Proposal of a Holistic Design Procedure for Ground Source Heat Pump Systems

Paolo Conti[1], Walter Grassi[1], and Daniele Testi[1]

[1]Italian Geothermal Union (UGI) members, University of Pisa, DESTEC, Largo L. Lazzarino, 56122 Pisa, Italy

Corresponding author telephone and e-mail: +39-0502217112; paolo.conti@unionegeotermica.it

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ABSTRACT

An innovative approach to the design of ground source heat pump (GSHP) systems has been developed, based on the evaluation of energy exchange during the operational time and on cost-benefit considerations.

Alternative algorithms are suggested, in order to switch from the "reference design months" approach to a method based on monthly energy performance evaluation. This latter procedure is also suited for examining the energy performance of design solutions in which GSHPs are coupled with other heat generation technologies.

All the three macro-systems governing the monthly energy balance of GSHPs are taken into account: building envelope energy loads, heat generator efficiencies, and thermal behaviour of the ground source. The outputs of the procedure are: thermal capacity of heat pump and back-up generators, length of the borehole heat exchangers, flow rate in the ground-coupled loop, monthly energy contribution to be requested to the GSHP, energy use during multi-year practise, together with an assessment of installation and operational costs.

A test case is presented, in which the proposed algorithm is applied and its effectiveness as a tool for system designers is demonstrated.

1. INTRODUCTION

Heat pump systems are a widely used technology for thermal energy generation, capable of efficiently delivering heating, cooling, and sanitary hot water for buildings. Particularly, ground-source heat pumps (GSHPs) are potentially able to reach higher performances with respect to their traditional alternatives, albeit special attention must be paid to the initial design of the overall system (heat pump equipment, ground heat exchanger, and connecting ductwork). The installation design must be the product of the complete view of the building needs, the system for energy production, the distribution system and controls, and the characteristics of the ground source. A holistic approach is the unique logics to follow in the design of complex systems, and this is particularly true for systems supported by GSHPs.

This paper targets the design issues of a specific technology: closed-loop ground-coupled vertical borehole heat exchangers (BHEs). Methods of different complexity are already available to designers (ASHRAE 2011, GEOTRAINET 2011, Lamarche et al. 2007, UNI 11466:2012, VDI 2001); however, a straightforward procedure and an easy-to-apply tool are required to be really effective in spreading a successful implementation of this technology and become a practical standard.

One of the main drawbacks of GSHP systems is their high initial installation cost, especially for the execution of the necessary drillings. Optimisation of the BHE lengths based on a careful cost-benefit analysis is a key step to speed up the market penetration of these systems.

Concepts that is necessary to address for a thorough and efficient design are:

- sustainability of the thermal performance of the ground source over multi-year operation;
- seasonal energy efficiencies of the heat pump, as opposed to nominal performance under peak-load conditions;
- optimal hydraulic distribution of the ground-coupled loop;
- optimisation of the fractions of the thermal load to be covered by the GSHP and by additional backup generators, as opposed to design for full load generation;
- efficient control of the system, to meet variable energy demands of the building users;
- optimal sizing of the heat pump unit and of the BHE field, based on cost-benefit considerations.

In the following paragraph, the proposed holistic design method is outlined, together with the accompanying set of heat transfer equations and energy balances; next, a test case is presented, in which we apply this novel procedure and critically discuss the results of the energetic and economic analyses.

2. GROUND-SOURCE HEAT PUMP MODEL DESCRIPTION

GSHP systems involve different subsystems: ground reservoir, ground heat exchangers (BHEs), geothermal loop, heat pump unit, back-up generators, and building end-user loop (see Fig. 1). The simulation of the overall system can be performed by means of a set of equations containing the mathematical model of each component.

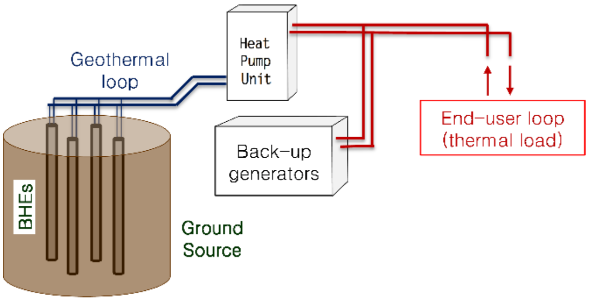

Figure 1: Scheme of the model subsystems.

The time evolution of the system is analysed through a quasi-stationary simulation. In each time step (a month), average quantities are considered in a condition of steady state.

