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Proposal of Technical Guidelines for Optimal Design of Ground-Source Heat Pump Systems

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ABSTRACT

An innovative design methodology for ground-source heat pump (GSHP) systems has been developed, based on the evaluation of energy exchange and performance during the entire operational life. This novel procedure takes into account design solutions in which GSHPs are coupled with other heating and cooling technologies and finds the reciprocal optimal shares of thermal loads in terms of cost-benefit indicators. The proposed method is holistic; in other words, it incorporates in a single set of equations all the interactions among the three macro-systems governing the energy balance of GSHPs: building thermal energy loads, efficiencies of generators (heat pump and back-up systems), and thermal response of the ground (taking into account the sustainability of the source). The optimal design parameters and energetic and economic outputs of the procedure are: - thermal capacities of the heat pump and back-up generators; - size, number and position of ground heat exchangers; - flow rate in the ground-coupled loop; - load shares between GSHP and back-up systems (control strategy); - required energy input during multi-year operation; - energy savings with respect to the exclusive use of conventional back-up systems or, conversely, to the use of the sole geothermal system; - installation and operational costs; - key investment indicators. Guidelines to be followed by professionals for an effective design procedure in the case of ground-coupled vertical borehole heat exchangers (BHEs) are illustrated step-by step.

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 (e.g. air heat pumps, condensing boilers, solar technologies), provided that special attention is 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.

Several standards are already available to designers (ASHRAE, 2011; Kavanaugh and Rafferty, 1997; UNI, 2012a; VDI, 2001) however, most of these methods are based on some operative parameters decided a priori (e.g. ground-coupled loop temperatures and flow rates, GHP capacity, heating/cooling load share assumed by the ground source, reference design month). As a consequence, despite their practical usefulness, current design procedures do not guarantee that the final design is the most cost-effective in terms of operative performance.

An alternative approach to GSHP design has been proposed in scientific literature (Retkowski and Thöming, 2014; Robert and Gosselin, 2013). In these works, borehole heat exchangers (BHEs) number, depth and spacing, together with GHP unit capacity, are optimized according to their impact on final operative performances. Additionally, Conti *et. al* (2013, 2014a) include the management strategy of the system within the design variables, showing the energetic and economic benefits that can be reached through an appropriate synergy of geothermal source and back-up generators.

In the following sections, we describe a general design method based on the optimization of the operative performance of GSHPs with vertical BHEs, integrating it in a straightforward procedure. This method can be applied by the professionals to identify the optimal design solution among possible equipment alternatives. Finally, a test case is presented in order to compare the results of traditional methodologies with the present approach.

2. PRELIMINARY CONSIDERATIONS ON GSHP OPTIMAL DESIGN

The performance of a GSHP system can be evaluated in terms of both energetic and economic savings with respect to other technologies. Optimal design is obviously dependent on the selected performance index (e.g. primary energy consumption or total costs), specific technical constraints, and economic context of the project; however, some general elements can be identified to set up the design procedure.

First of all, it is worth recalling that ground-coupled systems usually work in synergy with other generation technologies. The use of a GSHP system is convenient only when operative conditions (source temperatures and unit capacity ratio) allow delivering useful thermal energy with an energy consumption lower than back-up technologies. In other words, a proper design has to include, among other variables, the optimal shares of the building thermal load among the different generation systems.

In the present work, we refer to capacity ratio (CR) according to the following definition:

$$CR = \frac{Q_u}{\dot{Q}_{DC} \cdot \tau} \tag{1}$$

where:

- τ is the reference time scale (e.g. week, month, season) [h];
- Q_u is the useful thermal energy delivered by the HP during the time τ [Wh];
- $\dot{Q}_{DC}$ is the maximum deliverable thermal power (capacity) of the HP unit, when operating at the actual temperatures of the thermal sources, during the time τ [W].

The effect of CR on operative coefficients of performance depends on the choice of the HP unit size and on its modulation capability in response to the evolution of the thermal load.

We point out that CR is an important indicator also for the economic feasibility of the project: low CR values generally imply limited economic savings with respect to large installation costs of the HP unit. Therefore, design methodologies sizing the GSHP system on the basis of the building peak load are not recommended. Instead, the final goal of an optimized design procedure is to find the optimal geothermal share of the building energy load, with the corresponding generator capacities (GHP and back-ups), BHEs number, depth and position, and control strategy.

3. THE DESIGN PROCESS AS AN OPTIMIZATION PROBLEM

The previous considerations highlight how the GSHP design process is not a mere calculation of the size of every component, but is a comprehensive procedure based on the optimization of the overall performance of the system during its operational life. With the proposed holistic approach, feasibility study, sizing process, performance analysis, and design optimization are hence to be considered as the very same activity.

