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Shallow geothermal systems in dense urban areas: the issue of thermal interference and long-term sustainability

Adriana Angelotti[1]* and *Donatella* Sterpi[2]

[1]Politecnico di Milano, Department of Energy, Milano, Italy
[2]Politecnico di Milano, Department of Civil and Environmental Engineering, Milano, Italy

Abstract. Shallow geothermal systems, namely Ground Source Heat Pumps (GSHP) and Ground Water Heat Pumps (GWHP), are expected to give an increasing contribution to the decarbonization of the buildings climatization sector. A fully sustainable use should guarantee fair access to the shallow geothermal sources for new systems, given the potential thermal interference among neighbouring ones in dense urban areas, and address environmental concerns related to thermal pollution of ground and groundwater. In this paper the state of the art concerning environmental concerns, regulation approaches and sustainability metrics is firstly reported. Then, focusing on closed-loop systems, a simulation case study is developed to study the long-term thermal footprint in the ground. The Energy Imbalance indicator, summarizing the annual energy balance in the ground, drives the thermal drift produced by the bore-field and is therefore proposed as the main sustainability indicator. For given ground conditions, a maximum Energy Imbalance is identified, which limits the thermal perturbation distance to the borehole spacing and minimizes thermal interference with other systems.

1 Introduction

The use of the geothermal energy source represents today an effective and environmentally friendly solution to face the growing energy demand for the climatization of buildings and infrastructure while contributing, at the same time, to the decarbonization of a sector which on 2020 still relied on fossil fuels for 35% of its total energy demand [1]. The relevant role of geothermal energy comes from its large potential, availability, and accessibility. Its competitiveness stems also from being less dependent on fossil fuel market prices and allowing local autonomy in energy production.

To improve the diffusion of shallow geothermal energy systems, based on Ground Source Heat Pumps (GSHP) and Ground Water Heat Pumps (GWHP), three actions must be taken: raise investor and stakeholder awareness and confidence in the technology's potential and state of advancement, provide regulation to ease and align the authorization and administrative processes, and introduce simple tools for potential assessment and cost-benefit

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* Corresponding author: adriana.angelotti@polimi.it

analysis, where also environmental benefits, such as CO_2 emission reduction, are given monetary value [2].

In fact, one of the barriers to the spread of the technology is the lack and heterogeneity of regulations that, beside boosting confidence on such systems, could also ensure long-term sustainability. So far, the formulation of a unified regulation has been challenging due to the difficulty of aligning approaches on the geothermal system response (existing requirements appear to be more empirical in nature than scientifically based), the high variability of site-specific factors of influence, and the complexity in identifying clear and shared sustainability criteria [3,4].

First, in terms of technical and operational aspects of the system itself, the use of a shallow geothermal energy is sustainable when it guarantees a good energy performance of the system components throughout their useful life. This kind of "internal sustainability" is the aim of a proper design of GSHP and GWHP systems, then a responsibility of the designer. A careful sizing of the system entails simulating its operation and the ground/aquifer thermal response for enough years, accounting for the thermal inertia of the shallow geothermal sources and the existing heat trans-fer phenomena.

Along with the system's internal sustainability, an "external sustainability" should be considered, encompassing environmental and social aspects. Environmental sustainability implies minimizing the system's effects and ensuring no harm to the environment, whereas social sustainability ensures fair access to the source for other users, both neighbours and future generations. External sustainability is clearly related to the system design and operation but is mainly of interest to public authorities responsible for environmental protection and natural resource preservation. Environmental concerns about the use of shallow geothermal sources have in-spired regulations in many countries [3]. At the same time, as GSHP and GWHP are expected to provide an increasing contribution to the decarbonization of the climatization sector, the issues of ensuring fair access to the resource and preventing thermal interactions among neighbouring systems in dense urban areas become increasingly important. The evaluation of cities geothermal potential, with a focus on the diverse and frequently conflicting uses of urban underground space, is currently a subject of great interest [5].

The following paragraphs summarize current knowledge about the environmental impact of shallow geothermal systems and about the urban geothermal potential.

1.1 Environmental issues related to shallow geothermal systems

For shallow geothermal energy systems, environmental issues are concerned especially with groundwater pollution caused by hydrological, thermal and bio-geochemical impacts [6, 7]. The prevailing principle is that groundwater must be protected as a drinking water resource and as an autonomous ecological system, while also keeping in mind that the naturally slow dynamics of the groundwater environment makes induced alterations long lasting.

Even when wells construction and operation ensure the absence of cross-aquifer contacts and contaminant paths, the hydrological risks associated with open loop systems involve perturbations in groundwater streamlines and alteration of capture zones of extraction wells, potentially impacting water quality. Groundwater chemistry can be varied by water extraction and injection and by induced vertical fluxes that tend to mix waters with different chemical compounds (Figure 1).