<u>Ground modelling</u>

The ground is assumed to be a purely conductive homogenous medium. A cylindrical source model is used to simulate the temperature evolution of the ground (Ingersoll et al., 1954). The average temperature at the external surface of the BHEs as a function of time is calculated by means of time-superposition of monthly thermal steps (see equation [1]). The boreholes are supposed to be sufficiently far apart from each other, so that we can neglect spatial interference, according to the analytical solution.

$$T_g = T_{g0} + \sum_{i=1}^{n} G(Fo_i, R)[\dot{q}_{n-i+1} - \dot{q}_{n-i}] \quad [1]$$

where:

- T_g is the borehole surface temperature [°C];
- $Fo_i = \alpha \cdot i\Delta t / R^2$ is the Fourier number at the end of the i-th time step [-];
- R is the radius of the BHEs [m];
- $G(Fo, R)$ is the dimensionless function solving the cylindrical heat sources problem [-] (Ingersoll et al. 1954);
- $\dot{q}$ is the heat flow per unit length [W/m].

<u>Borehole ground heat exchanger</u>

The heat transfer performance of the BHEs is modelled by means of the classical heat exchanger effectiveness method. Equations [2-5] are adopted:

$$\dot{Q}_g = \dot{m}_w c_{pw} (T_{win} - T_{wout}) \quad [2]$$

$$T_{wout} = T_{win} + \varepsilon (T_g - T_{win}) \quad [3]$$

$$\varepsilon = 1 - \exp(-NTU) \quad [4]$$

$$NTU = \frac{N_{BHE}}{\dot{m}_w c_{pw}} \frac{H}{R_b} \quad [5]$$

where:

- $\dot{Q}_g$ is the monthly average thermal power exchanged by each BHE with the ground [W];
- ε is the exchanger effectiveness [-];
- $\dot{m}_w$ is the total mass flow rate of the geothermal loop [kg/s];
- H is the depth of a single BHE [m];
- R_b is the so-called borehole thermal resistance [m·K/W].

As above-mentioned, T_g is assumed to be constant during each monthly time step.

<u>Heat pump unit</u>

We consider heat pumps with fixed capacity (on/off control). Heat pump performance is evaluated according to the current Italian technical standard UNI 11300-4:2012, reasonably extended to the summer period. The methodology interpolates second-law efficiencies (obtained by manufacturer data) at the sources temperatures, in order to find the operative conditions of the heat pump. A penalisation factor for COP/EER depending on the capacity ratio[1] (CR) is considered, in agreement with the technical standards UNI 11300-4:2012 and EN 14825:2012.

The following parameters are determined: condenser thermal power (Q_T), evaporator thermal power (Q_F), electrical power input (P), coefficient of performance for heating (COP) and cooling (EER), and capacity ratio (CR).

Two seasonal coefficients, f_H and f_C, are defined for the heating and cooling periods. They represent the fraction of seasonal building load delivered by the heat pump.

$$f_{H/C} = \frac{\dot{Q}_{T_n} \cdot \tau}{Q_{load_n}} \quad [6]$$

where:

- $\dot{Q}_{T_i}$ is the monthly average thermal power delivered to the building by the GSHP during the n-th month [W];
- τ is the number of hours of the n-th mont [h];
- Q_{load_n} is the energy need of the building in the n-th month [Wh].

<u>Hydraulics of the geothermal loop</u>

We consider that the BHEs are arranged in parallel. A constant flow rate is imposed. As a common rule, the electrical energy supplied for pumping is included in the evaluation of the overall system COP/EER.

[1]Monthly thermal energy delivered by the heat pump divided by the declared heating/cooling capacity of the unit at the same temperature conditions (EN 14825:2012).

Back-up systems

Back-up systems are included in the model: an additional boiler for winter heating and a chiller for summer cooling. The boiler generation efficiency and the EER of the chiller are set to 1 and 3, respectively.

Buildings loads

Monthly profiles of the building thermal loads and temperature of the end-user source are assumed to be an input of the GSHP design procedure.

Overall system

The mathematical model of the whole system includes equations [1-6]. As a consequence of the imposed steady-state condition for each month, the total energy exchanged between the BHE field and the ground has to be equal to the heat transferred to the evaporator/condenser.

