both inside and outside the building. Regarding the indoor conditions, for the present study, two scenarios were considered and analysed:

- the first one illustrates the standard situation of the greenhouse used as university lab. It is based on the environmental monitoring campaign, developed in the period 2009-2012. Practically, Scenario 1 refers to the indoor temperature and humidity values recorded during the monitoring campaign. These values are related to the experimental campaigns underway within the experimental greenhouse and are not imposed by production needs. This scenario was mainly used to validate the energy model described in section 2.1 and the validation was obtained by comparing the real energy consumptions of the greenhouse (derived from the bills) with those assessed by the numerical model.
- the second one considers the optimal indoor conditions for crops with different endurance. Scenario 2 considers optimal indoor temperature and humidity values derived by the literature in the field, for three ornamental crops. Three very spread crops, grown in greenhouse in the cold periods, were selected in the works having different thermo-hygrometric optimal conditions, so to test the designed heating system under different operative conditions. Obviously, considering their ornamental purpose, the indicated daytime and night-time values, for both temperature and humidity, are the optimal values to maintain inside the greenhouse in order to have the best aesthetic performance avoiding crop damages, frequently caused by sudden modifications in temperature and/or humidity.
- Regarding the outdoor conditions, the measured data are considered representative of the weather conditions of the region and then they were used for both scenarios.

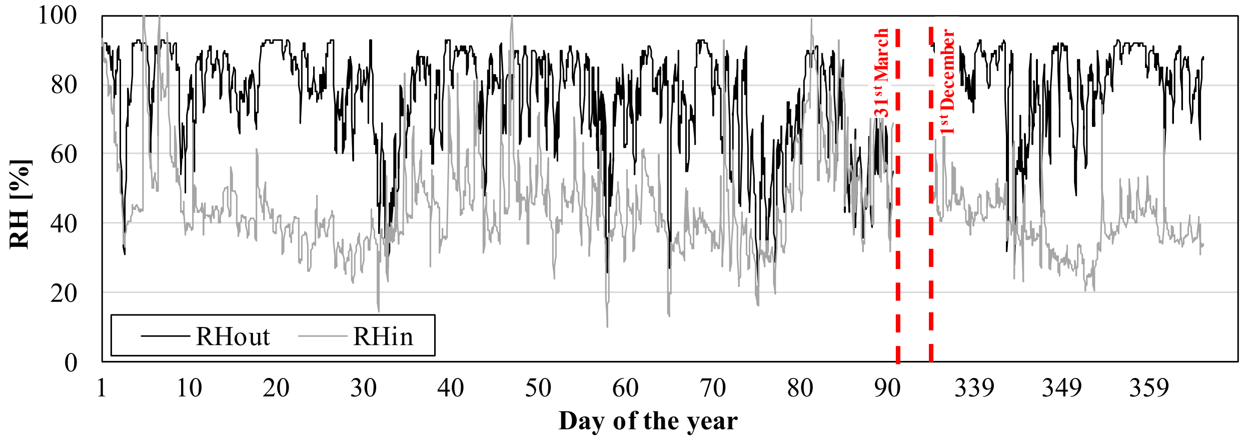
2.3.1 Scenario 1: environmental monitoring data

To measure ambient data, two thermo-hygrometer data loggers PCE HT 71 with an accuracy of ± 3% on rH and ±1°C on temperature were positioned inside the greenhouse (according to Barbaresi et al. [54] procedure) and recorded indoor T_{in} and rH_{in} from January 1st, 2009 to December 31st, 2012. Outdoor thermo-hygrometric parameters were measured, for the same period, by a weather station located in the proximity of the building. The hourly temperature recorded for the cold months (i.e.

January, February, March and December) of the year 2010 are reported as an example in Figure 4a. Similarly, in Figure 4b the rH_{out} trends are showed. The solar radiation, instead, was calculated using the available data from the closest weather station of ARPA database [55,56]. Analysing the weather data, a significant diversification of temperatures was noticed for the different years, thus in this study the recorded environmental values were chosen for the outdoor conditions, instead of the typical meteorological year of Emilia-Romagna Region.



(a)



(b)

Figure 4. Example of environmental parameters monitored during the year 2010. (a) Indoor and outdoor trend of the air temperature. (b) Indoor and outdoor trend of the air RH.

Having the records of indoor and outdoor data, a first scenario of analysis was realised. It was used firstly for the evaluation of the performance parameters of the heating system in the current configuration and then for the comparison of performances and savings after the introduction of the BGHE-GSHP equipment.

Moreover, for the case of existent heating system, the comparison among the energy values obtained by the adopted numerical model (see Paragraph 2.1) and the real energy consumptions reported in the greenhouse bills, allowed the evaluation of the reliability and accuracy of the model adopted in this work.

2.3.2 Scenario 2: optimal conditions for crops cultivation

A second analysis scenario was created based on the theoretical thermo-hygrometric conditions for the optimal growing of three different protected crops. In this case, the outdoor air conditions in input are the same used in the previous case (i.e. the recorded data in the years 2009-2012), while the imposed indoor conditions were the optimal T_{in} and rH_{in} values of each crop. The three crops were selected with different endurance, in order to cover different temperature ranges so to test the performance of existing and design heating systems under different conditions. The three flower crops selected for the study are the following:

- *Anthurium:* a very delicate plant. It is a tropical plant, so the thermo-hygrometric parameters needed for a proper growing are different from those typical of the Mediterranean climate. The optimal conditions [57,58] have a reduced range of variation:
  - temperature considered for nightly hours: T_{in} 18°C,
  - temperature considered for daily hours: T_{in} 20°C,
  - relative humidity for daily and nightly hours: rH_{in} 85 %.
- *Chrysanthemum:* a moderately sensitive plant. Optimal conditions can afford higher variation [59,60]:

    - temperature considered for nightly hours: T_{in} 14°C,
    - temperature considered for daily hours: T_{in} around 22°C,
    - relative humidity for daily and nightly hours: rH_{in} 65 %.
- *Masdevallia orchid:* plant able to resists temperature colder than the first two considered. It results less sensitive to the variations in the thermo-hygrometric conditions [61,62]:
    - temperature for nightly hours: T_{in} 10°C,
    - temperature for daily hours: T_{in} 17°C,
    - relative humidity for daily and nightly hours: rH_{in} 65 %.

2.4 Investigation on potential of BGHE

In order to quantify the thermal exchange potential between the ground and a SGHE, the most common technique is the thermal response test (TRT), which consists in injecting heat (through a fluid) inside the pipes for a limited amount of time and analyse the thermal response. For vertical probes, being the air temperature fluctuations generally negligible, such type of analysis can provide information on the equivalent ground thermal parameters (thermal conductivity and heat capacity), ground temperature and geothermal gradient and deviation between theoretical thermal performance and the one derived by practical installation [52,63]. On the contrary, BGHE performances are strongly affected by seasonal air temperature fluctuations, therefore it is not possible to get stable design values from a TRT. On the other hand, the insertion of a BGHE inside the ground is much less affected by practical deviations than vertical probes, so the thermal design is supposed to be respected in the field. For all these reasons, a TRT performed on a BGHE allows to evaluate the thermal response of the ground limited to the specific weather and boundary conditions of the test.

By knowing thermal parameters of BGHE, design loads of the building, parameters of the heat pump, behaviour of ground temperature waves along the year, as well as some weather data such as rainfall quantity, it is possible to simulate a realistic thermal exchange between the ground and the BGHE for different periods of the year.

A long term TRT on the BGHE considered in the present study was performed on a site with similar geological, hydrogeological and weather conditions and located in the proximity of the greenhouse case study. This allowed integrating existing datasets and benefit of longer time series. This procedure was performed with a machine specifically built for this test and returned precise experimental data that integrated the literature data improving the reliability of simulations. All details of the TRT can be found in Ferrari et al. [64] and Tinti et al. [32], and the main data useful for the design are synthetically reported in the Appendix.

The ground temperature data of the original TRT were modified to respect the new information of outdoor temperature collected by the greenhouse weather station and respecting a slightly different stratigraphy.

The definitions of the ground thermal parameters were deduced by the results of mentioned previous works and from the use of standard tables according to UNI 11466 [65]. They are summarized in Table 2.

Table 2. Thermo-physical properties of the soil

Heat capacity C_{tg} [J·(K^{-1}·m^{-3})]	Density ρ_g [kg·m^{-3}]	Thermal conductivity λ_g [W·(m^{-1}·K^{-1})]	Mean diffusivity α_g [m^2·d^{-1}]
3277240	2.1	1.1	0.029

The ground temperature curve was approximated by the analytical equation of heat diffusion in a semi-infinite plane due to a sinusoidal trend of temperature, inserting the information on weather station and ground thermal properties [66].