An introductory scheme of this method was outlined in Conti *et al*. (2013) and fully developed in Conti *et al*.(2014a, 2014b). Design and control-strategy variables (namely, "control variables" u) are optimized by means of a "multistage decision problem" (Rao, 1996):

$$P(\underline{U}) = \min_{\underline{U}} \sum_{n=1}^{N} R(\underline{u}^n; \underline{x}^n) \tag{2.a}$$

subject to:

$$\underline{x}^{n+1} = f(\underline{u}^n; \underline{x}^n) \tag{2.b}$$

$$h_j(\underline{x}^n) = 0 \qquad j = 1,2,... \tag{2.c}$$

$$g_k(\underline{x}^n) \leq 0 \qquad k = 1,2,... \tag{2.d}$$

$$u_{m_{\min}} \leq u_m \leq u_{m_{\max}} \tag{2.e}$$

where:

- $\underline{u}^n = (u_1{}^n, u_2{}^n, ...)$ is the vector of control variables at the n^{th} stage;
- $\underline{x}^n = (x_1{}^n, x_2{}^n, ...)$ is the vector of state variables at the n^{th} stage;
- $P(\underline{U})$ is the objective function (also known as the "*performance index"*);
- $\underline{U}$ is the set containing all the u^n;
- $R(\underline{u}^n; \underline{x}^n)$ is the so-called *"return function"*; it represents the contribution of the n^{th} stage to the total objective function;
- $f(\underline{u}^n; \underline{x}^n)$ is the mathematical model for GSHP simulation (see set of Eqs. 3); f relates the state variables of a stage to the control and state variables of the previous stage;
- h_j is the j^{th} equality constraint;
- g_k is the k^{th} inequality constraint.

Typical control variables ($\underline{u}$) to be optimized in GSHP design are:

- *control-strategy variables*: capacity ratio of GHP unit (CR);
- *design variables*: number (N_{BHE}), depth (H) and spacing (Z) of BHEs, GHP and back-up generators capacities, flow rate in ground-coupled loop ($\dot{m}_w$).

The overall system model f is expressed through the full set of Eqs. 3, where each subsystem model has to be "solved" concurrently: in this way, all the interactions among the GSHP components are considered. The two coefficients f_H and f_C represent the control strategy: their value corresponds to the fraction of building load delivered by the geothermal heat pump in heating and cooling mode, respectively.

$$Q_{E/C} = Q_g \quad (3.a)$$

$$Q_{E/C} = \dot{m}_w c_w \left| T_{w_{in}} - T_{wout} \right| \tau \quad (3.b)$$

$$Q_{E/C} = F\left(T_{w_{in}}, T_l, CR\right) \quad (3.c)$$

$$Q_g = H\left(\dot{m}_w, T_{w_{in}}, R_b, H, N_{BHE}\right) \quad (3.d)$$

$$T_g = S\left(T_g^{\ 0}, Fo_g, Pe_g, Q_g\right) \quad (3.e)$$

$$f_H = \frac{Q_E}{Q_l}\left(\frac{\langle COP \rangle}{\langle COP \rangle - 1}\right) \qquad f_C = \frac{Q_C}{Q_l}\left(\frac{\langle EER \rangle}{\langle EER \rangle + 1}\right) \quad (3.f)$$

$$Q_{E/C} = F\left(T_l, CR\right) \quad (3.g)$$

$$Q_{bk} = \left(1 - f_{H/C}\right) \cdot Q_l \quad (3.h)$$

The set of equations includes:

- Eq. 3.a, which imposes that the total heat exchanged between the BHE field and the ground (Q_g) is equal to the heat transferred to the evaporator/condenser ($Q_{E/C}$);
- Eq. 3.b, which is the energy balance for the fluid of the ground loop at the evaporator/condenser section;
- Eq. 3.c, representing the heat pump unit; the function $F(\ )$ correlates the HP performance to the operative conditions;
- Eq. 3.d, representing the BHE field; the function $H(\ )$ correlates Q_g to the ground temperature at the borehole surface (T_g), to the BHEs characteristics, and to the ground-coupled loop operative parameters (flow rate and temperature);
- Eq. 3.e, representing the ground source; the function $S(\ )$ correlates T_g to heat fluxes, thermo-physical properties, and groundwater seepage;
- Eq. 3.f, which is the definition of the GSHP shares of the building load for heating (f_H) and cooling (f_C);
- Eq. 3.g, representing the back-up system; similarly to the heat pump unit, the performance of the back-up generator is influenced by its capacity ratio and by the temperature of the end-user loop; the function $B(\ )$ characterizes the employed back-up technology;
- Eq. 3.h, which imposes that the building thermal load (Q_l), up to the end-user distribution system, is given by the sum of the thermal energies delivered/removed in heating/cooling mode by GSHP and back-up generators.

Formulas for subsystems modelling can be easily found in scientific literature (Cui *et al.*, 2008; Nagano *et al.* 2006; Pardo *et al.,* 2011) and in several technical standards (CEN 2008; UNI 2012b).