When the geometry of the BHE field and the flow rate are fixed, the entire set of equations can be solved for each n-th time step.

$$\begin{cases} \dot{Q}_{T/F} = \dot{Q}_g \\ \dot{Q}_{T/F} = F(T_{win}; T_{wout}; T_s; f_{H/C} \cdot Q_{load}) \\ f_{H/C} = \frac{\dot{Q}_T \cdot \tau}{Q_{load}} \\ \dot{Q}_g = \dot{m}_w c_w (T_{win} - T_{wout}) \\ T_{wout} = T_{win} + \varepsilon(T_g - T_{win}) \\ \dot{q} = \dot{Q}_g / (H \cdot N_{BHE}) \\ T_g = T_{g0} + \sum_{i=1}^{n} G(Fo_i, R)[\dot{q}_{n-i+1} - \dot{q}_{n-i}] \end{cases} \quad [7]$$

where:

- $\dot{Q}_{T/F}$ is the heat transferred to the evaporator/condenser [W];
- $F(T_{win}; T_{wout}; T_s; f_{H/C} \cdot Q_{load})$ is the function accounting for the UNI 11300-4:2012 methodology;
- n is the current time step;
- T_s is the temperature of the end-user source;
- N_{BHE} is the number of BHEs connected to the heat pump unit;
- the meaning of the other terms is the same as in the previous equations.

3. OPTIMISATION ALGORITHM

The objective function to be minimised is the primary energy consumption of the overall system. The depth of a single BHE (H), the flow rate of the geothermal loop ($\dot{m}_w$), and the $f_{H/C}$ coefficients are the design variables. A 10-year operating period is simulated in the optimisation process.

The algorithm is described by the following steps:

(a) *Set of design parameters:* ground thermo-physical properties, monthly profiles of the building thermal loads, heat pump datasheets, number of BHEs, borehole thermal resistance;

(b) *First stage of the optimization routine:* we search for the best combination of f_H and f_C coefficients, while H and $\dot{m}_w$ are fixed to their limit values (maximum H and minimum $\dot{m}_w$);

(c) *Second stage of the optimization routine:* we determine the optimal values of H and $\dot{m}_w$ and we refine the f_H and f_C values, using the previous results as initial estimates.

The constraints on the values of the optimisation variables are the following:

- the depth of a single borehole (H) cannot exceed 100 m;
- the flow rate ($\dot{m}_w$) must be large enough to guarantee a Reynolds number of at least 6000 and/or a fluid velocity within the ducts not less than 0.3 m/s;
- f_H and f_C take values between 0 and 1.

The flowchart in Fig. 2 further illustrates this procedure.

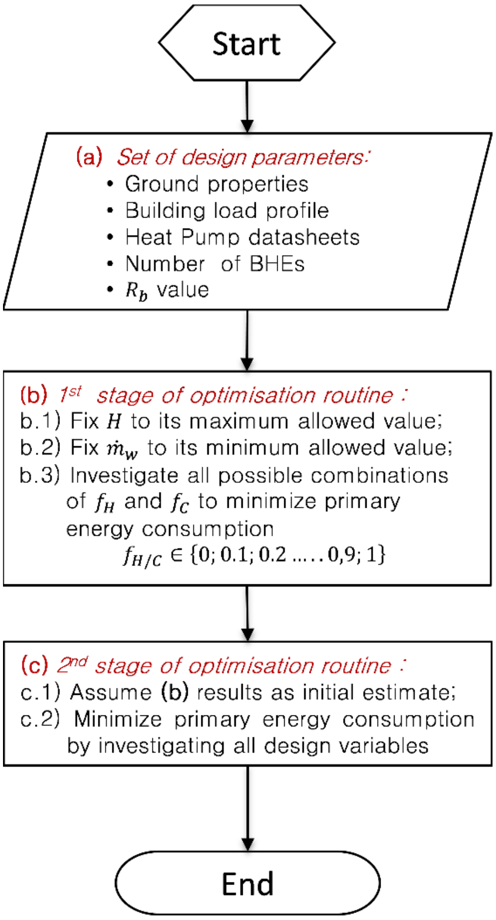

Figure 2: Optimisation algorithm flowchart.

4. DEFINITION OF A DESIGN CASE

The application of the described design procedure is illustrated for a test case. Heating and cooling loads are imposed for a typical medium-scale office building located in Southern Europe. The monthly profiles are based on a numerical example given in UNI 11466:2012. The global seasonal energy demands almost balance each other, as shown in Table 1.

Table 1: Monthly heating and cooling loads of the tested office building.

Month	Heating demand* [kWh]	Cooling demand** [kWh]
January	8 056	0
February	5 834	0
March	3 472	0
April	694	0
May	0	3 750
June	0	7 222
July	0	8 611
August	0	8 611
September	0	3 472
October	694	0
November	4 166	0
December	6 944	0
Total	**29,860**	**31,670**

*Delivery temperature of the building end-user loop: 40°C.
**Delivery temperature of the building end-user loop: 7°C.