Moreover, with the moving average technique, a temperature data set was calculated considering a period of one year and, by means of the least square regression, was used to calibrate the model starting from the outdoor temperature. Average yearly air temperature (coinciding with average ground temperature) and amplitude, measured in the weather station, are respectively T_g = 15.39°C and Amp=16.09°C. Finally, to set up a starting point of the ground temperature wave, the coldest day of the year must be used. By the experimental data in the four-year considered period, the 21/12/2009 was selected. The ground temperature, at 11.0m of depth, shows the maximum variation of 0.12°C from the average T_g. It represents the 0.78% of the average temperature of the model. At 12.0m of depth, the maximum variation is about 0.38%. On the other hand, the temperature at the depth of installation of the BGHE (around 2 m) has 34.5% of maximum variation from the temperature of the neutral zone.

Four different trends of the ground temperature are shown for four chosen depths, interesting the BGHE, with equal support intervals. As an example, the ground temperatures trends are shown in

Figure 5 for some reference depths, for the Year 2010. All the acquired information allowed to simulate the behaviour of the BGHE under different loads along the year, by using the methodology described in Tinti et al. [32].

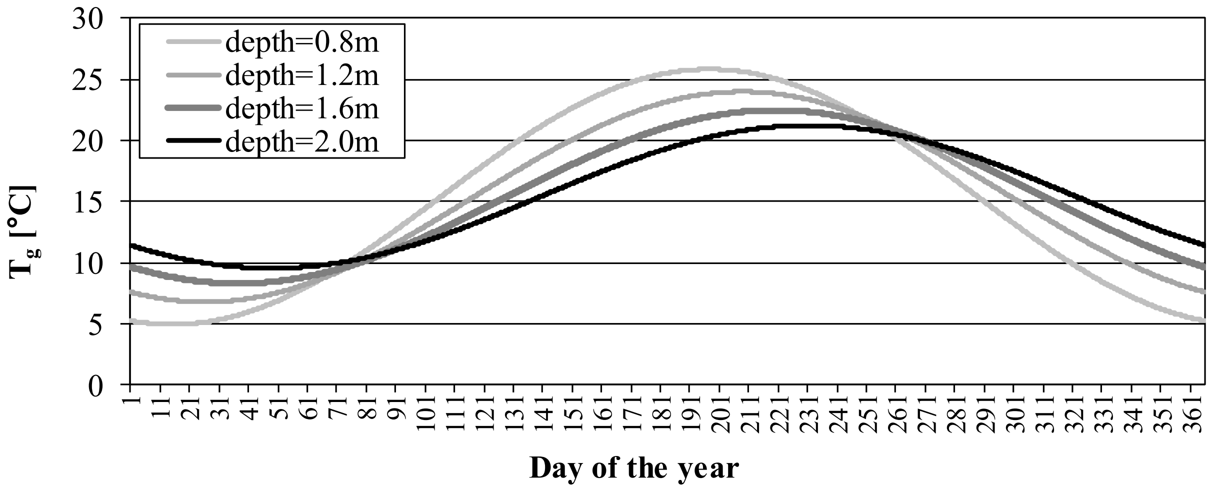


Figure 5. Trend of ground temperature T_g to different reference depths, for the Year 2010.

2.5 Design of the geothermal hybrid system

For the purposes of this paper, the BGHE-GSHP system will be added, as support, to the current heating system. Being the outdoor available space not sufficient for the BGHE to work alone in any condition of the year, it was thought to exploit the maximum efficiency from all the systems already present combining them with the GSHP. For this purpose, to optimally cover the heating demand, the hybrid system was designed to work in different ways during day and night. During the night, with the maximum heat request, the existent PGB works coupled with the BGHE-GSHP. Differently, during the day, the PGB works coupled to the ASHPs (exploiting the mildest T_{out}), thus allowing the ground to thermally recover.

Figure 6 presents a simplified scheme of the heating working system in the two modes: day and night, for the cold season.

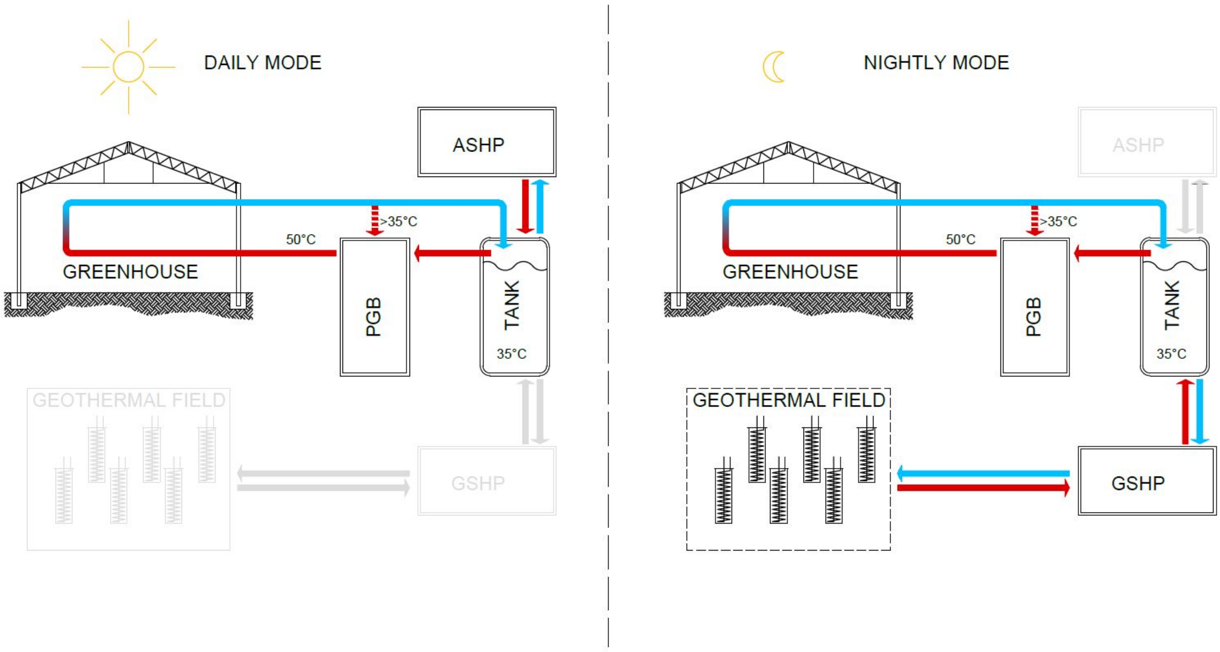


Figure 6. Simplified operating scheme showing the main parts of the system in the design configuration.

The circulating fluid working temperature in the radiators (50°C) do not allow GSHP and ASHP to work in parallel with PGB to cover the total thermal energy demand at acceptable efficiencies. Therefore, the system design includes the pre-heating by the two heat pump systems of the fluid contained in the PCB storage tank, keeping it at constant value of 35°C, and thus limiting the use of natural gas for reaching the desired 50°C. In the mild winter periods, or in exceptionally periods of work at partial loads, a three-way valve allows the bypass of heat pumps when pre-heating is not necessary.

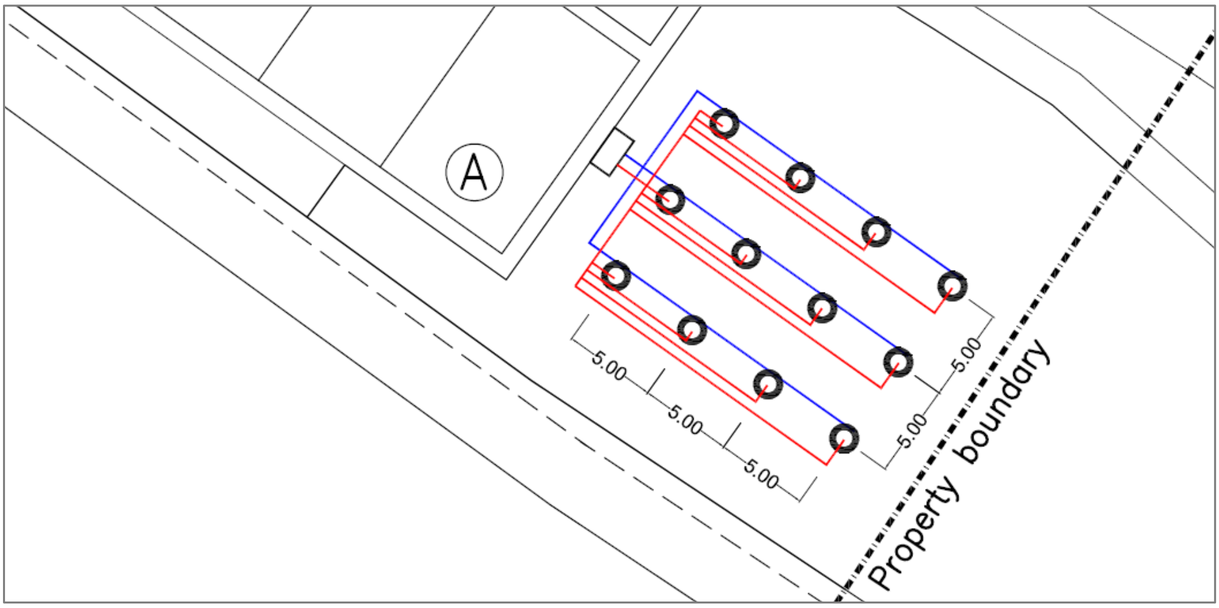
The authors considered a hybrid system since, integrated with other heating systems, BGHE coupled with GSHP can work in a partial way and only for some hours of the day, so to limit the daily ground thermal depletion and consequently avoiding efficiency losses along time. The selection of the activation hours of the GSHP is based on the solar radiance data (*R*) throughout the year: when *R* value is null, GSHP switches on to cover the base load. Therefore, during the day, with the GSHP switched off, the ground can absorb solar radiation thus partially recovering the extraction rate of heat from the BGHE field. With this load scenario, it was calculated to keep the seasonal performance factor (*SPF*) around 4.4, which is a very high value for standard SGHE solutions. For the design of the geothermal system, the parameters reported in Table 3 were adopted.