Both open and closed loop systems are naturally bound to cause temperature variations in the subsoil, with a yearly fluctuating trend and the possibility of permanent drift in the long term if heat injection and extraction are not balanced throughout the year. These effects, besides to being detrimental to the system energy efficiency, represent an additional thermal stress that, in summer periods, combines with the heat discharge from urbanization and climate change.

Temperature changes are well known to influence water physical properties and soil-water chemical kinetics, favouring carbonate precipitation, silicate dissolution, organic matter oxidation and sorption alterations. Even if temperature changes appear to have minor effects when limited to deviations less than about 15°C, re-search is still ongoing for specific red-ox processes and chemical elements [8]. Existing research, on the other hand, does not consistently agree on the impact of temperature variation on subsoil microorganisms and fauna, due to a variety of other factors that influence ecosystem functions, such as pH, salinity, and the presence of oxidizing or reducing agents [9]. While some studies have found that limited temperature changes have no significant effect on bacterial counts, the possibility of temperature-related microbial population shifts is still being investigated. Increased groundwater temperatures may promote microbial activity, potentially benefiting remediation in polluted urban areas but posing hygienic concerns, due to promotion of pathogenic microorganism survival, transport, or growth. Although little research has been conducted on the effects on groundwater fauna, it is known that some species thrive in specific ecological environments and are highly sensitive even to minor temperature changes.

As a result, some current guidelines and regulations for shallow geothermal systems authorization require or recommend limits on induced maximum and minimum temperatures, as well as maximum temperature variations with respect to un-disturbed conditions. To avoid interferences with neighbouring uses, also the respect of minimum distances is often required or recommended.

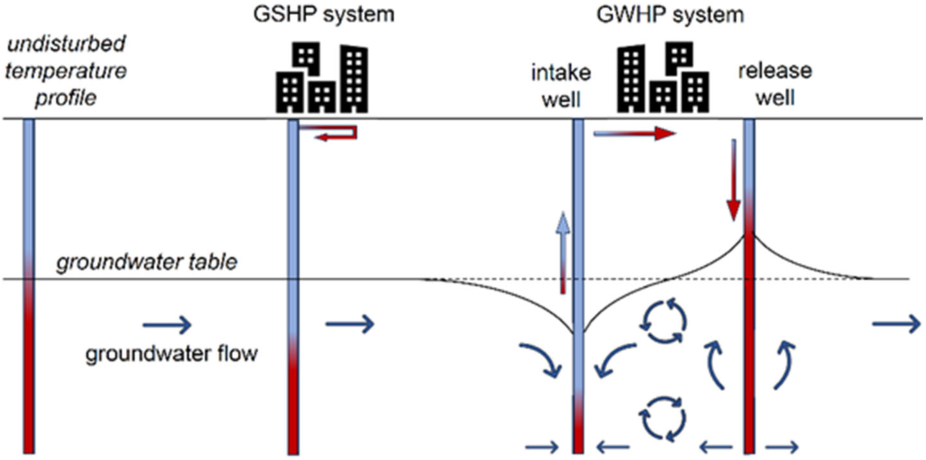

Fig. 1. Temperature and groundwater alterations with GSHP systems (closed loop) and GWHP systems (open loop) during building heating operation

1.2 Regulation approaches

Following considerations of sustainability, some countries have regulated the access to the geothermal resource, imposing criteria on temperature changes in released water for GWHP and on distances for both GWHP and GSHP, but generally disregarding the transient nature of the heat transfer and the resulting heat waves propagation and heat accumulation over time. Due to key uncertainties and site peculiarities, the overall regulative framework appears fragmented. Indicatively and as not exhaustive examples, Switzerland regulations require a maximum of ±3 °C variation from the mean natural temperature and minimum distances of 3-4 m and 5-8 m from the closest property and the closest installation respectively; Germany recommends a maximum of ±6 °C variation and an admissible temperature range of 5 °C-20 °C, as well as minimum distances of 3-5 m and 5-10 m from other properties and installations; Denmark establishes an admissible temperature range of 2°C-25°C and minimum distances from properties and sensitive services like drinking water wells and wastewaters [3].

In Italy, any borehole drilling activity is regulated by law to protect groundwater and avoid hazardous material leakage and cross-aquifer contacts [10]. Special national Legislative Decrees for the exploitation of renewable energy sources regulate authorization and incentives [11, 12], but do not specify criteria for the installation of geothermal energy systems. Regional directives compensate for this gap, although the result is an uneven regulatory system. The most comprehensive set of directives and guidelines is perhaps from Lombardia Region, where GSHP installations must be registered into a regional georeferenced database, and an authorization is required only for borehole depths greater than 150 m. In the latter case, the submitted documents must prove that the installation does not pose a risk of soil or groundwater pollution. In addition, a minimum distance of 4 m from the property border and respect for protected zones, such as water wells, must be observed. GWHP installations require authorization and can only exchange water with shallow phreatic groundwater. Temperature increase must be limited to +5 °C, with a maximum temperature of 21-23 °C. Flow and heat transfer models are suggested for predicting the impact on water levels and temperatures, and in presence of large water discharges changes in water biochemical properties must be also monitored.