We assumed typical values of the ground properties, as reported in Table 2. In the same table, diameter and thermal resistance of the BHE (considering a single "U-tube" arrangement) are also shown. The R_b value was calculated as in Lamarche et al (2010).

Table 2: Ground thermal properties and BHE characteristics.

Property	Value
Ground thermal conductivity [W/(m·K)]	1.66
Ground thermal diffusivity [mm^2/s]	0.837
BHE diameter [cm]	12
BHE pipe diameter [cm]	6.4 – 5.8
Minimum spacing between BHEs [m]	10
Grouting thermal conductivity [W/(m·K)]	1.7
BHE thermal resistance [m·K/W]	0.12

At first, we employed standard design procedures. Specifically, the capacity of the heat pump was chosen in accordance with EN 15450:2007 for winter heating and with UNI 11466:2012 for summer cooling.

An alternative sizing approach is to consider the average power demand of the design months or even of the entire heating/cooling season, rather than the peak loads. The characteristics of the selected heat pumps are shown in Table 3.

As for the BHEs length, an initial estimation was obtained by the ASHRAE (2011) method, resulting in a total length of about 800 m. The methodology proposed in UNI 11466:2012 was also performed, obtaining a total length of about 600 m. Next, we took into account cost-benefit considerations, in order to avoid unnecessary installation costs without significant improvement of the system energy performance, following the optimisation procedure described in the previous paragraph.

5 RESULTS OF THE APPLICATION OF THE PROPOSED DESIGN METHOD TO THE TEST CASE

Primary energy consumption in the absence of a GSHP system (i.e., only with back-up generators) is 562 MWh after a 10-year operation. The primary energy factor for electrical energy is assumed to be 2.5, in agreement with European Directive 2012/27/EU on energy efficiency. Using the previously defined heat pumps with optimal working parameters, we obtain the savings illustrated in Figure 3, depending on the number of BHEs.

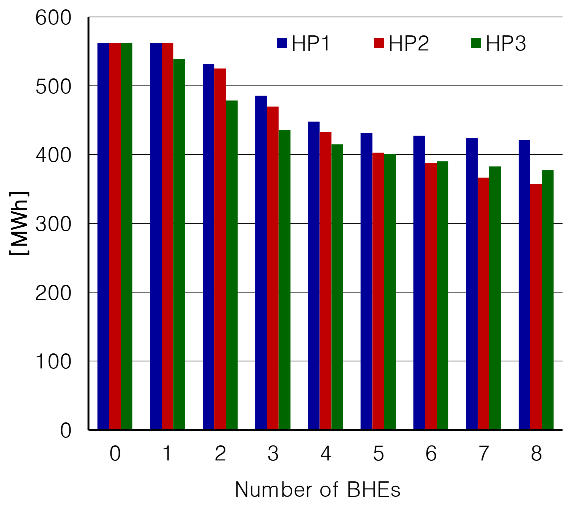

Figure 3: Primary energy consumption after 10 years of operation for different numbers of BHEs.

In any case, primary energy consumption of HP1 is greater than HP2 and HP3. HP3 performs better than HP2 up to 6 boreholes. For the three heat pumps, at a high number of BHEs, energy consumptions decrease, but the incremental savings are lower. For this reason, it seems appropriate to choose a reduced total length of the boreholes, based on a cost-benefit analysis.

Table 3: Capacities of the examined heat pumps.

	HP1 Heat pump sized on the peak load	**HP2** Heat pump sized on the average power demand of the design months	**HP3** Heat pump sized on the seasonal average power demand
Heat pump manufacturer and model	Rossato Group ACTEA MAXI 36 (electrically driven)	Rhoss THHEY 112 (electrically driven)	Rhoss THHEY 105 (electrically driven)
Heating declared capacity under reference condition (EN 14511:2008)	47.8 kW	11 kW	5.1 kW
Cooling declared capacity under reference condition (EN 14511:2008)	58.6 kW	17.8 kW	7.7 kW

The results also provide useful indications for optimal values of BHEs length and flow rate within a geothermal loop. In all cases, the optimal depth equals to the allowed maximum (100 m), while the flow rate is close to the minimum.

In this work, we refer to geothermal loops with a constant flow rate. In the presence of variable flow (i.e., variable speed drive), the constrains on minimum Reynolds number and velocity have to be checked at the lower controlled flow rate. Another check to be performed on the design flow rate is its compatibility with the values accepted by the heat pump unit.

A rough economic analysis was performed parametrically, in terms of installation costs, going from 20 to 120 euros per metre of drilling. Other economic parameters are shown in Table 4. Investment metrics are calculated neglecting the discount rate and the inflation of energy prices.