Table 3. Parameters adopted for design the geothermal system.

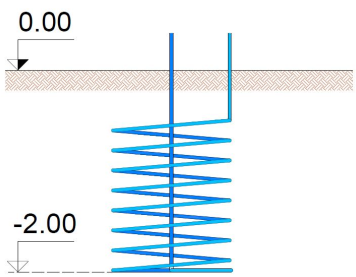
Parameters		
T_g = 289.24	[K]	*Design temperature of the ground in the winter season at the average depth of system*
$Q_{g,h}$ = 4453	[W]	*Design thermal power ground side for heating*
P_m = 0.99	[Ø]	*Correction factor for the pipes*
F_h = 0.546	[Ø]	*Load factor for heating in the design month*
R_p = 0.0826	$[(m \cdot K) \cdot W^{-1}]$	*Thermal resistance of the pipe*
R_g = 4.770	$[(m \cdot K) \cdot W^{-1}]$	*Thermal resistance in the stationary conditions*
$T_{w,i}$= 273.15	[K]	*Inlet water temperature to the GSHP (ground side)*
$T_{w,o}$= 268.15	[K]	*Outlet water temperature to the GSHP (ground side)*

To cover the total greenhouse peak demands, SGHE technology would require a larger space than the space available in this case study. This space can be sufficient for vertical probes, but it would require a highest initial investment to guarantee adequate power and long-term efficiency. Moreover, the system would result tailored on one crop application, with limited margins to modify heating requests. The limited amount of available space is a problem in many real cases of productive applications for the installation of GSHP systems [20].

The layout of BGHE field was designed with a 5m of distance between each BGHE centres, using all available space in the area surrounding the case study greenhouse (about 460 m^2), thus simulating a real case application. This allowed to distribute three sets of BGHE connected in parallel, each one containing four BGHE connected in series (see Figure 7a), for a total of twelve. Basket pipes are made of high-density polyethylene (HDPE). The spirals of the geothermal basket are positioned at a depth ranging from of 0.65m to 2.15m from ground level. After sizing the BGHE field, the preliminary static design was set by considering the most critical months, with regard to the outdoor conditions and the thermal response of the ground. The heat transfer fluid adopted is a mixture of water and propylene glycol so to reach working temperatures below 0 °C. The adoption of such mixture is possible, since the very shallow system does not meet prominent aquifers, thus nulling the risk of leakages and subsequent pollution. The graphical details of the BGHE field are presented in Figure 7b whereas the main features of a BGHE are summarized in Table 4.



(a)



(b) (c)

Figure 7. Design configuration of the BGHE. (a) Layout of the geothermal field. (b) Vertical section of a basket. (c) Example of installation of a cylindrical geothermal basket.

Many transient tests, performed with the simulator developed in Tinti et al. [32], indicated that, with the 12 baskets installed, a base load around 5.5 kW can be maintained with a minimum seasonal efficiency of 4.4. Therefore, the GSHP was chosen accordingly.

Table 4. Design features of a BGHE.

Length [m]	Height [m]	Diameter [m]	Thermal conductivity [W·m^{-1}·°C^{-1}]	Outer/Inner pipe diameter [cm]	# spirals [-]
80.0	1.50	1.50	0.40	3.20 / 2.54	16

The technical features of the three parts of the heating system in the design configuration are the following:

- GSHP: the peak thermal power, calibrated as the maximum energy that such basket configuration can extract from the ground, is equal to 5.7 kW with a nominal value of Coefficient of Performance (*COP*) 4.6. The system is designed to work during nightly hours;
- two ASHP: with a peak thermal power of 22.4 kW and nominal *COP* value of 3.3, are designed to work during daily hours when warmer air can allow a greater system efficiency;
- the existent PGB: having a peak thermal power of 211 kW and a useful thermal power of 192 kW. The existent boiler is largely oversized with regard to the peak power demand of the portion of greenhouse considered in the present study (area A2 in Figure 3) since the existent system is used for heating the whole greenhouse building, including area B and area C in Figure 3.

2.6 Performance indicators

The resolution of the energy balance described in Eq. (2) provides an assessment of the energy needs of the greenhouse for a prescribed thermo-hygrometric scenario. The indicators used in the present paper to evaluate the energetic needs and thermal performance of the heating systems analysed are:

- energy needs *EN* [kWh]:

$$EN = \sum_i Q_{gh} \tag{9}$$

  evaluated for a defined time period with *i* number of hours;

- primary energy savings S_E [%]:

$$S_E = \frac{(PEN_{exi} - PEN_{des})}{PEN_{exi}} \tag{10}$$

  evaluated as difference among primary energy consumptions with existent (PEN_{exi}) and design (PEN_{des}) heating system normalized by consumptions in the existent configuration. The primary energy needs in design configuration is the sum of the primary energy consumed by PGB and ASHP and GSHP components. For the comparison, the PGB efficiency η (assumed equal to 0.91 according to the producer data for a new boiler) and the performance values of the heat pumps, for both GSHP and ASHP, were necessary. For ASHP, working the system during the day with the highest air temperatures thus at maximum efficiency, the *SPF* has been judged equal to nominal *COP* (3.3). For GSHP, the *SPF* is the result of the calculations for the optimization of GBHE field (4.4, see paragraph 2.5). Once found the total consumptions of the two energy vectors (natural gas and electricity) the primary energy factors indicated by Regional Authority [67] were used:

  - Natural gas: 1.05;
  - Electricity: 2.42 (derived by the integration of renewable and non-renewable systems).

- operating cost savings S_C [%]:

$$S_C = \frac{(C_{exi} - C_{des})}{C_{exi}} \tag{11}$$

evaluated as difference among operating heating costs with existent (C_{exi}) and design (C_{des}) heating system normalized by costs in the existent configuration. The costs were inserted by considering a reliable market cost as derived by the greenhouse bills:

- electrical energy of 0.25 €/kWh
- natural gas 1.5 €/sm^3

where: sm^3 is the standard cubic meter. For the comparison, the natural gas volume V_G (in sm^3), necessary to obtain a defined energy needs *EN* (in kWh), was obtained by the following expression:

$$V_G = \frac{EN}{(c_i \times \eta\ )} \quad (12)$$

where: c_i is the lower calorific value of the methane gas assumed equal to 9.94 kWh/sm^3 and η is the PGB efficiency assumed 0.91 according to the producer data. Moreover, considering the boiler's age (i.e. 10 years actually), which affects efficiency of the machine, this value is considered conservative, since the savings in using GSHP-BGHE are expected to be higher.

- greenhouse gas emissions saving S_{GHG} [%]:

$$S_{GHG} = \frac{(EMI_{exi} - EMI_{des})}{EMI_{exi}} \quad (13)$$

evaluated as difference among CO_2 equivalent emissions from existent (EMI_{exi}) and design (EMI_{des}) heating systems normalized by emissions in the existent configuration. The *EMI* values calculated used the emission coefficients 1.980kg CO_2/sm^3 for natural gas and 0.355kg CO_2/kWh for electricity, characteristic of Emilia Romagna Region, where the case study is located [68].

In the study, considering the four years from 2009 to 2012, only the consumptions relative to four months were calculated and analysed since the growth of the selected crops ranges in a period from 14 to 16 weeks. The selected months were the coldest of the year for the site investigated, e.g. January, February, March and December. The selected months, obviously, are the most heating energy demanding all along the year.

3. Results and Discussion

3.1 Scenario 1

The Section presents and discusses the main results achieved, considering the indoor thermo-hygrometric conditions (T and rH) measured in the greenhouse for the years 2009-2012. Data were inserted for the resolution of the system of Equation (2). Since two data-loggers were used to collect indoor data, the values used in the calculation were the average for each time interval. The two heating system configurations analysed were:

a) existent: only PGB;

b) design: using geothermal and aerothermal energy contribution with BGHE-GSHP + PGB working during the nightly hours and PGB + ASHP working during the daily hours.