4. SUGGESTED DESIGN PROCEDURE

The suggested overall procedure for optimal GSHP design is based on a sensitivity analysis of performance index value $P(\underline{U})$ on possible design alternatives. In a similar fashion to Kavanaugh (2008), we now provide a list of suggested operative steps, followed by their description for practical application:

1. Calculate heating and cooling needs of the building;
2. Determine ground thermal properties;
3. Decide BHEs configuration and evaluate corresponding heat transfer performance;
4. Provide first guess of BHEs number, depth and spacing using traditional design methods (e.g. ASHRAE)
5. Create set of possible GHP unit alternatives;
6. Create corresponding set of back-up generators;
7. Perform sensitivity analysis (calculate $P(\underline{U})$ values for all combinations of GHP units and BHEs number).

4.1. STEP 1: Calculate heating and cooling loads

An accurate evaluation of building thermal load is the basis for any design methodology. Technical standards of different accuracy and complexity are widespread throughout the world (ISO, 2008; UNI, 2008) and are not repeated here for the sake of conciseness. Dedicated software are widely employed, too (e.g. Energy Plus, TRNSYS). Whatever method is used, thermal loads have to be aggregated according to the operative simulation time scale (see Section 2). We suggest to choose one month as the reference time for averaging all the involved quantities, being neither too long to miss significant variations of the ground-coupled system operative conditions, nor too short to require detailed building and systems usage schedules, generally unavailable during the design phase.

4.2 STEP 2: Determine ground thermal properties

Undisturbed temperature, thermal conductivity and thermal diffusivity of the ground are required in any design method. Whenever possible, these three parameters should be determined by means of in-situ surveys (e.g. Thermal Response Test); otherwise, reference values can be found in several technical standards, handbooks, or scientific literature.

4.3. STEP 3: Decide BHEs configuration and evaluate corresponding heat transfer performance

Boreholes act like any heat exchanger, therefore we can analyze them through the classical heat exchanger theory (see, for instance, Lavine *et al*. 2011). The main parameters affecting BHEs performance are: the so-called borehole thermal resistance (R_b), the depth of the hole (H), and the flow rate within the ducts ($\dot{m}_w$). The influence of these parameters on heat transfer effectiveness (ε) is shown in Eq. 4:

$$\varepsilon = \frac{Q}{Q_{\max}} = 1 - \exp\left(-\frac{H}{\dot{m}_w c_w R_b}\right) \tag{4}$$

where:

- Q is the actual heat transferred between the ground and the fluid;
- $Q_{\max}$ is the maximum heat that could be transferred if the exchanger were ideal: namely, if the outlet temperature of the fluid were equal to the temperature of the ground.

H and $\dot{m}_w$ are investigated within the overall optimization procedure, because their optimal values depend on several coupling effects among GSHP components and economic context. On the other hand, the borehole thermal resistance can be minimized in any case. The R_b value is given by three contributions: convective thermal resistance between the fluid and the pipe wall, conductive thermal resistance across the pipe, and thermal resistance of the grout. The contribution of convective resistance can be neglected when the flow regime within the BHEs ducts is turbulent (Conti *et al.* 2014b). Hence, the main parameters influencing R_b are: thermal conductivity of the pipe and of the grout, radius of the pipe and of the BHE, and shank spacing between the U-legs. Intending to reduce R_b , we suggest choosing the 2-U configuration, together with large diameter ducts and highly conductive materials. Feasibility constraints are given by the costs of the materials.

4.4. STEP 4: Provide first guess of BHEs number, depth and spacing using traditional design methods

Traditional design standards (e.g. ASHRAE method) can be used to evaluate BHEs number and spacing as the first guess and starting value for the optimization procedure.

4.5. STEP 5: Create set of possible GHP unit alternatives

The overall procedure finds the best GHP size, comparing the performance of different alternatives. We suggest to test at least two devices with different nominal capacities, chosen in the following way: the capacity of the first HP unit should be based on the greatest monthly average power demand between heating and cooling design months; the capacity of the second unit should comply with the greatest seasonal average power demand between the entire heating and cooling periods. Peak loads are not taken into account due to their negative impact on GHP capacity ratio (see Section 2). In any case, according to their personal evaluations, designers are encouraged to include any other unit in the set of HPs under comparison.

4.6. STEP 6: Create corresponding set of back-up generators

We suggest to select the capacity of back-up generators as the difference between the peak heating/cooling loads of the building and the nominal capacity under heating/cooling mode of the selected GHP unit.