Table 4: Parameters of the economic analysis.

Parameter	Value
Assumed unit price of electrical energy [€/kWh]	0.20
Assumed unit price of natural gas [€/kWh]	0.09
HP1 retail price* [€]	16,450
HP2 retail price** [€]	12,000
HP3 retail price** [€]	10,000

*(Rossato Group 2012)
**Prices are purely indicative (not confirmed by the manufacturer).

Estimates of simple payback periods (SPP) for the three examined GSHPs are presented in Fig.4. We observe that the optimal number of boreholes is between 3 and 6, depending on the capacity of the heat pump and on the installation costs per metre of drilling. In any case, the design length of BHEs is shorter than the one previously calculated in accordance with standard methodologies.

Table 5 reports the calculated simple payback periods as a function of BHEs installation costs for the optimal configuration of each heat pump. 40 euros per metre of drilling seems to be the maximum allowable cost to obtain positive net values after a typical 20-year lifespan of a heat pump unit. The cost-benefit analysis suggests choosing the smaller heat pump (i.e., HP3).

Table 5: Estimated SPP for the optimal number of boreholes (solutions with SPP<20 years are in red).

	HP1		HP2		HP3	
	SPP	# BHEs	SPP	# BHEs	SPP	# BHEs
20 €/m	19.9	5	13.8*	6	12.7**	4
40 €/m	27.1	4	20.5	5	17.7***	3
60 €/m	33.7	4	26.9	5	22.5	3
80 €/m	40.4	4	33.3	4	27.4	3
100 €/m	47.41	4	39.3	4	32.3	3
120 €/m	53.8	4	45.4	4	37.0	3

*Net value after 20 years: 10,719 €; profitability index: 1.45.
**Net value after 20 years: 10,265 € profitability index: 1.57.
***Net value after 20 years: 2.837 €; profitability index: 1.13.

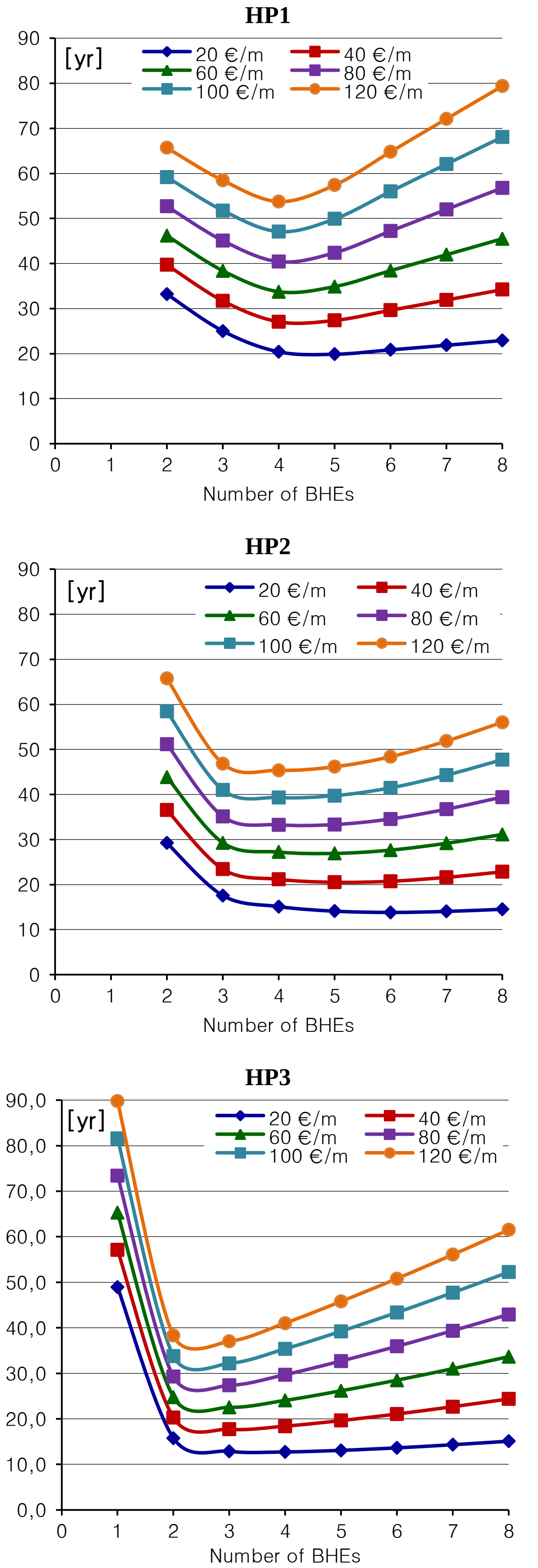

Figure 4: Estimated simple payback periods for the three heat pumps and different numbers of BHEs.