As first, the daily *EN* during the cold season (January, February, March and December months for a total of 485 days since 2012 is a leap year) were calculated for every studied year (i.e. 2009-2012), using the equations of Paragraph 2.1. They are, obviously, function of the indoor/outdoor conditions and they are showed in Figure 8a. As they show, the maximum daily peak is around 500 kWh and occurs in December in the years 2009-2011 and in February in 2012. It is interesting to consider also the distribution of the values since provides useful suggestions on the average daily consumptions. Figure 8b represents the cumulative energy for the 485 daily values, while Figure 8c the frequency of the energy daily needs occurred. For majority of the days, the energy needs range between 200 and 400 kWh, thus confirming the high-energy demand. Being the GSHP-BSHE designed (due to the land availability) to provide a maximum of 85.5 kWh (5.7kW×15h) per day, with high efficiency, it is evident that it must be supported by the PGB for more than 90% of time during winter season in order to guarantee a high efficiency and a sustainable heat exploitation from the ground. Figure 8d shows the *EN* during the cold season by separating the contributions accumulated during the daily hours from those obtained during the nightly hours, thus highlighting the two operation modes of the heating system. Day and night needs have the same order of magnitude and have similar trends for the various months and, as expected, the nightly consumptions reach the higher peak values.

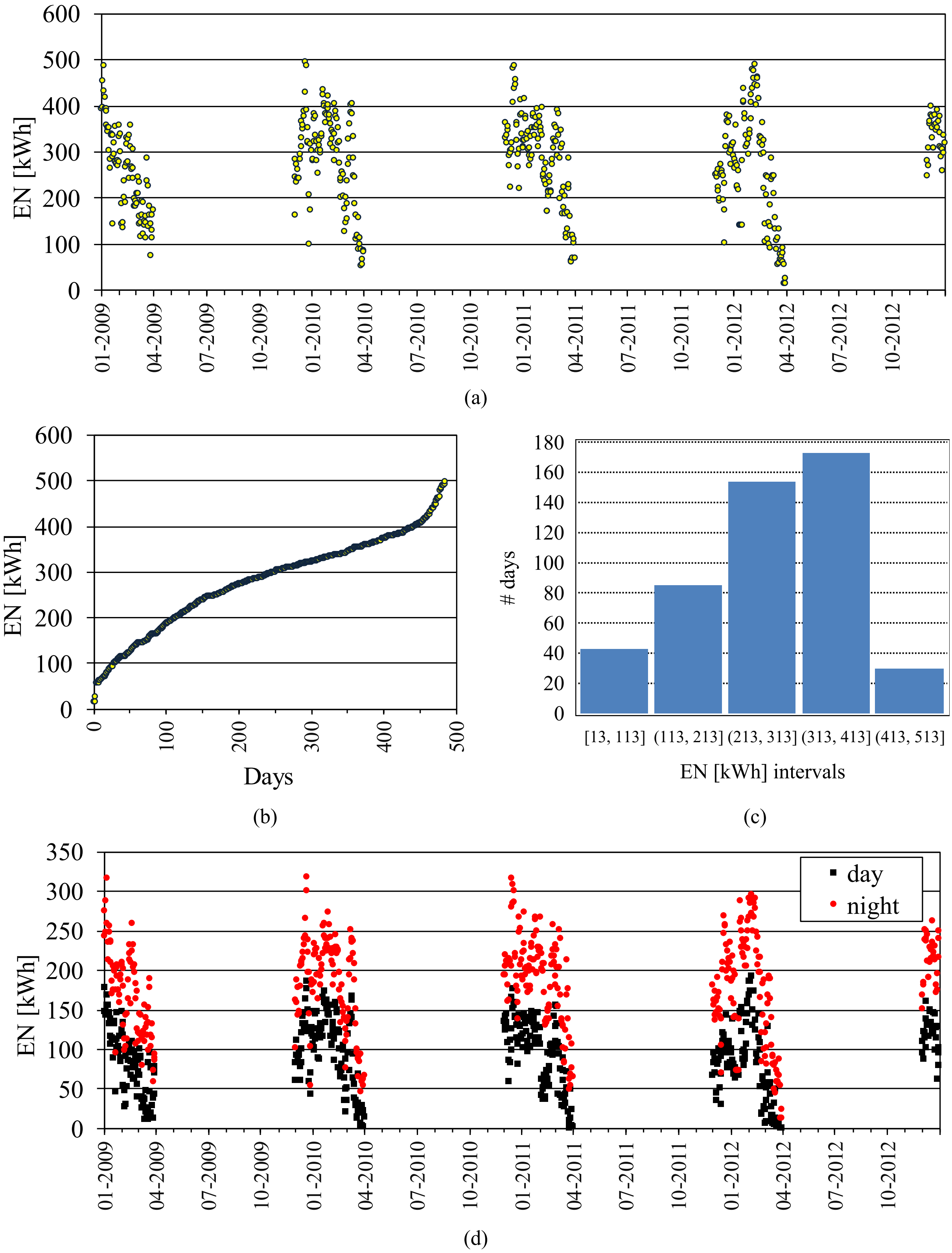


Figure 8. Daily energy need *EN* [kWh] (considering January, February, March and December months, 485 days in total, for the Scenario 1. (a) Time-history of the values; (b) Increasingly order distribution of the values; (c) Histogram graph of the values.

Along the year span, the most convenient situation occurs in February and March, when, in the daily hours, *EN* rapidly decrease, whereas in the night, *EN* are almost covered by the GSHP. Finally, the design *EN* for the greenhouse, for the four years, are summarized in Table 5. They range from 31 000 kWh to 35 000 kWh and so they were adopted for the preliminary comparison with the real consumptions of the existent heating system of the greenhouse. From the natural gas consumptions extracted from the bills, for the periods considered in the present study, the total energy provided by the PGB heating system for the four reference winter months was calculated. The difference between values of energy provided (derived from the bills) and values of energy need *EN* (calculated using the energy model) ranges from 6% (for year 2010) to 8% (for year 2009).

The energy model is therefore considered reliable and able to provide a suitable evaluation of the thermal needs and thermal behaviour of the greenhouse.

Table 5. Yearly energy need *EN* for the examined years (considering January, February, March and December months) for the Scenario 1.

	Year 2009	Year 2010	Year 2011	Year 2012
EN_{tot} [kWh]	32 040	35 766	31 093	33 251

In order to obtain the response of the heating system in the design configuration (PGB+GSHP-BGHE+ASHP), a spreadsheet file was created to implement the energy model. From the spreadsheet, by introducing in input the hourly thermo-hygrometric conditions, the ground temperature (as obtained from the ground model discussed above) and the values of the operating temperature of the GSHP condenser (see Figure 6), the average monthly values of heat transfer fluid temperature in the BGHE, both inlet and outlet of the evaporator, and the correspondent *COP*, were evaluated. Then, the compatibility of the temperature of the heat transfer fluid with the adopted technical solutions was checked. For the sake of brevity, in Table 6 the results for the most critical year only, i.e. Year 2010, are reported. The compatibility check on the temperature of the system provides positive response for all the years.

Table 6. Average values, referred to month/year of the temperature of the heat transfer fluid, inlet and outlet from the evaporator, Coefficient of Performance (*COP*) and Coefficient of Performance considering the auxiliary devices (COP_{aux}), i.e. the water circulation pumps of the primary and secondary loop, outdoor air temperature (*Average* T_{out}) and

the minimum outdoor air temperature observed in the period (*Min* T_{out}). The data are referred to Year 2010 for the Scenario 1.