Temperature changes are also addressed by special National Technical Standards. UNI Standard 11468 [13] recommends a risk analysis approach for assessing the level of environmental compatibility of a GSHP or GWHP system. The method necessitates a preliminary estimate of the geothermal reservoir features and volume and the verification of potential interference with other sensitive underground facilities and GSHP-GWHP systems. For the evaluation of transient thermal impacts in the reservoir, numerical simulations are recommended, and a temperature maximum variation of 1°C is suggested at the location of drinking water wells.

The literature suggests regulatory approaches to ensure the resource's sustainable exploitation and equitable distribution. Among others, Attard et al. [14] introduce the concept of thermal protection perimeter, estimated on the basis of the thermal capture probability, as the area that ensures an installation does not experience any detrimental thermal alteration from other installations, thus optimizing the use of the resource; Alcaraz et al. [15] propose a market-based approach, where individuals or entities can acquire rights to utilize the resource in a regulated manner; Garcia-Gil et al. [16] present a concession process protocol in which a fraction of the resource is reserved for potential third-party installations. These approaches are seen as an advance in resource management at the city scale.

1.3 Geothermal potential evaluation

Although there is a general agreement on the viability of shallow geothermal energy for urban heating and cooling, a review of the literature reveals a lack of consistent concepts for assessing geothermal potential [5]. The numerous heat sources and the variety of interferences that occur in subsurface uses complicate the urban context.

The technical potential, identified as the fraction of the total theoretical potential stored in the reservoir that can be exploited using existing technology, is estimated by methods that rely on planning tools and modelling, resulting in diverse outcomes especially for urban installations, due to the city's highly variable subsoil conditions. Then, economic considerations, such as variable technical costs, market readiness and government financial incentives further reduce the technical potential to what is economically feasible. On this, regulatory factors addressing sustainability and fair use of geothermal resources superimpose, sometimes enforcing additional constraints, sometimes only recommending, and thus limiting geothermal potential to a developable smaller share.

If the analysis is limited to the technical potential evaluation, mapping heat sources and considering hydrogeological conditions, such as the groundwater flow, are essential elements for modelling heat transport and accounting for interferences [17-19]. Numerical models provide a broad application field and enhanced flexibility in reproducing realistic urban soil conditions, although they require a significant amount of input data and computational effort. Analytical models, on the other hand, are useful at least for a pre-liminary assessment, but are limited by simplifying assumptions, such as the domain geometry and soil homogeneity.

Multi-scale approaches that incorporate local assessments into larger energy management plans have shown promise. The support of a GIS platform enables the integration of spatial information from hydro-thermo-geological data and the evaluation of the geothermal potential in a compact georeferenced 3D model [20, 21]. Mapping the geothermal potential and combining it with heat demands enable decision-making processes at the city scale, including reference to likely future scenarios where the waste heat from the subsurface urban heat island can be best exploited [22]. In complex contexts, a monitoring plan is always recommended, first to validate and calibrate the model, and then to contribute to management strategies by controlling performance and interferences [23].

1.4 Aim of the study

Given the heterogeneity of existing regulations and the necessity that they reflect long-term sustainability principles, this study aims to provide a contribution in terms of scientifically based sustainability criteria. To this purpose, a simulation case study of a GSHP system under various scenarios is developed, allowing to analyze spatial and temporal long-term induced perturbations and highlighting the key sustainability indicators.

2 Methodology

In order to study the long-term behavior and the thermal impact of a borefield coupled with a GSHP, a simplified physical model was developed and implemented in a Matlab script. A reference case study was then identified, consisting in a typical GSHP system supplying heating and cooling to an office building. Starting with the reference case and varying one parameter at a time, several case studies were developed. In each case, the model was used to simulate the operation of the borefield over its useful lifetime and the thermal impact was assessed and discussed.