In Table 6, we report the main results of the optimization procedures for the two best configurations: 6 BHEs for HP2 and 4 BHEs for HP3.

Table 6: Main results of the optimisation procedure for the two best configurations.

	HP2	HP3
Total length of BHEs [m]	100 x 6	100 x 4
Total flow rate [kg/s]	1.48	0.85
f_H	1	0.78
f_C	1	0.65
SCOP	3.3	3.5
SEER	5.4	5.5
CR (winter/summer)	0.51 / 0.64	0.68 / 0.92
Heat flow per unit length (winter/summer) [W/m]	9.2 / 17.0	8.3/16.6
Primary energy consumption (after 10 years) [MWh]	381 (-32.5%)	415 (-26.2%)
Economic savings (after 10 years) [€]	17,359	14,133

Further insights on the energy performance and preliminary economic results are given in Figs. 5-10.

Particularly, Figs. 5 and 6 show the 10-year evolution of COP and EER for the two best cases. The trends are almost periodic, with no significant penalisation of the heat pump performances year after year. HP3 maintains a more constant COP with respect to HP2, because its CR values are higher and less variable.

The contribution of GSHPs and back-up generators to satisfy the monthly building energy demands is illustrated in Figs. 7 and 8. We can observe that HP2 is supposed to be off during the months of April and October, since it would work at a COP below 2.5, making it less efficient of the back-up boiler. Differently from HP2, HP3 is not capable of delivering the entire energy need during the more critical winter and summer months, due to its limited capacity, but it operates efficiently throughout the whole year.

Finally, Figs. 9 and 10 report, on a monthly basis, the expenses for natural gas (used by the back-up boiler) and electrical energy and the economic savings obtained by means of the GSHPs.

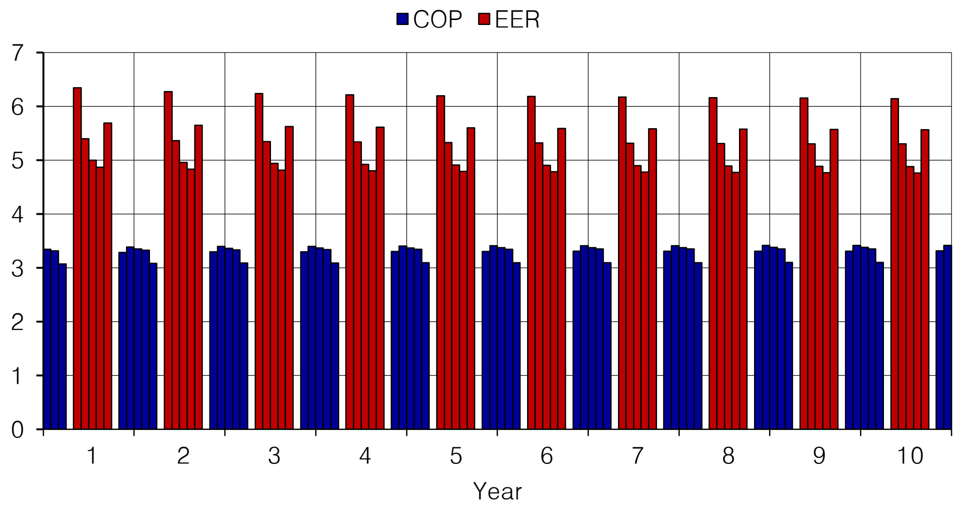

Figure 5: COP and EER evolution during 10 years of operation (HP2, 6 BHEs).