	$T_{ev,in}$ [°C]	$T_{ev,out}$ [°C]	*COP* [-]	COP_{aux} [-]	*Average* T_{out} [°C]	*Min* T_{out} [°C]
January	-2.53	-7.53	4.29	3.71	2.91	-4.80
February	-0.69	-5.69	4.51	3.82	6.02	-4.31
March	3.21	-1.79	5.07	4.10	9.61	-3.47
December	-1.70	-6.70	4.39	3.74	5.87	-3.46
Year	-0.42	-5.42	4.57	3.84	6.10	-4.80

Furthermore, the graphs in Figure 9 provide the contributions of the main components of the heating system in design configuration, in terms of *EN* for the year 2010, again selected as representative of the most critical conditions (i.e. the most energy demanding) among the four years considered here. With reference to nightly hours, Figure 9a displays the contributions of PGB and GSHP-BGHE whereas, with reference to daily hours, Figure 9b shows the contributions of PGB and two ASHPs. The plateau in first graphic shows how the geothermal system has been exploited at 100% of its potentialities for almost 1500 hours in the investigated period (88% of total time) entailing the system sizing fits the energy needs (as backup). This result shows a remarkable difference with several installations and experiments reported in the Section 1, where the geothermal field is sized to cover the energy peak. In the examples reported in literature, the field dimension is huge, due to the need of covering the peak demand. As examples:

- Arabkoohsar et al [18] studied the work hypothesis of covering the demand of 60000 m^3 of greenhouses located in North Iran with vertical probes and solar collectors. It resulted in 35 probes 150 m deep and 430 collectors;
- D'arpa et al [17], realised a model of greenhouse (of total floor area 10200 m^2) located in Southern Italy to evaluate the convenience of using vertical probes or horizontal collectors to cover the entire load. Details on the potential land use are not given but the indicated capital costs (around 1140000 € and 910000 €) suggest high area extensions;

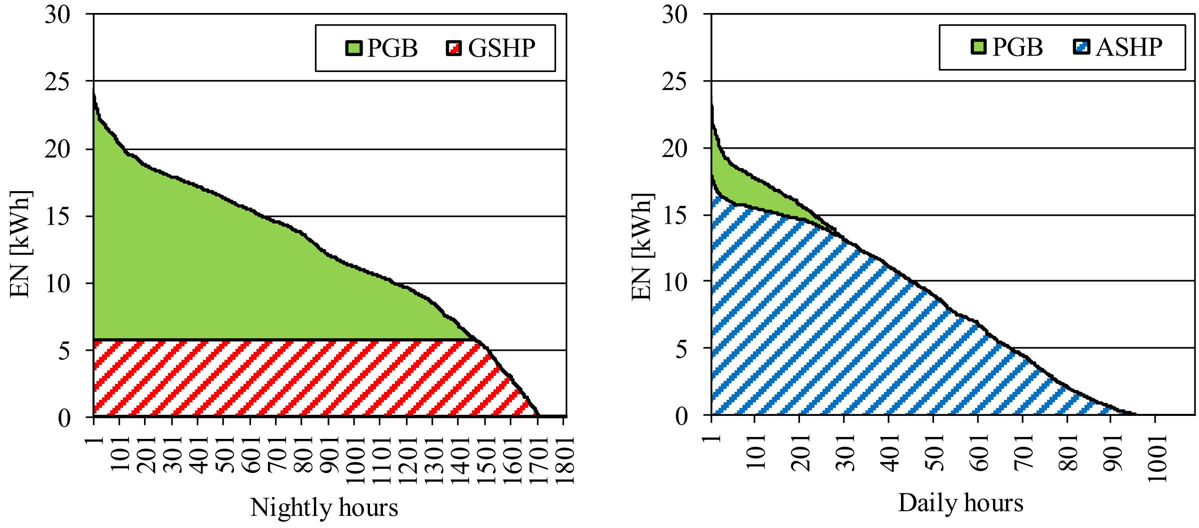
- Benli [19] analysed how to cover the energy demand of a small greenhouse of 60 m^2 located in Turkey; results led to a vertical probe of 60 m or a horizontal collector of 246 m, alternatively;
- Anifantis et al. [31] monitored the behaviour and evaluated the efficiency of a GSHP system composed by a heat pump of 7 kW capacity and a vertical probe of 120 m, to heat a university experimental greenhouse of 144 m^3 located in Southern Italy;
- Boughanmi et al. [47] monitored the behaviour and evaluated the efficiency of a GSHP system composed by a heat pump of 16 kW capacity and a set of agrotherms plus two conical heat exchangers, to heat an experimental greenhouse of around 15 m^2 located in Tunisia.

It is worth noticing that the different climates influence on the peak demand of the various greenhouses illustrated, varying the capacity and efficiency of GSHP systems. On the contrary, here the sizing as backup system allows the total geothermal exploitation for the majority of the time.

Table 7. *EN* covered by the different components of the heating system in design configuration for Year 2010 for the Scenario 1.

	EN_{day} [kWh] (%)	EN_{night} [kWh] (%)	EN_{tot} [kWh] (%)
GSHP	0.0 (0)	9321.0 (39)	9321.0 (26)
ASHP	10564.6 (89)	0.0 (0)	10564.6 (30)
PGB	1247.9 (11)	14632.4 (61)	15880.3 (44)
Yearly total	11812.6 (100)	23953.4 (100)	35766.0 (100)

Then, in Table 7 the contributions to *EN* covering of each component for the Year 2010 are summarized. In the design configuration, the GSHP provides around 26% of the total yearly need, the ASHPs about 30% and the PGB must still provide 44% of the *EN* of the year. Specifically, for each one of the four years in the period (i.e. 2009-2012), the contribution of the GSHP is around 29%, 26%, 30% and 27% permanently covering more than one fourth of the whole *EN* for heating the greenhouse.



(a) (b)

Figure 9. Hourly *EN* for year 2010 for the Scenario 1. (a) Nightly hours. (b) Daily hours. The values are decreasingly ordered.

3.2 Scenario 2

After validating the effectiveness of the greenhouse energy model on the real data of the years 2009-2012, a second scenario was studied in the present work to consider different data sets for the indoor thermo-hygrometric conditions. The new indoor parameters are those described in the sub-paragraph 2.3.2 and refer to the thermo-hygrometric conditions for the optimal growing of three different protected crops. All the other input data sets are the same of the previous Scenario 1. In this case, the aim is to simulate the needs of a productive farm growing flower crops so to estimate the possible benefits from the renewable energy hybrid conversion of the heating system having the biggest impact among the equipment used for the protected crop production. The application of the energy model used here produces the main outcomes summarized in Figure 10 in terms of hourly *EN*, again for January, February, March and December months, for the same four years of the previous scenario (i.e. 2009-2012).

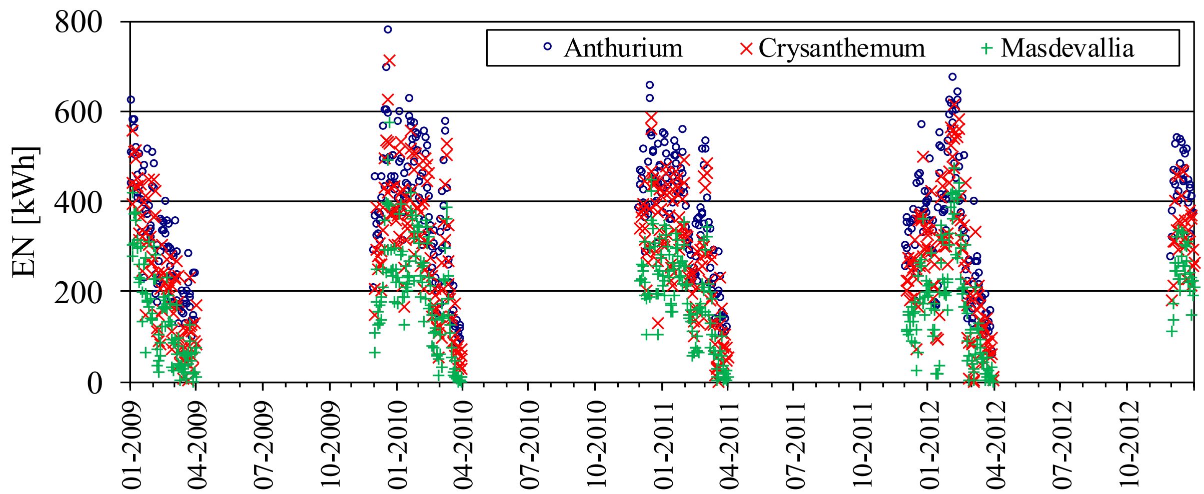


Figure 10. Daily energy need *EN*, considering January, February, March and December months, for the Scenario 2 considering the three different flower crops, reported for the Years from 2009 to 2012.

The graphs summarized the consumptions for all the three different crops, i.e. Anthurium, Chrysanthemum and Masdevallia. The results of the yearly *EN* are reported in Table 8.

Table 8. Yearly EN_{tot} (night hours and day hours) for the examined years considering January, February, March and December months for the Scenario 2 and for the three different crops.

Crop	EN_{tot} [kWh]				
	Year 2009	Year 2010	Year 2011	Year 2012	Average
Anthurium	41 803	46 397	41 332	42 912	43 111
Chrysanthemum	32 322	36 109	31 023	32 651	33 026
Masdevallia	20 619	24 656	20 152	22 232	21 915

Figure 10 and Table 8 confirm, as expected, the Anthurium cultivation is the most energy demanding with an average EN_{tot} practically double then Masdevallia. The energy need increases linearly accordingly to the requested temperatures: Masdevallia 10°C 22000 kWh, Chrysanthemum 14°C 33000kWh and Anthurium 43000 18°C kWh.