2.1 Heat transfer model

The model is able to simulate temperature perturbations in the ground due to the operation of a borefield supplying assigned thermal loads. The building energy demand profile Q_b is given in either monthly or seasonal steps and turned into a ground energy load Q_g by means of the heat pump COP or EER, depending on the operation mode, as in the following equations:

$$Q_{g,h} = -\frac{COP-1}{COP} Q_b \tag{1}$$

$$Q_{g,c} = -\frac{EER+1}{EER} Q_b \tag{2}$$

Note that the negative signs in Equations (1) turns a positive building demand (heating demand) into a negative ground load (heat extraction). A similar comment holds for Equation (2). Once the ground energy load Q_g is obtained, a ground power load per borehole and per unit length q_g is simply obtained by dividing Q_g by the overall number of boreholes N_s, their depth H and the time duration (month or season). Each borehole heat exchanger is then simulated as a finite line source with a constant heat rate per unit length q_g (W/m). The finite length source choice, compared to the infinite length one, allows to better take into consideration the three-dimensional effects that become more important in the long-term [24]. The ground is considered a homogeneous and isotropic semi-infinite medium where heat transfer occurs only by conduction. A uniform initial temperature is assigned in the ground, namely the geothermal gradient and the climatic influence are both neglected. The Finite Line Source (FLS) analytical solution is used to calculate the temperature variation in the ground ΔT with respect to the unperturbed temperature as a function of the time, due to a step heat extraction or injection. Specifically, the average temperature perturbation over the BHE depth is calculated using the speditive FLS formulation [25]. Following the classical approach by Eskilson [26], the ground load profile per source is modelled as a step-wise function composed of N_t piecewise constant values $q_{g,i}$, each active in the time interval $t_i < t < t_{i+1}$, as in Equation (3):

$$q_g(t) = \sum_{i=1}^{N_t}\left(q_{g,i} - q_{g,i-1}\right) \cdot He(t - t_i) \tag{3}$$

where He is the Heaviside function defined by Equation (4):

$$He(t) = \begin{cases} 1 & t \geq 0 \\ 0 & t < 0 \end{cases} \tag{4}$$

Therefore, the temperature response in the ground at a given time is obtained by summing the responses to the heat pulses active at that time. Subsequently, using the spatial superposition principle, the average over depth temperature perturbation in a given point of the ground is obtained by summing the perturbations due to the N_s sources:

$$\langle \Delta T(r,t) \rangle_H = \sum_{k=1}^{N_s} \langle \Delta T(r_k,t) \rangle_H \tag{5}$$

where r_k is the distance between the given point and the source k.

2.2 Case studies

The GSHP system described in the Appendix H3 of UNI 11466 [27] is taken as the base case study. It refers to an office building with peak heating and cooling loads equal to 60 and -80 kW respectively. The heat pump has a seasonal COP equal to 3.7 and a seasonal EER equal to 3.3. The ground has a thermal conductivity equal to 1.7 W/(m K) and a volumetric heat capacity equal to 2.5 MJ/(m^3 K). By applying the ASHRAE methodology, the borefield sizing is found to be driven by the cooling demand and results in a square grid of 5 x 3 heat exchangers with a borehole-to-borehole distance equal to d = 7 m. Each borehole is 97 m deep, rounded to 100 m for this study. The borefield layout (Figure 2) allows to identify the vertical and horizontal lines passing through the central borehole as symmetry axes. Therefore, observation points are located along the horizontal symmetry axis, from the borefield centre to the outside, up to a maximum distance equal to H/2 from the borefield borders.

The monthly energy demands of the office building Q_b given in the Appendix H of the standard [27] are reported in Figure 3 with the corresponding specific ground loads q_g. Simplified seasonal profiles obtained by averaging the monthly values are also shown. Since seasonal profiles require less computational effort, the first step of the analysis evaluated the influence of the temporal resolution of the ground profiles.

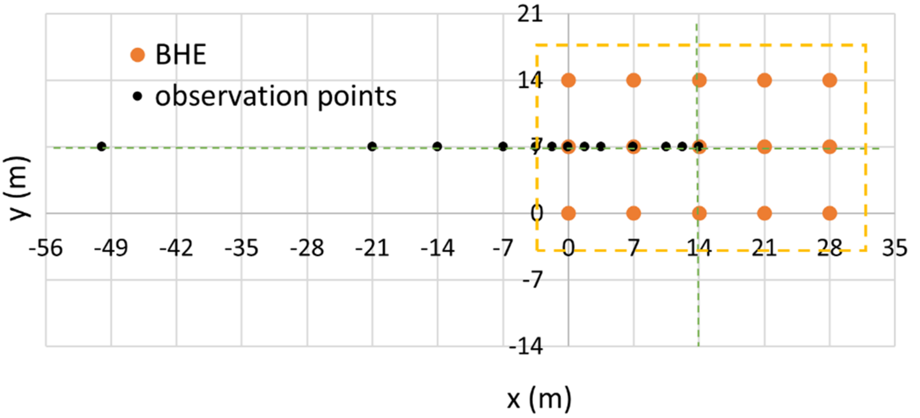

Fig.2 – Borehole Heat Exchangers layout, with observation points and A_{BHE}.