4.7 STEP 7. Perform sensitivity analysis

Overall system performance has to be optimized for all the units in the GHP set and for all the BHEs numbers between 1 and the result of Step 4. The optimization problem is formulated as in Eqs. 2. The following routine illustrates a possible strategy for its resolution (see also Fig. 1):

1. select the ground-coupled heat pump unit, the back-up generators and the number of BHEs;
2. provide an initial guess for: ground-coupled loop flow rate and BHEs depth and spacing; suggested values are:
   - the flow rate ($\dot{m}_w$) have to guarantee a turbulent flow ($\mathrm{Re}_D \geq 6000$) within the ducts;

- the depth of a single borehole (H) is the maximum allowed by economic and environmental consideration; typical values span from 80 to 120 m;
- the spacing (Z) among BHEs is typically 6-8 m (Kavanaugh, 2008);

3. as 1st stage of the optimization routine, seek the optimal sequence of f_H and f_C coefficients, while H and $\dot{m}_w$ are fixed to their current values;

4. as 2nd stage of the optimization routine, determine the optimal values of H , Z and $\dot{m}_w$, assuming the results of point (c) as control strategy;

5. iterate between points (c) and (d), until a convergence criterion is satisfied.

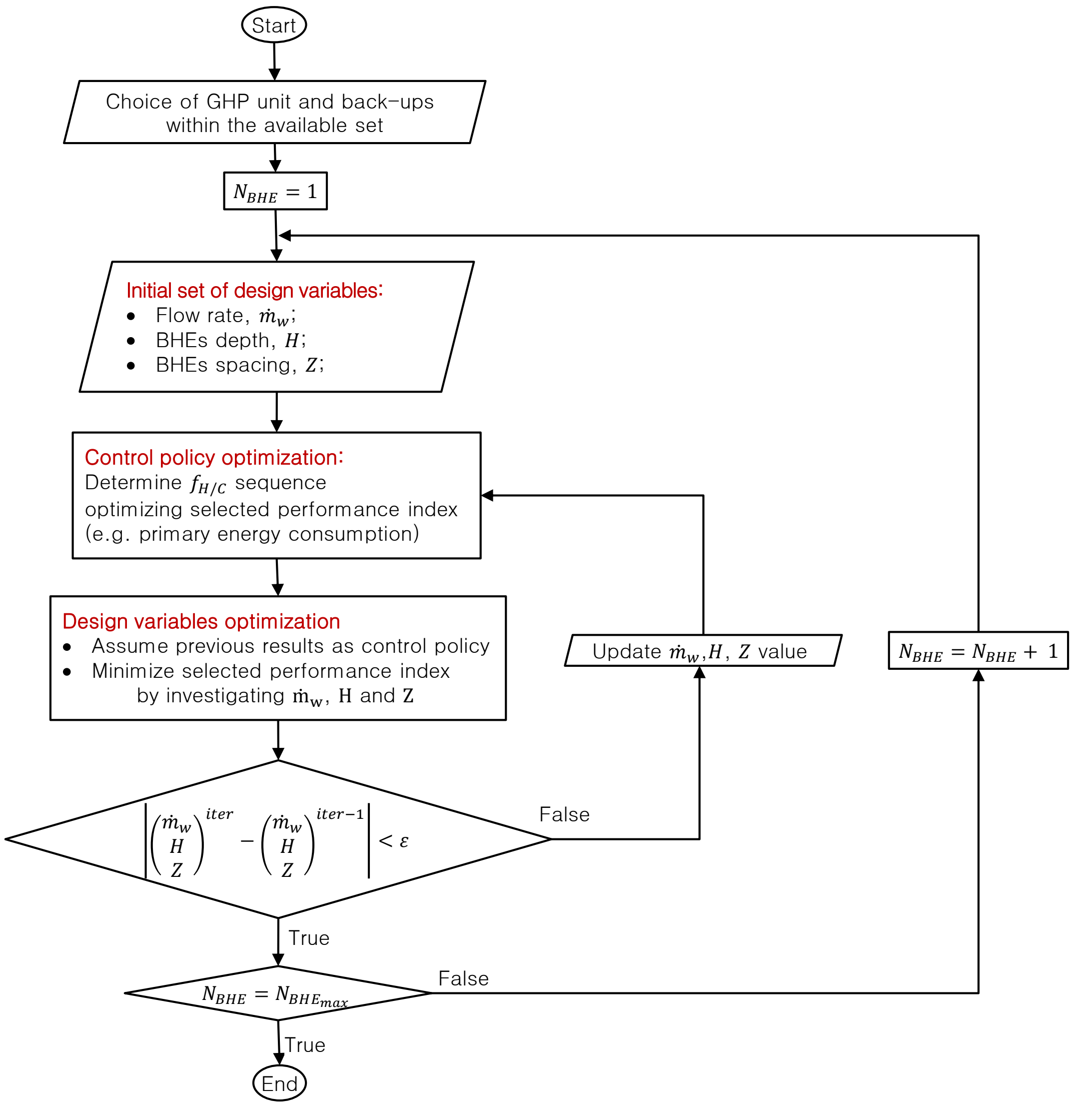

Figure 1: Suggested algorithm for the resolution of the optimization problem (Eqs. 2).

5. DEFINITION OF A DESIGN CASE

The application of the described design procedure is illustrated for a case study. Heating and cooling loads were imposed for a typical medium-scale office building located in Southern Europe (STEP 1). 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.