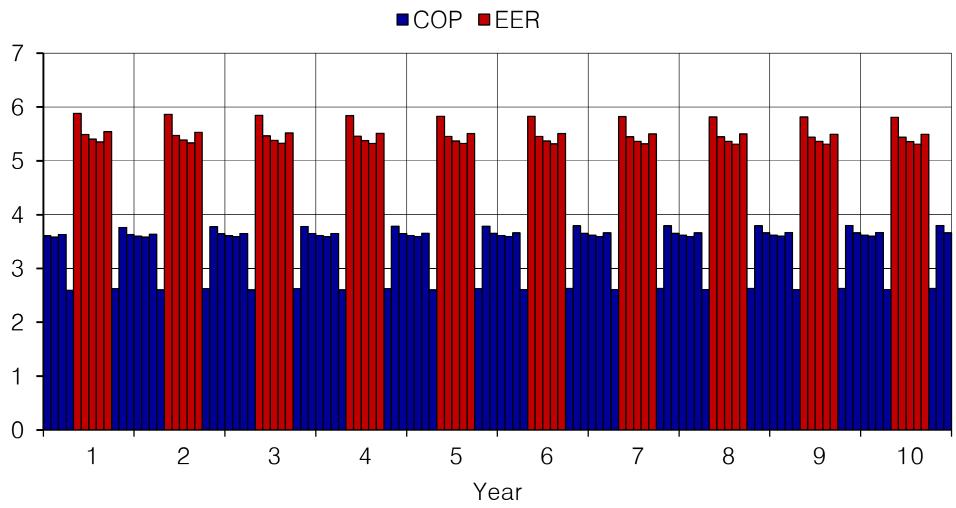

Figure 6: COP and EER evolution during 10 years of operation (HP3, 4 BHEs).

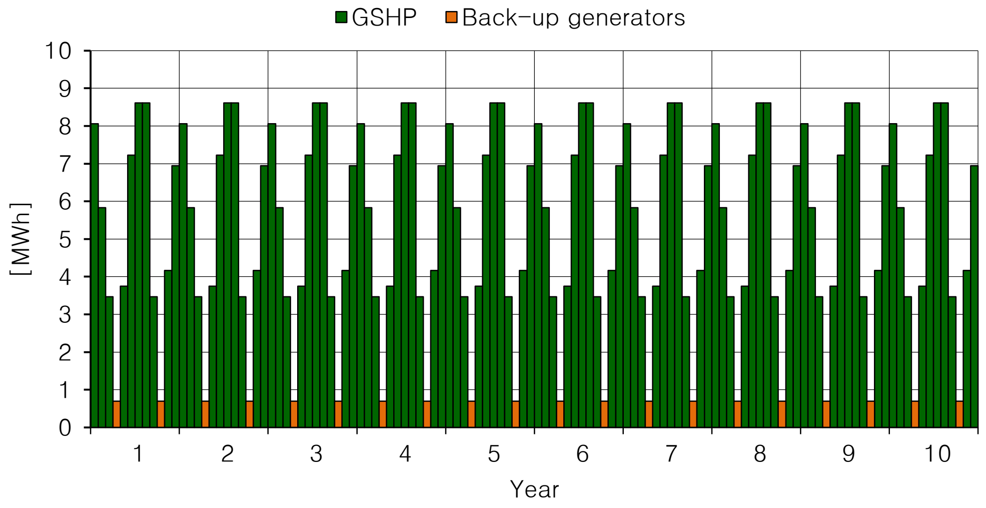

Figure 7: Thermal energy delivered to the building during 10 years of operation (HP2, 6 BHEs).

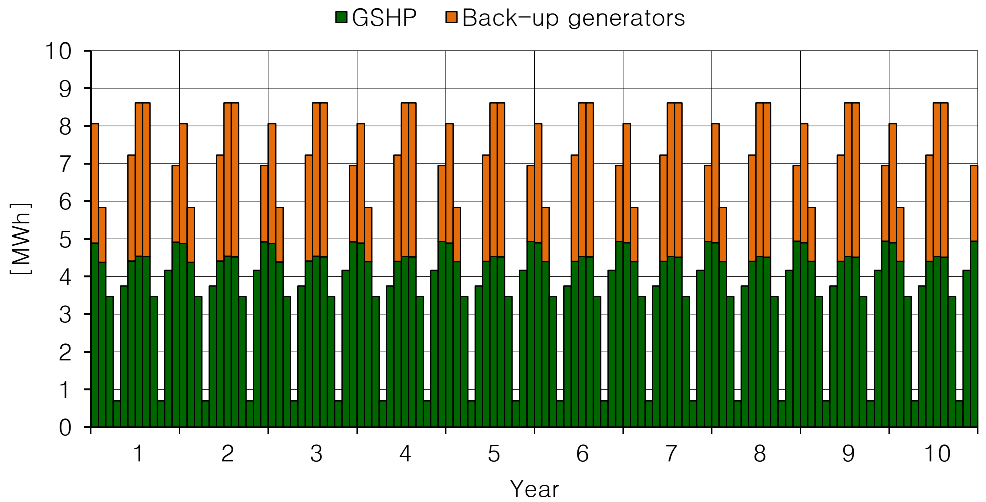

Figure 8: Thermal energy delivered to the building during 10 years of operation (HP3, 4 BHEs).