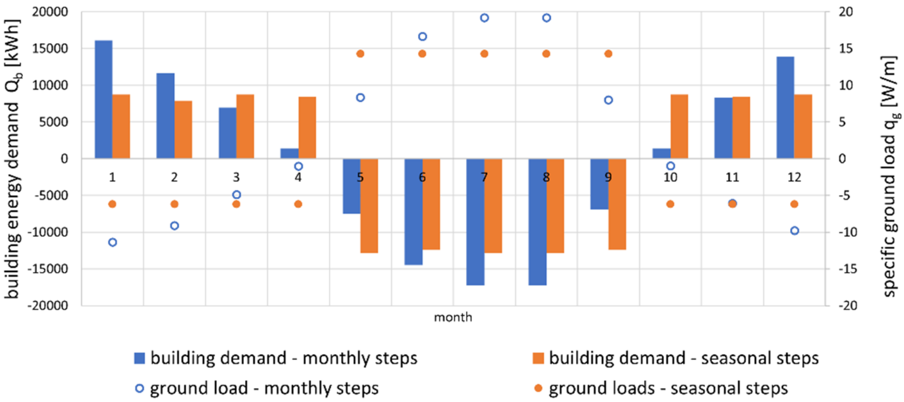

Fig.3 – Building monthly energy demand for the base case study taken from the standard [27], together with a simplified seasonal demand profile (left axis); corresponding ground loads (right axis)

The base case, identified with the ground loads shown in Figure 3, is thus characterized by overall heat extraction $Q_{g,h}$ = -47015 kWh and heat injection $Q_{g,c}$ = +78779 kWh per year, resulting in a net ground energy balance of +31764 kWh. We define the Energy Imbalance (EI) as the net yearly budget divided by the maximum of the two seasonal ground energy loads, as in the following equation:

$$EI = \frac{Q_{g,h}+Q_{g,c}}{max\,(|Q_{g,h}|,Q_{g,c})} \tag{6}$$

The base case is thus characterized by EI = 40%. Moreover, we define the area occupied by the borefield by attributing each BHE a square with side equal to the grid spacing d and centred on the BHE (Figure 2), namely:

$$A_{BHE} = d^2 \cdot N_s \tag{7}$$

In order to quantify the intensity of exploitation of the ground source, the Energy Density indicator (ED) is then proposed:

$$ED = \frac{max\ (|Q_{g,h}|, Q_{g,c})}{A_{BHE}} \tag{8}$$

In the base case, where the maximum seasonal ground load is the summer one, we obtain ED = 107.2 kWh/m^2.

Table 1– Simulation case studies.

Case ID	α (m^2/s)	$Q_{g,h}$ (kWh)	$Q_{g,c}$ (kWh)	EI (ND)	ED (kWh/ m^2)
Base	$6.8.10^{-7}$	-47015	78779	40%	107.2
EI=0	$6.8.10^{-7}$	**-78779**	78779	**0%**	107.2
EI=10%	$6.8.10^{-7}$	**-70901**	78779	**10%**	107.2
EI =15%	$6.8.10^{-7}$	**-66962**	78779	**15%**	107.2
EI=20%	$6.8.10^{-7}$	**-63023**	78779	**20%**	107.2
EI=60%	$6.8.10^{-7}$	**-31512**	78779	**60%**	107.2
diff+10%	$\mathbf{7.5.10^{-7}}$	-47015	78779	40%	107.2
diff-10%	$\mathbf{6.1.10^{-7}}$	-47015	78779	40%	107.2
ED+10%	$6.8.10^{-7}$	**-51717**	**86657**	40%	**117.9**
ED-10%	$6.8.10^{-7}$	**-42314**	**70901**	40%	**96.5**

Different scenarios are then created by varying the Energy Imbalance, the Energy Density and the ground thermal diffusivity α (Table 1). In all scenarios the borefield remains the same, as the parameter variations are not significant enough to necessitate a new sizing of the ground heat exchangers. Indeed, the Energy Imbalance is varied while keeping the summer ground load constant, which has no effect on the sizing since the system is cooling dominated. The Energy Density is in-creased or decreased by 10% to account for uncertainty in building demand, e.g. due to climatic variations. Finally, the ground thermal conductivity and then diffusivity are varied by a maximum of 10%, which is consistent with the common un-certainty in ground thermal properties.

3 Results

The sensitivity of the results to the time resolution of the ground load cycle is analyzed by considering the temperature perturbation profiles obtained with either monthly or seasonal steps (Figure 4, top) in two points of the domain, located on the y = 7 m axis, for the first 10 years of operation. One point is chosen as if it was at the wall of the mid borehole (x = -0.06 m, see also Figure 2), and the other is chosen outside the borefield at a distance equal to half the BHE spacing (x = -3.5 m).