Again, it is possible to label the Year 2010 as the "energetically most demanding" for all the three crops. In general, the Year 2010 was an unfavourable year with average temperature lower than the other investigated here. The daily *EN*, for each crop, are showed in Figure 11 by separating the supply contribution of each heating system component, i.e. PGB, GSHP and ASHP. For more details, the daily *EN* for Year 2010 are reported in Table 9, splitting the contribution of the nightly hours from daily hours. Moreover, the total energy provided by the three heating components of the design configuration was reported in percentage. As expected, because of lower temperature, the energy needs during night hours are higher, 2-3 times, than those of the daily hours.

Table 9. *EN* for 2010 year for the different crops with heating system in design configuration and correspondent supply from the three systems (Boiler, GSHP and ASHP yearly supply expressed as a percentage of EN_{tot}).

Crop	EN_{tot} [kWh]	EN_{day} [kWh]	EN_{night} [kWh]	PGB supply (%)	GSHP supply (%)	ASHP supply (%)
Anthurium	41 332.0	11 655.6	29 676.4	51.7	23.7	24.6
Chrysanthemum	31 023.0	12 595.3	18 427.7	38.9	25.5	35.6
Masdevallia	20 152.0	6 851.7	13 300.3	26.1	40.1	33.8

Then, with the introduction of the GSHP and the two ASHPs in the heating system, the supply of the PGB results considerably lowered with respect to the current configuration, and the geothermal energy source provides a contribution ranging from 24% to 40% for the different crops. It is interesting to notice that in this case the GSHP contribution is very similar for Anthurium and Chrysanthemum and significantly higher for the Masdevallia. This is probably due that in the night the temperatures are very close (and sometimes even higher) to the temperature requested by the Masdevallia, therefore low power is needed, and the system can cover it with the geothermal energy only. This allows noticeable energy, cost and emission saving as showed in Table 10.

Table 10. Saving for the three different crops: primary energy (S_E), operating costs for heating (S_C) and reduction of the GHG emission (S_{GHG}).

Crop	Year 2009	Year 2010	Year 2011	Year 2012	Average
			S_E		
Anthurium	20%	21%	22%	25%	22%
Chrysanthemum	28%	26%	29%	31%	29%
Masdevallia	41%	33%	36%	37%	37%
			S_C		
Anthurium	11%	11%	12%	12%	12%
Chrysanthemum	14%	7%	11%	10%	11%
Masdevallia	34%	23%	35%	30%	31%
			S_{GHG}		
Anthurium	8%	8%	9%	16%	10%
Chrysanthemum	10%	3%	7%	12%	8%
Masdevallia	31%	19%	32%	31%	28%

In fact, looking at the S_E indicator defined in the subsection 2.6, the yearly primary energy (considering the four months investigated) savings can range from 20% to 41% for the different crop types. As far as the heating operating costs (S_C) are concerned, the yearly savings could range between 7% and 35% and analogously the average CO_2 emissions saving result from 8% to 32% of the actual emissions, evaluated by means of the S_{GHG} indicator defined above.

Finally, considering sufficiently representative the four-year period used for the monitoring, the following ranges for the three indicators can be calculated:

- energy savings from 22% (Anthurium) to 37% (Masdevallia);
- operating cost savings from 11% (Chrysanthemum) to 31% (Masdevallia);
- CO_2 emission reduction from 8% (Chrysanthemum) to 28% (Masdevallia).

Recalling that the geothermal field was sized according to the external surface availability, the geothermal system, as designed, appears highly effective for the three crops, in particular for the Masdevallia. This difference is evident in percentage (22% vs 37%) on the other hand the energy savings in absolute value reports 29 700 kWh for Anthurium vs 13 300 kWh for Masdevallia. This finding highlights that in non-residential buildings the efficiency of a conditioning system should be evaluated taking into account also the building intended use.

At this stage, a payback analysis can maybe result imprecise since many factors were not considered in the work. Moreover its validity could be strictly limited to the geographical context, nevertheless a first preliminary cost evaluation of the GBHE field installation shows as a homemade installation can return a further remarkable cost savings, in accordance with previous calculations [46].

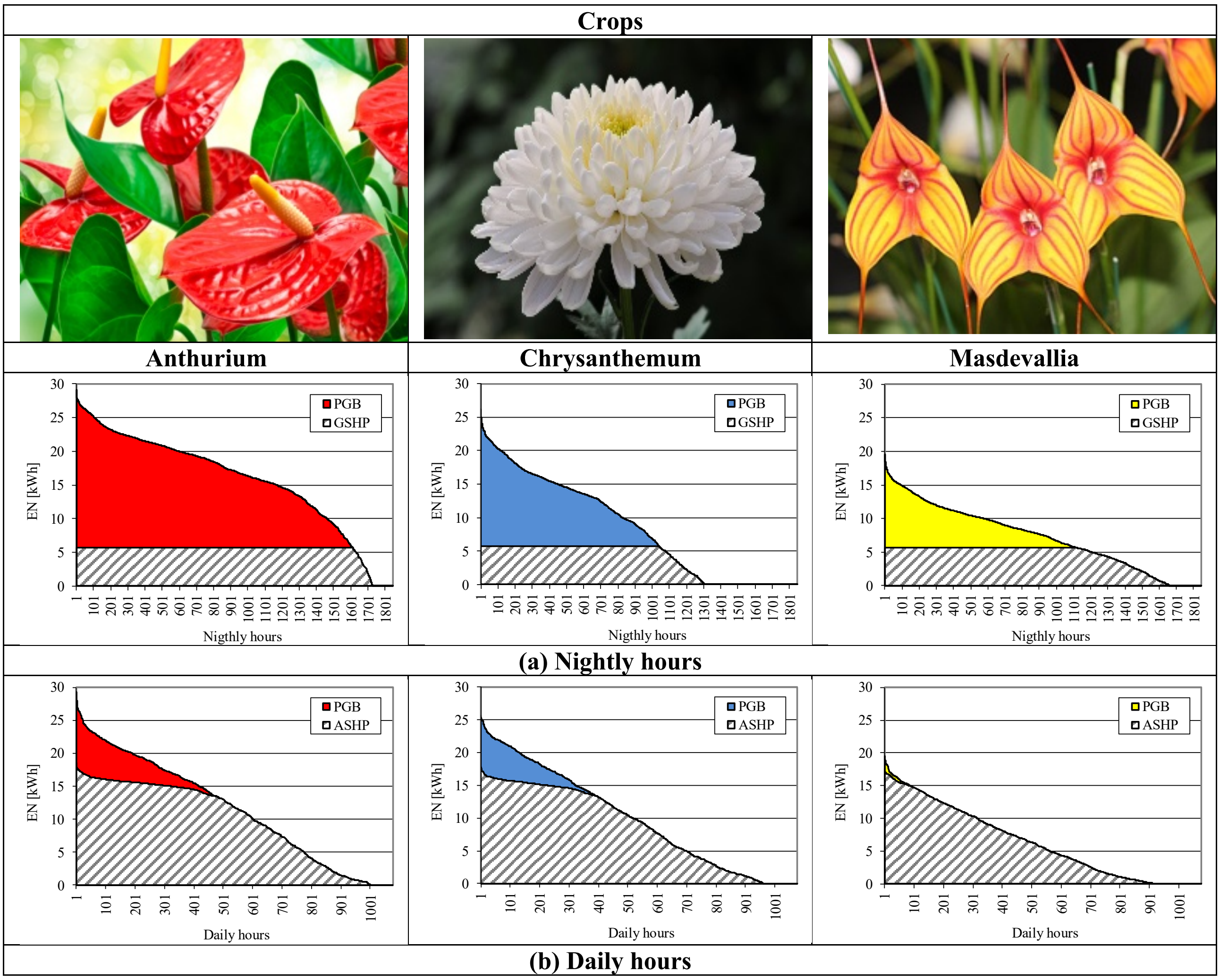


Figure 11. Hourly *EN* for year 2010 for the three different crops for the Scenario 2. (a) Nightly hours. (b) Daily hours. The values are decreasingly ordered.

In fact, several greenhouse farms have available equipment, labour and tools to directly install the baskets and pipes. For comparison, Table 11 shows the cost analysis of the basket furniture and installation made by a professional company whereas Table 12 shows the same geothermal field but installed by the farm workers themselves. The prices were taken from a regional official price list [69]. In both cases, considering the operating costs, the total amount for the realization of the geothermal field can be totally amortized in few years, especially if the second option is considered where the owner can save as much as 74% of the realization cost.

Table 11. Cost analysis of basket probes installed by a professional company.