We assumed typical values of the ground properties, as reported in Table 2 (STEP 2). In the same table, diameter and thermal resistance of the BHE (considering a double “U-tube” arrangement) are also shown(STEP 3).

At first, we employed standard design procedures (STEP 4). As for the BHEs length, an initial estimation was obtained by the ASHRAE method, resulting in a total length of about 700 m (7 x 100 m).

Then, we created the set of GHP units (STEP 5) and back-up generators (STEP 6). The characteristics of the selected heat pumps are shown in Table 3. According to the described methodology, we considered the average power demand of the cooling design month (Conf. 2) and the seasonal average power demand of the cooling season (Conf. 3). We included also a unit based on peak load (Conf. 1), in order to show the negative effects caused by GHP oversizing. Finally, we simulated the energy consumption of a non-geothermal system, with exclusive use of back-up technologies.

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

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**
Peak load	**30 kW**	**40 kW**

*Delivery temperature of the building end-user loop: 45°C (heating) and 7°C (cooling).

Table 2: Ground thermal properties and BHE characteristics (STEP 2 and STEP 3).

Property	**Value**
Ground thermal conductivity [W/(m·K)]	1.7
Ground thermal diffusivity [mm²/s]	0.68
BHE diameter [cm]	15
BHE configuration	Double U
Spacing between boreholes [m]	8
Grouting thermal conductivity [W/(m·K)]	1.7
BHE pipe diameter (inner – outer) [cm]	2.62 – 3.2
U-legs shank spacing [cm]	9.4
Pipe thermal conductivity [W/(m·K)]	0.35
BHE thermal resistance R_b [m·K/W]	0.062

Table 3: Declared capacities (DC) of the generators in the examined configurations (UNI 14511-2, 2013).

	Ground-coupled (water/water) unit		**Condensing boiler**	**Air/water unit**
	Heating DC	Cooling DC	Heating DC	Cooling DC
Configuration 1 Heat pump sized on the peak load	35.0 kW	40.5 kW	-	-
Configuration 2 Heat pump sized on the average power demand of the cooling month	10.7 kW	12.1 kW	23.9 kW	29.1 kW
Configuration 3 Heat pump sized on the average power demand of the cooling season	12.1 kW	8.88 kW	23.9 kW	32.9 kW
Configuration 4 Non-geothermal solution	-	-	33.5 kW	44.2 kW

Primary energy consumption is the selected performance index. The optimized variables are: generators configuration (GHP and back-ups), BHEs number and depth (N_{BHE} ; H), flow rate within ground-coupled loop ($\dot{m}_w$), and control strategy (monthly values of f_H and f_C). In this work, dealing with a limited number of BHEs (<10), we decided not to include BHEs spacing among the optimization variables; a typical distance of 8 m was imposed (Table 3), so to avoid heat transfer impairing effects due to interference among the boreholes.

6. RESULTS OF THE APPLICATION OF THE PROPOSED DESIGN METHOD TO THE CASE STUDY

Optimal design variables and control strategy were found and the corresponding primary energy consumptions were calculated (STEP 7) for all configurations as a function of BHEs number (Fig. 2). Primary energy consumption in the absence of a GSHP system (i.e., only with back-up generators, Conf. 4) is 1,035 MWh after 20 years of operation.

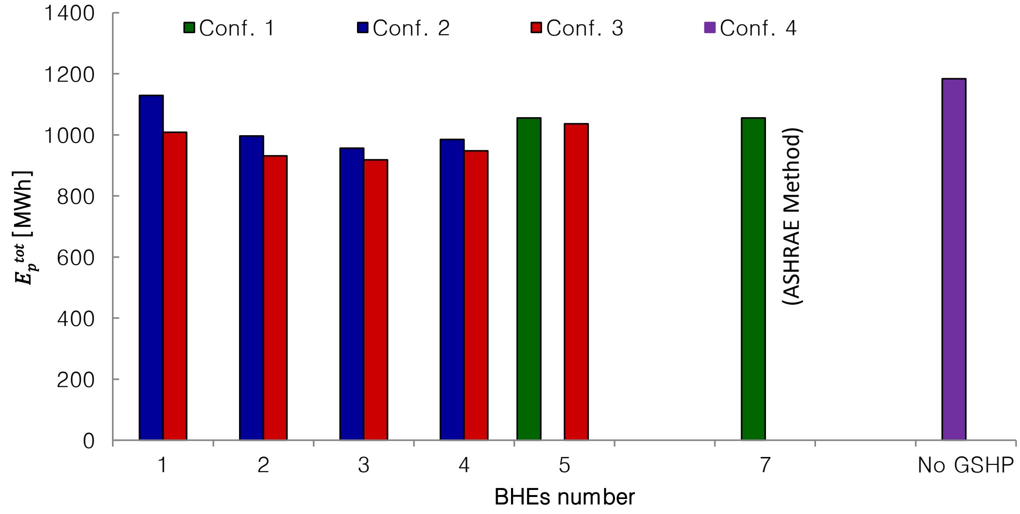

Figure 2: Primary energy consumption after 20 years of operation for different numbers of BHEs.