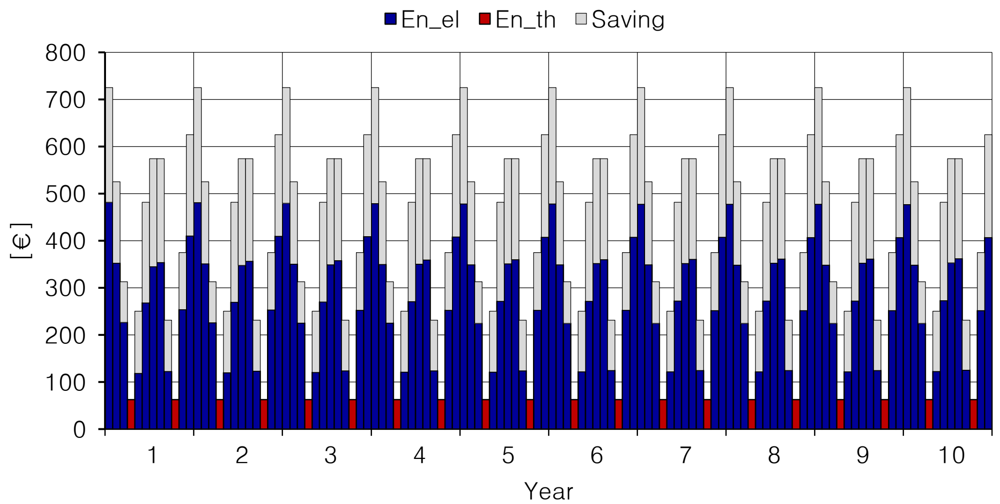

Figure 9: Breakdown of expenses for gas and electrical energy and economic savings obtained by the GSHP during 10 years of operation (HP2, 6 BHEs).

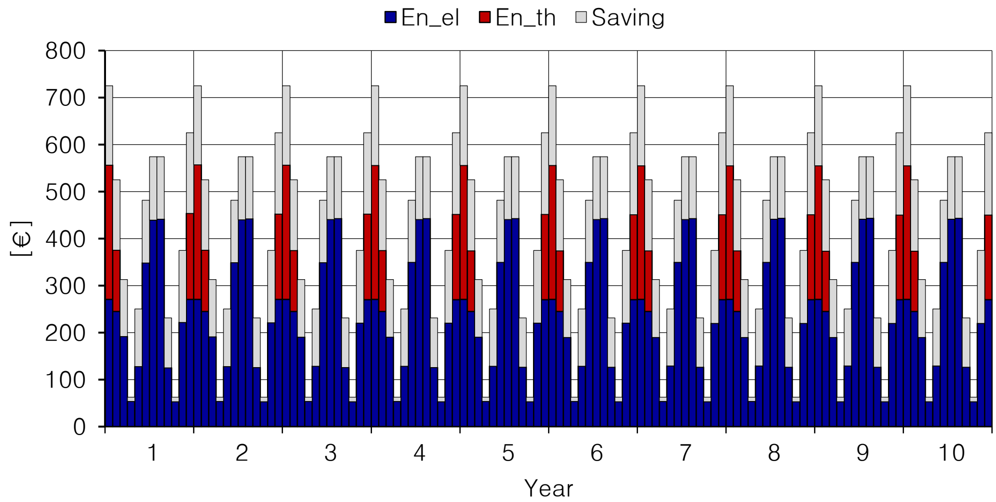

Figure 10: Breakdown of expenses for gas and electrical energy and economic savings obtained by the GSHP during 10 years of operation (HP3, 4 BHEs).

6. CONCLUSIONS

In the present work, we proposed an innovative holistic approach to the design of GSHP systems, based on energetic and economic cost-benefit considerations. We also emphasised the limits of current standard design procedures.

We described a comprehensive model for the simulation of the performance of GSHP systems with closed-loop ground-coupled vertical BHEs. The model was coupled to an optimisation algorithm, in order to find the design parameters that minimise the use of primary energy. The main design outputs of the method are: optimal capacity of the heat pump unit and optimal number of BHEs.

Seasonal average thermal demands, rather than peak loads, have to be used as a reference for the sizing of the heat pump. Units with a larger capacity suffer the penalisation factor of COP/EER due to low CR values. In fact, we remind that only fixed capacity units have been analysed. The effects of capacity controls in GSHP systems will be simulated in future works.

The method was applied to a test case. Energy savings obtainable by means of GSHPs proved to be remarkable. However, we point out that installation costs are the main drawback of this technology, possibly limiting its diffusion, unless payback periods are shortened by providing substantial financial incentives or due to relevant inflation of energy prices.

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