			Number	Height	Width	Length	#	Total	**9 669.94**
Excavation	18.00	€/m³						85.56	1 540.08
Basket			12	2.0	1.3	1.3	1	40.56	
Ducts			3	0.5	1.0	20	1	30	
			1	0.5	1.5	20	1	15	
Excavator rent	80.00	€/day						6	480.00
Basket placement			12	1	1	1	0.4	8	
Steel	1.80	€/kg						300	540.00
Basket structure			12	1	1	1	25	300	
1" HdPE pipe (material and installation)	5.00	€/m						1 280	6 400.00
Basket			12	1	1	60	1	720	
Pipes			4	1	1	50	2	400	
			4	1	1	20	2	160	
Pipe fixing	1.00	€/each						100	100.00
			100	1	1	1	1	100	
Basket fixing	0.40	€/each						240	96.00
			12	1	1	1	20	240	
Burying	6.00	€/m³						85.56	513.36
			12	2.0	1.3	1.3	1	40.56	
			3	0.5	1.0	20	1	30	
			1	0.5	1.5	20	1	15	

Table 12. Cost analysis of basket probes installed by the farm workers.

			Number	Height	Width	Length	#	Total	**2 547.20**
Excavator rent	80.00	€/day						6.64	531.20
Basket excav.			12	1	1	1	0.08	0.96	
Duct excav.								2	
Basket burying			12	1	1	1	0.04	0.48	
Burying ducts								2	
Basket placement			12	1	1	1	0.10	1.20	
Steel	1.80	€/kg						300	540.00
Basket structure			12	1	1	1	25	300	
1" HdPE pipe (material)	1.00	€/m						1 280	1 280.00
Basket			12	1	1	60	1	720	
Pipes			4	1	1	50	2	400	
			4	1	1	20	2	160	
Pipe fixing	1.00	€/each						100	100.00

			100	1	1	1	1	100	
Basket fixing	0.40	€/each						240	96.00
			12	1	1	1	20	240	

3.3 *Energy performance of the greenhouse*

Similarly to the residential sector, the yearly consumption referred to the building dimension is an important indicator to assess the energy performance of the greenhouse. For production buildings, the energy need is usually referred to the volume, but considering that the crop extension is defined by the floor area only (independent from the room height), the energy need will be related to floor surface. Considering the Scenario 1 is related to the University needs – whose consumptions can remarkably differ from commercial greenhouses – the present analysis is reported for the Scenario 2 only (commercial crops).

The Table 13 reports the energy performance for the selected crops. Results are shown in terms of total energy performance, the energy performance related to the primary energy only (total energy without the GSHE contribution) and the contribution of each basket to the primary energy saving.

Table 13. Energy performance of the greenhouse related to the selected crops.

	Anthurium	Chrysanthemum	Masdevallia
EP_{tot} [kWh/(m^2·y)]	674.0	516.0	342.0
$EP_{pr.en}$ [kWh/(m^2·y)]	525.0	366.0	216.0
EP_{basket} [kWh/(m^2·y/basket)	9.3	9.4	7.9

The energy needs are in line of a recent study [16] that reports the energy performance EP_{tot} between 175 and 474 kWh/(m^2·y) for a productive greenhouse in the same geographical area. The higher consumptions we found are mainly due to the greater height of the experimental greenhouse we considered, having geometry slightly different from the typical greenhouses used for productive use. The third row in Table 13 exhibits the contribution of baskets to energy performance. This value is very similar for the first two crops, whereas for *Masdevallia* the performance appears reduced. The lower value derives from the lower energy need, which makes the geothermal system oversized in the mild seasons. In this context, EP_{basket} values for *Anthurium*, *Chrysanthemum* and *Masdevallia* can be considered as a first benchmark of geothermal baskets contribution in enhancing energy savings in floriculture sector. The topic deserves to be deepened in further studies and enlarging the variety of crops, in order to take into account the intended use to provide a complete energy assessment.

4. Conclusions

The aim of the study has been to assess the efficacy and the expected performance of a low-enthalpy shallow geothermal system using basket geothermal heat exchangers in a hybrid configuration, in order to partially cover the heating demand of a greenhouse building currently using a natural gas boiler. Despite the low performance in terms of power extracted from the ground, this type of heat exchanger can be a valid solution when working to cover the base load, keeping relatively high the total seasonal performance factor and not thermally depleting the ground. Moreover, these baskets are characterized by low installation costs. In the paper, the geothermal field was sized according to the available land surrounding the greenhouse, allowing the installation of 12 BGHEs spaced 5 m each other in a rectangular configuration.

Therefore, in the present paper, the geothermal system works as a backup of the main heating system for the winter months and is used only in the most severe occasions (mainly during the night). Specifically, this solution allows the soil to recover its normal temperature during the unused period (daylight time) entailing the baskets not to suffer a heat-exchange depletion and subsequent efficiency loss (which is normal in traditional BGHE fields used to cover the whole building energy need).

The study exploits the outcomes of previous in-field TRTs conducted on a similar system and quantifies the reduction in terms of energy needs, running costs and CO_2 emissions potentially achievable by inserting the GSHP-BSHE in a hybrid configuration with PGB and considering two different scenarios. The first one calculates the savings by using the real temperature and humidity conditions recorded inside the greenhouses for the four-year monitoring period (i.e. years 2009-2012); the second investigates the theoretical savings, by adopting three different thermo-hygrometric conditions requested for the optimal growing of the *Anthurium*, *Chrysanthemum* and *Masdevallia*

Orchid, very common protected crops. By means of the analyses performed in the frame of the first scenario, the reliability of the energy model was validated by applying it to a storehouse building, the compatibility of fluid temperature was checked for the adopted technical solutions and the expected *COP* for the GSHP was verified. As far as the performance assessment of the hybrid heating system is concerned, the main outcomes were established based on Scenario 2. They could be summarized in the following synthetic outcomes:

- the study of the behaviour of the heating system during the coldest four months of the year (i.e. January, February, March and December since the crops have a growing period ranging from 14 to 16 weeks), allowed to estimate the contribution of the geothermal energy source, which provides a contribution ranging from 23% to 40% for different crops;
- the yearly primary energy savings can range from 20% to 41% for the different examined years, but on average always higher than 22% of the actual energy needs;
- the hybrid system allows to reach a reduction from 10% to 30% of the average operating costs for heating.
- The system is expected to reduce carbon emission reductions from 8 to 28% with respect to current configuration, different for the three analysed crops.

Besides, these values are referred only to the four coldest months of the year and therefore larger savings could be expected if all the 12 months are considered.

The most important remarks are reported in the following points:

- an integrated system using two different heat sources (ground and air) has proved to be highly effective;
- the alternate use of the sources allows the ground to recover whole of its heat transfer capacity, thus increasing the efficiency;
- even though applied to an existing system, this solution can be design for new installations. In this case a double source heat pump system is an option to take into account;

- the results returned by this study (in particular those concerning the energy consumptions per area) can be considered as reference for future studies and installations, especially in the floriculture and horticulture sectors, where poor literature on energy data is available;

Finally, the hybrid nature of the investigated system increases the cost effectiveness and allows the adoption almost everywhere, even in limited space conditions. This peculiarity could favour the mobilisation of distributed funds and subsidies, specific for energy efficiency in agriculture, at different levels (regional, country, European). Moreover, the exploitation of higher efficiency hybrid systems, such as the one presented here, could lower primary energy consumption producing indirect environmental benefits as well, since non-renewable energy would be preserved, and greenhouse gases reduced.

In conclusion, this work can be considered as a contribution to widen the literature on energy consumptions providing precise data for both crops cultivated in an experimental environment and those for sale. The energy results integrated with a simple cost evaluation show as the installation of GBHE field should be amortized in few years thanks to the remarkable yearly cost savings especially in the case of a homemade installation and without considering any subside or governmental aid.

Future developments of the work will be the use of the PGB flue gases, after appropriate filtering, for the carbon fertilization inside the greenhouse. This practice is necessary, especially in winter season, when the air changes are at the minimum and the level of carbon dioxide concentration drastically falls during the early hours of the photosynthetic activity.

APPENDIX

In this appendix, the work performed for a specific thermal response test on a geothermal basket is briefly resumed. The work was presented at European Geothermal Congress in 2016 [64].

The basket was realised on site and installed in the shallow underground in a place of Emilia Romagna Region (Italy), in a clayey soil at a depth of 2.0 m below ground level (included the 0.5 m soil coverage above the basket). A monitoring borehole, equipped with three temperature sensors PCE-HT71, was installed down to 6 m depths, beside the basket, and the measured values were used to calibrate the ground temperature wave, with the result of identifying an equivalent value of ground thermal diffusivity, around 0.029 m^2/days.