In general, as it is shown in Figure 4 (middle), the temperature perturbation at a given distance is the superposition of a periodic signal, varying with a period of 1 year as for the ground load, and a slowly increasing signal, namely the temperature drift. The latter can be better identified by taking the yearly mean, reported in Figure 4 (bottom).

It can be noticed that close to the borehole (x = -0.06 m) the temperature perturbation is sensitive to the shape of the ground load. In particular, the more de-tailed ground load composed of monthly steps results in larger temperature fluctuations. On the contrary, at the point located at d/2 outside the domain, the temperature profiles produced with the two different loads are almost superimposed. In any case, looking at the yearly mean temperature trends (Figure 4, bottom), there is no appreciable difference between monthly and seasonal steps load profiles. Therefore, if one is interested in studying the temperature drift produced by the GSHP operation, the seasonal steps load profile can be used with no loss of accuracy. The temperature profiles at different points outside the borefield area along the median line y = 7 m are then shown in Figure 5 (top), for the base case and 30 years of operation. It can be remarked that the amplitude of variation of the periodic signal decreases with the distance from the borefield border, becoming almost completely damped at a distance equal to 14 m, or, in this case, twice the borehole spacing d.

As Figure 5 (bottom) shows, 30 years are not sufficient to reach steady state, as the temperature drifts continue to increase. Even if the temperature in the ground is not yet stable, 30 years are a reasonable useful lifetime for GSHP operation and thus the temperature field after 30 years is used here to identify the thermal footprint of the system.

The temperature profiles along the horizontal symmetry axis y = d = 7 m at the 30th year are shown in Figure 6 and Figure 7, where the continuous lines refer to the end of the last heating cycle (summer) and the dotted lines to the end of the last cooling cycle (winter). To ensure readability, only some of the cases described in Table I are plotted. In Figure 6 the effect of the Energy Imbalance can be observed: as the base case is not balanced (EI = 40%) the winter and summer profiles are both positive in sign; on the contrary in the perfectly balanced case (EI = 0) they have opposite signs. Moreover, if the annual energy balance in the ground is null, the thermal impact of the system outside the area occupied by the boreholes appears very limited.