Conf. 1 needs 5 boreholes to cover the building thermal load alone; with respect to the ASHRAE method based on peak loads, we saved 2 BHEs, even without considering a synergy between GSHP system and back-ups. However, the energy savings with respect to the No-GSHP solution are negligible, emphasizing again the issue of GHP oversizing.

Primary energy consumptions of Conf. 2 and Conf. 3 are always lower than the ones of Conf.1 and Conf. 4 (No-GSHP), showing the benefit of an appropriate synergy between geothermal source and back-up technologies. Both HP2 and HP3 perform better up to 3 boreholes with an energy consumption of 899 MWh and 848 MWh, respectively. The best configuration (HP3) saves about 15 % of primary energy with respect to the No-GSHP solution or to the use of the sole geothermal system.

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 is equal to the allowed maximum (100 m), while the flow rate is close to the minimum.

A rough economic analysis was performed parametrically, in terms of BHEs installation costs, going from 20 to 100 euros per meter of drilling. Other economic parameters are shown in Table 4. Investment metrics are calculated neglecting the discount rate and any inflation of prices.

Table 4: Parameters of the economic analysis.

Energy fees	
Assumed unit price of electric energy [€/kWh]	0.20
Assumed unit price of natural gas [€/kWh]	0.08
Retail prices of generators*	
Conf. 1	
GHP [€]	18,500
Conf. 2	
GHP [€]	5,200
Boiler [€]	4,000
Air unit [€]	8,500
Conf. 3	
GHP [€]	4,600
Boiler [€]	4,000
Air unit [€]	10,000
Conf. 4	
Boiler [€]	5,000
Air unit [€]	14,000

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

Estimates of simple payback periods (SPP) as a function of BHEs installation costs for the two best energetic configurations (HP2, 3 BHEs – HP3, 3 BHEs) are presented in Fig. 3 and Table 5. We note that the highest unitary costs (€/m) allowing to obtain a SPP shorter than 20 years are 45 €/m for Conf. 2 and 56 €/m for Conf. 3. Net values and profitability indices at the end of the considered operative life (20 years) are also shown in Table 5. In Table 6, we report the main results of the optimization procedure for the two best configurations.

Further insights on the energy performance and preliminary economic results are given in Figs. 4-6. Particularly, Fig. 4 shows the 20-year evolution of COP and EER for the best case. The trends are almost periodic, with no significant penalization of the heat pump performance year after year.

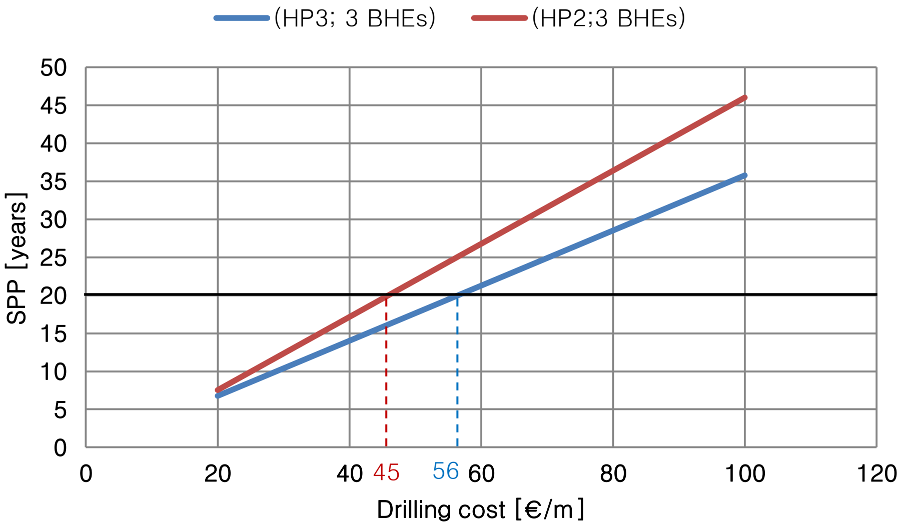

Figure 3: SPPs as a function of the drilling costs for the two best configurations (Conf. 3; 3 BHEs – Conf. 2; 3 BHEs).

Table 5: Estimated SPPs, net values (NV), and profitability indices (PI) for the optimal configurations.