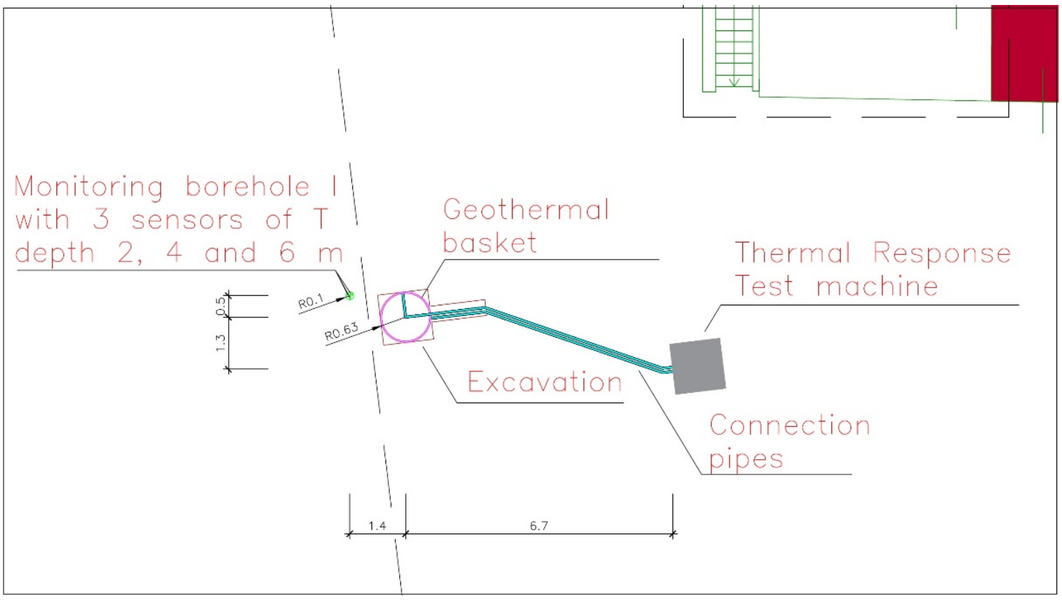


Figure A.1. Detail of the system installed to monitor the ground and system performance: monitoring borehole, geothermal basket and Micro-Thermal Response Test machine.

The geothermal basket was connected to a Micro-Thermal Response Test machine (M-TRT) with a maximum heating power of 1.5kW (Figure A.1). Together with the basket, four additional temperature sensors were installed, two at its centre (at depths 0.5 and 2.0 m) and two at its border (0.5 and 1.0 m). The central return pipe of the basket and the connections between the basket and the TRT machine were properly insulated. Table A.1 resumes all the details concerning the geothermal basket, while Table A.2 reports all monitoring sensors installed to conduct the TRT. The TRT was conducted uninterruptedly for 12 days, with a constant flow of 800 l/h. The time laps were divided in 3 periods equally distributed, with different power levels: 500 W (1st period), 1000 W (2nd period) and 1500 W (3rd period).

Table A.1. Details of the geothermal basket.

Design features	Value
Width of the basket	1.2 m
Height of the basket	1.5 m
Length of the pipes	60.0 m
Number of coils	13
Pipes material	PE 100 DN 32 PN 16
Ground coverage above the basket	0.5 m
Depth of the basket	2.0 m

Subsequently to the machine's switch off, a release period occurred, keeping the circulation pump active and lasting additional 12 days.

Table A.2. List of monitoring sensors during TRT.

Group	Sensor	Measurement	Unit
TRT	PT100	T fluid inlet	°C
	PT 100	T fluid outlet	°C
	FPR204P-PC	Fluid flow	l/h
	CT, split-coil transformers	Power heater	W
	CT, split-coil transformers	Power pump	W
Basket	PCE-HT71	T at 0.5 m	°C
	PCE-HT71	T at 1.0 m	°C
	PCE-HT71	T at 0.5 m	°C
	PCE-HT71	T at 2.0 m	°C
Borehole I	PT 100	T at 2.0 m	°C
	PT 100	T at 4.0 m	°C
	PT 100	T at 6.0 m	°C

Figures A.2 and A.3 report the behaviour of power and fluid temperature during the TRT. The beginning temperature of the circulating water was around 12.7°C, while the average ground temperature along the basket height was around 8.6 °C. The TRT was performed in March. Together with the identification of the ground temperature waves at different depths, data analysis of TRT allowed to define the method for the dynamic calculations of geothermal basket performance under different conditions, applied also to the present work on the geothermal greenhouse.

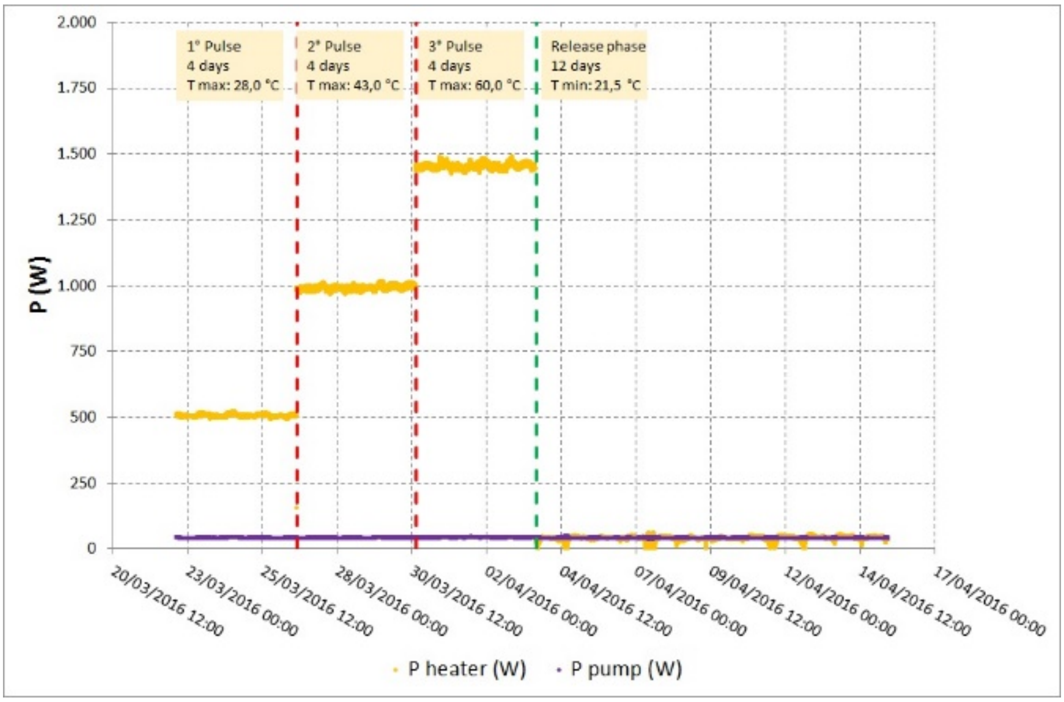


Figure A.2. Multi-step power evolution of Thermal Response Test performed.

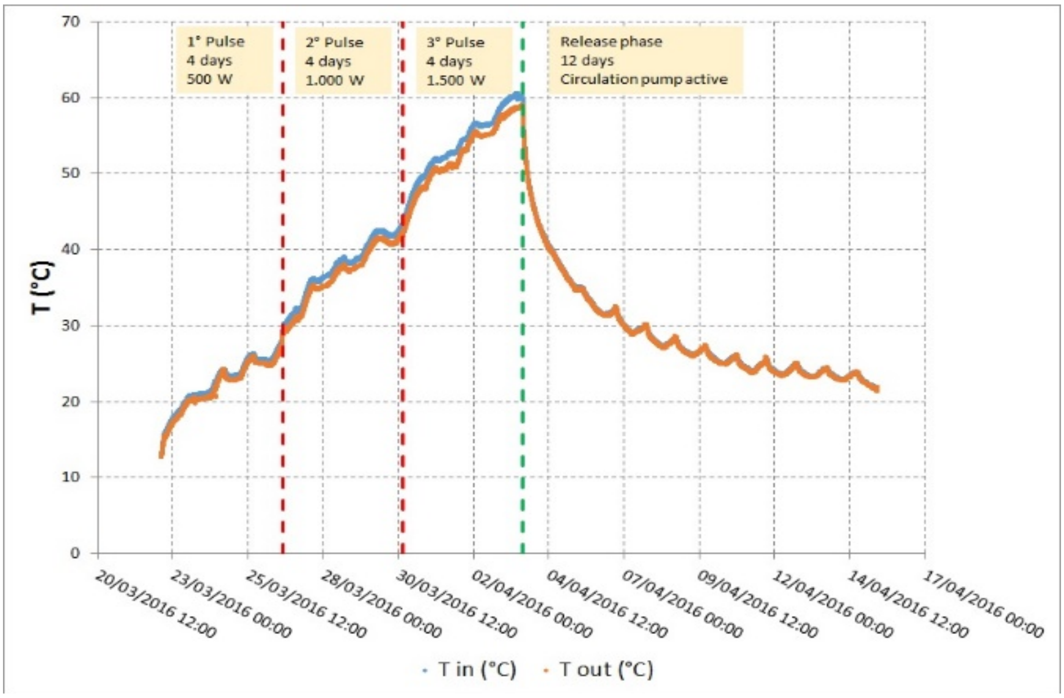


Figure A.3. Behaviour of inlet and outlet fluid temperature.

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