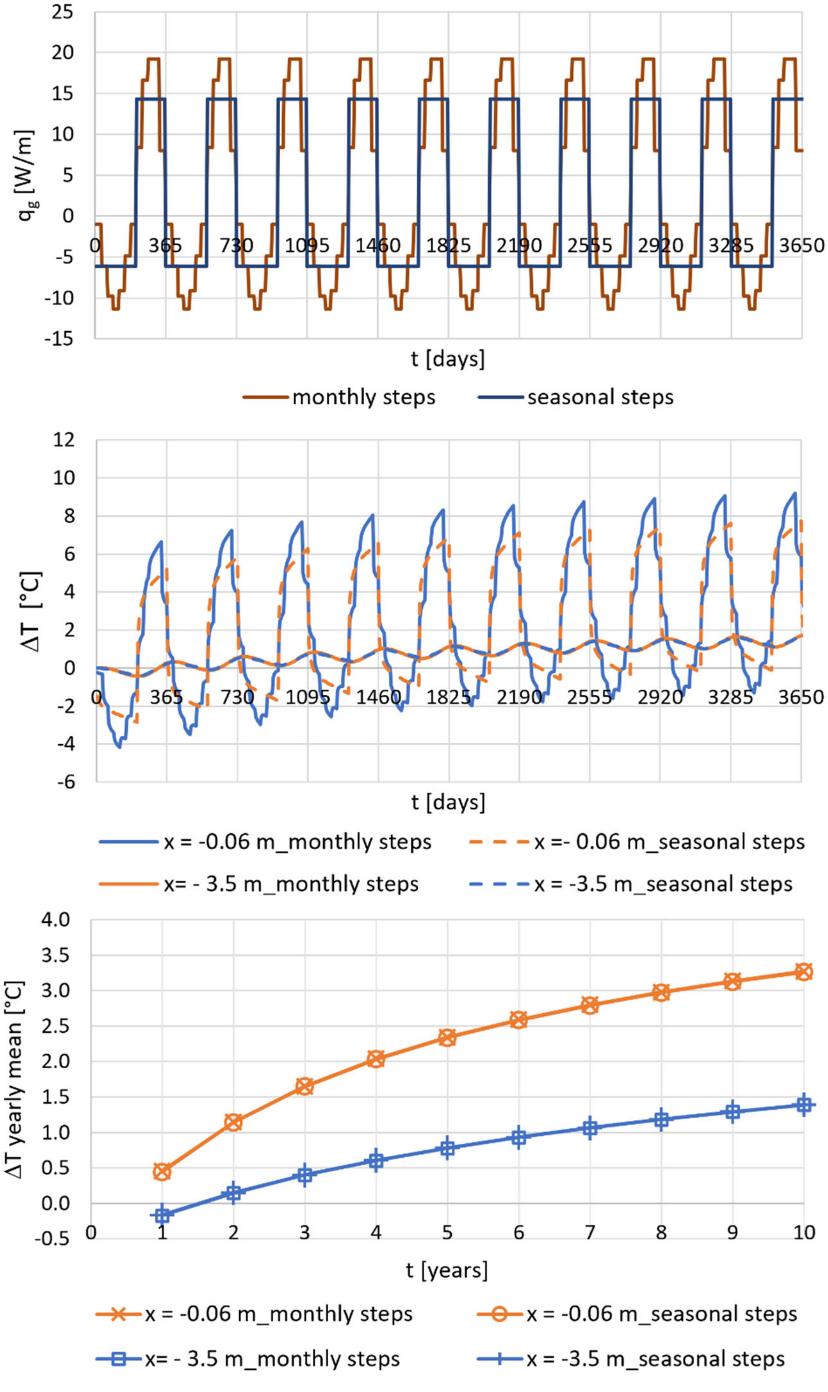

Fig. 4 - Base case: ground load profiles (top); temperature perturbation versus time at points (-0.06 m, 7 m) and (-3.5 m, 7 m) (middle); yearly mean temperature perturbation versus time at points (-0.06 m, 7 m) and (-3.5 m, 7 m).

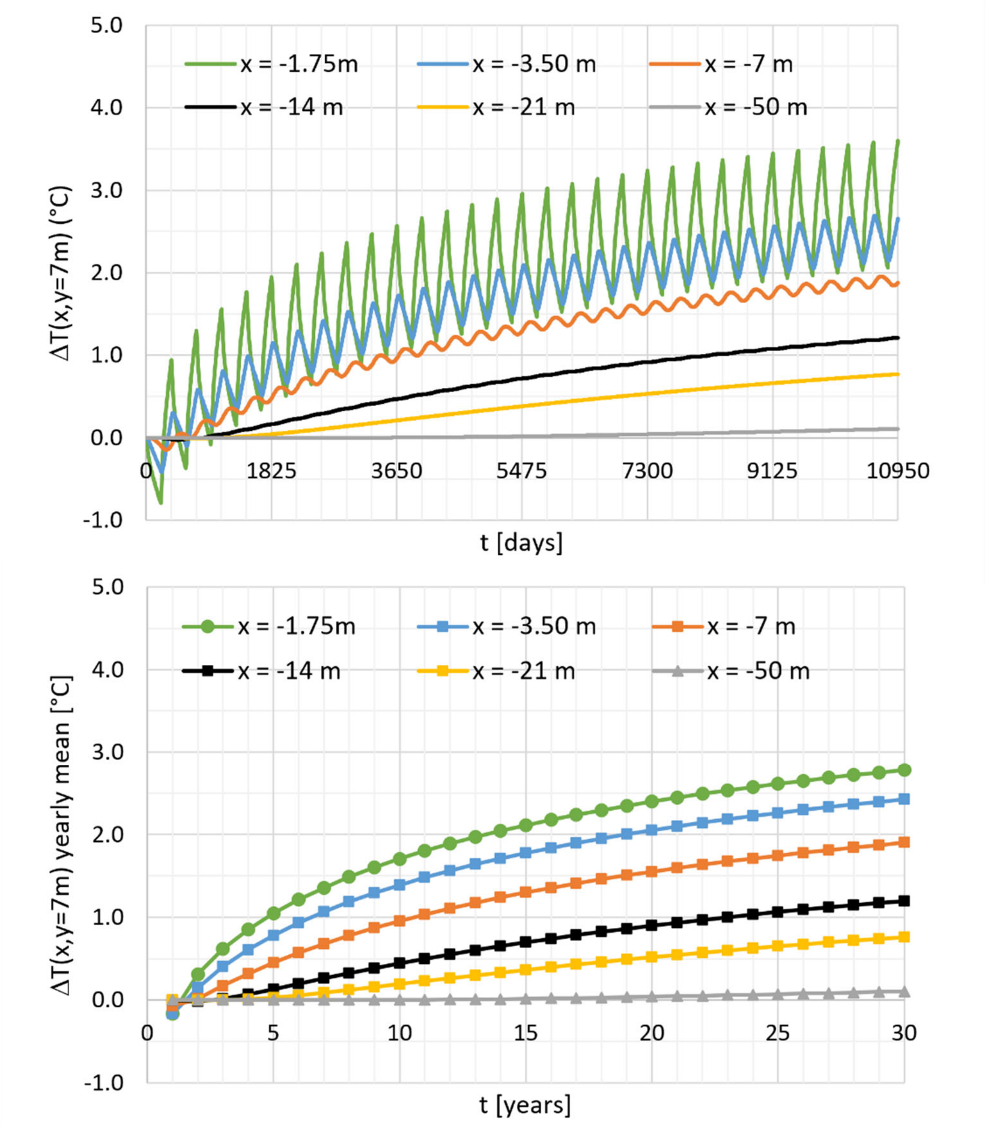

Fig. 5 - Base case: temperature perturbation vs time at different points along the line y = 7 m outside the borefield (top) and corresponding yearly mean trends (bottom)