	HP2 – 3 BHEs			HP3 – 3 BHEs		
Drilling costs	SPP	NV [k€]	PI	SPP	NV [k€]	PI
20 €/m	8	7.8	0.33	7	10.9	0.45
40 €/m	17	1.8	0.06	14	4.9	0.16
60 €/m	27	< 0	< 0	21	< 0	< 0
80 €/m	36	< 0	< 0	29	< 0	< 0
100 €/m	46	< 0	< 0	36	< 0	< 0

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

	HP2 – 3 BHEs	HP3– 3 BHEs
Total length of BHEs [m]	100 x 3	100 x 3
Total flow rate [kg/s]	1.02	1.02
f_H	0.93	0.86
f_C	0.78	0.38
$< COP >$	3.41	3.48
$< EER >$	3.60	3.81
Boiler efficiency	1.09	1.09
$< EER >$ air unit	3.09	3.94
CR (heating/cooling)	0.38 / 0.69	0.45 / 0.50
Heat flow per unit length (heating/cooling) [W/m]	19.4 / 34.5	18.3 / 37.3
Primary energy consumption (after 20 years) [MWh]	899 (-9.4 % vs. Conf. 4)	848 (-15.1% vs. Conf. 4)

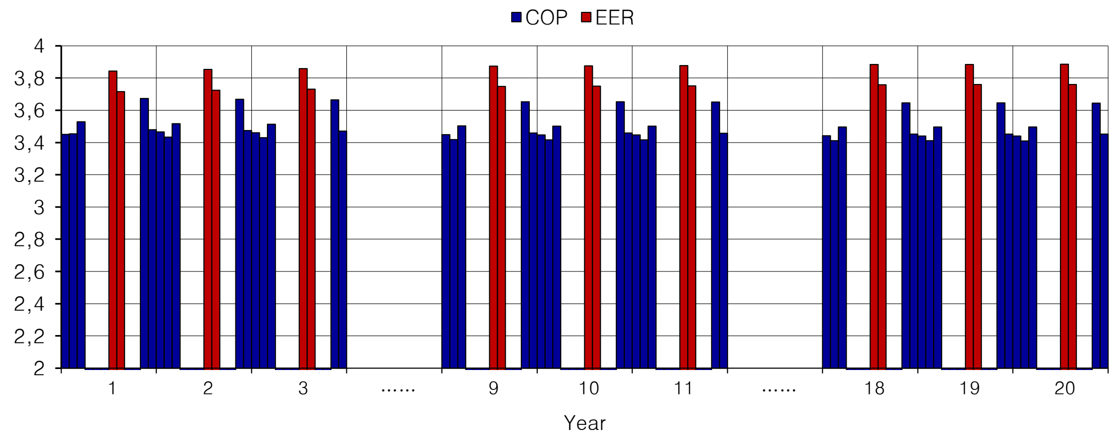

Figure 4: COP and EER evolution during 20 years of operation (HP3, 3 BHEs).

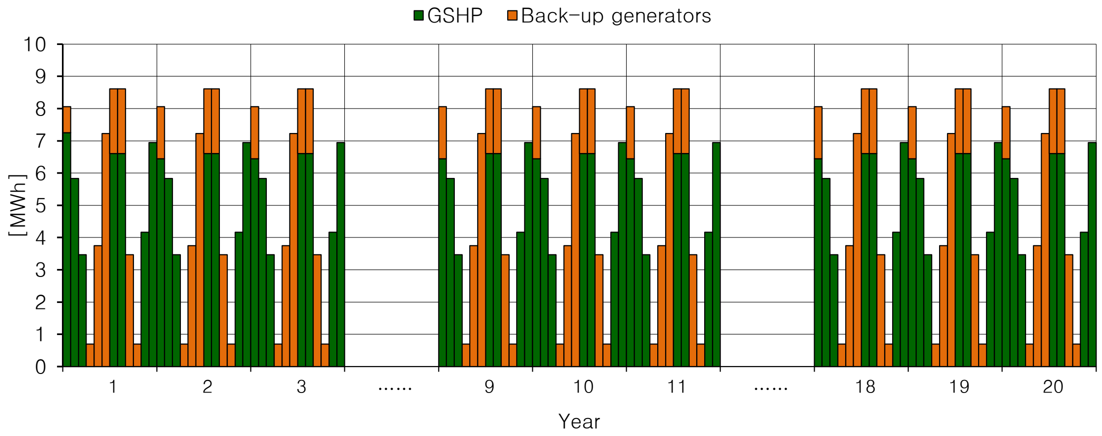

Figure 5: Thermal energy delivered to the building during 20 years of operation (HP3, 3 BHEs).

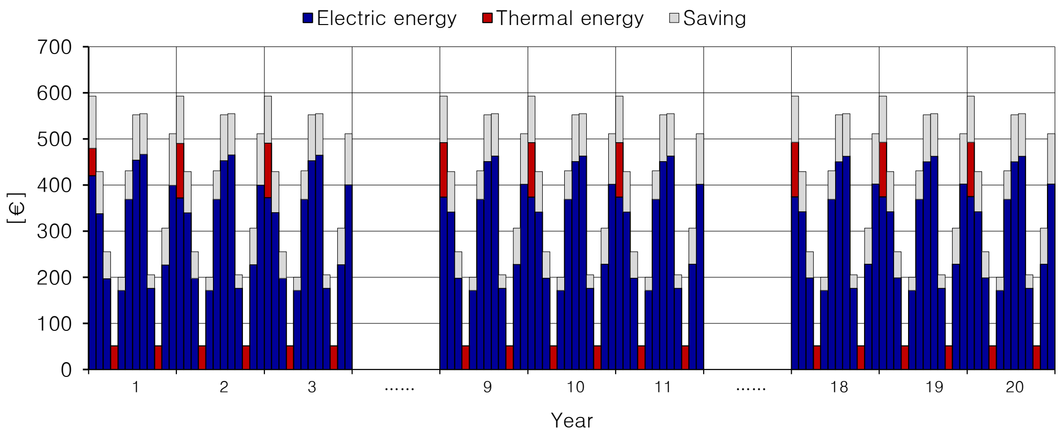

Figure 6: Breakdown of expenses for gas and electrical energy and economic savings obtained by the GSHP during 20 years of operation (HP3, 3 BHEs).

The contributions of HP3 and back-up generators to satisfy the monthly building energy demands are illustrated in Fig. 5. We can observe that the geothermal heat pump is supposed to be off during the months of April, May, June, September, and October, since it would work at an energy efficiency lower than back-ups. Also, HP3 is not capable of delivering the entire energy need during the other months, due to its limited capacity; this notwithstanding, the simulations show that this GHP, together with the corresponding back-up generators, is indeed the optimal solution in terms of overall energy performance. Finally, Fig. 6 reports, on a monthly basis, the expenses for natural gas (used by the back-up boiler) and electric energy and the economic savings obtained by means of the GSHP.

6. CONCLUSIONS

In the present work, we proposed an innovative holistic approach to the design of GSHP systems, based on the optimization of energy exchange and performance during the entire operational life. We also illustrated a step-by-step procedure to be followed by professionals for an effective design of vertical ground-coupled systems.

A physical model for GSHP systems was coupled to an optimization algorithm, in order to find the design parameters that minimize a specific objective function (e.g. primary energy consumption). The main design parameters optimized through the procedure are: thermal capacities of the ground-coupled heat pump and back-up generators, size, number and position of ground heat exchangers, flow rate in the ground-coupled loop, load shares between GSHP and back-up systems (control strategy).

The proposed methodology guides the professionals towards the best choices for the specific case under exam: operative parameters are not decided on the basis of previous experiences, but they are the result of an ad-hoc procedure. In this way, all the coupling effects among ground source, equipment, and building thermal load are considered and optimized.

The proposed methodology was applied to a test case, proving remarkable energetic and economic benefits with respect to traditional methods. Energy consumption decreased up to 18 % in the best configuration, thanks to an optimized cooperation between geothermal source and back-up technologies. Furthermore, both installation and operational cost were reduced: the number of BHEs decreased from 7 (ASHRAE method based on peak loads) to 3 and about 800 € were annually saved.

However, we point out that installation costs remain the main drawback of this technology, possibly limiting its diffusion, especially for small-medium buildings. The net value after 20 years resulted positive only for drilling costs lower than 50 €/m. Payback periods can be shorter if significant financial incentives on energy efficiency are provided or in the presence of relevant inflation of energy prices.

NOMENCLATURE

Symbols and Acronyms

C	Specific heat (J/kg/K)
CR	Capacity ratio (see Eq. 1)
$f_{H/C}$	GSHP share of building load in heating/cooling mode
Fo_{BHE}	Fourier number at borehole surface: $\alpha_g t / R_{BHE}^2$
GHP	Ground-coupled heat pump unit
H	Borehole depth (m)
$\dot{m}$	Mass flow rate (kg/s)
N_{BHE}	Number of boreholes
Pe_{BHE}	Péclet number at borehole surface: $u_{eff} R_{BHE} / \alpha_g$
$\dot{q}$	Heat flow per unit length (W/m)
Q	Thermal energy (Wh)
$\dot{Q}$	Thermal power (W)
R	Return function
R_b	Borehole thermal resistance (m K/W)
R_{BHE}	Borehole radius (m)
T	Temperature (K or °C)
u	Fluid velocity (m/s)
$\underline{u}$	Vector of control variables
$\underline{U}$	Set containing all the $\boldsymbol{u}^n$
W	Electric energy (Wh)
$\dot{W}$	Electric power (W)
$\underline{x}$	Vector of state variables
Z	BHEs spacing

Greek Letters

α	Thermal diffusivity (m^2/s)
ε	Heat exchanger effectiveness
τ	Reference time scale (h)

Subscripts

bk	Back-up generator
C	Condenser
DC	Declared capacity
E	Evaporator
eff	Effective
G	Ground
gw	Groundwater
in	Inlet/supply
L	Building thermal load
out	Outlet/return
W	Fluid circulating within the ground-coupled loop

Superscripts

0	Initial time

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