In Figure 7 the base case is confronted with two cases having the same EI = 40% but a different value of either the ground thermal diffusivity or the system Energy Density. It can be remarked that a larger diffusivity tends to reduce the temperature perturbation, due to the higher heat transfer capability of the ground. A higher Energy Density on the contrary tends to raise the temperature perturbation level, since the borefield is used more intensively.

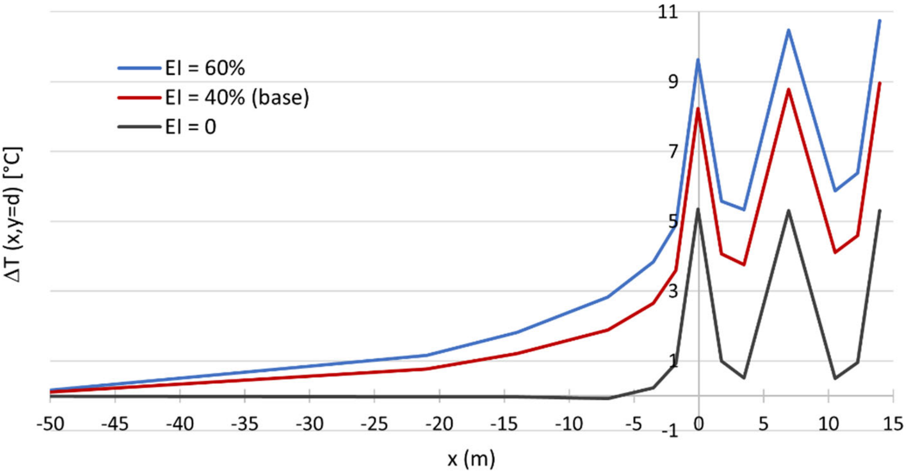

Fig. 6 - Temperature perturbation along the y = 7 m line at the end of the 30th heating cycle (continuous lines) and at the end of 30th cooling cycle (dotted lines) for different Energy Imbalances

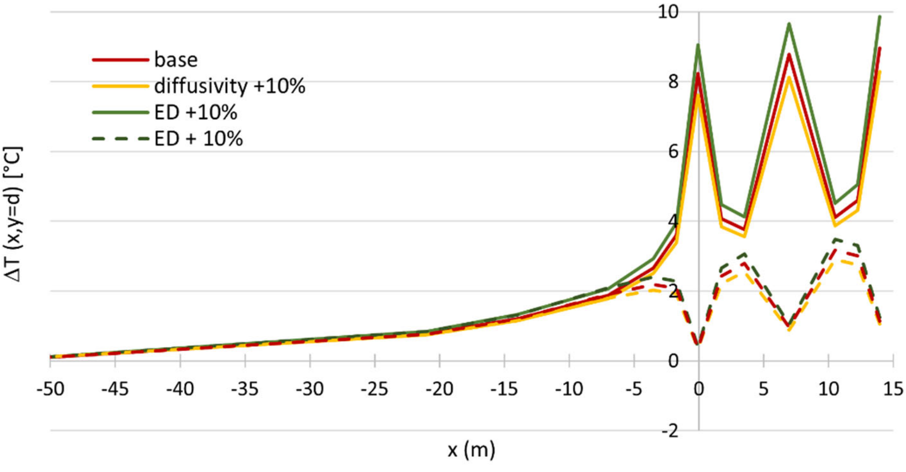

Fig. 7 - Temperature perturbation along the y = 7 m line at the end of the 30th heating cycle (continuous lines) and at the end of 30th cooling cycle (dotted lines) for the base case, the case where ground diffusivity is increased by 10% and the case where the Energy Density is increased by 10%

In order to evaluate the thermal footprint in the ground due to the system operation during its lifetime, the temperature perturbation profiles at the end of the 30th heating cycle are used. The aim is to identify both a perturbation zone and an exploitation zone, by introducing two corresponding thresholds for temperature in-crease, named ΔT_p and ΔT_e respectively, where $\Delta T_p < \Delta T_e$. The perturbation zone should represent the area where the operation of the system causes a significant temperature variation that could influence neighbour or future systems. The exploitation zone in turn represents the area, obviously including the borefield, more directly involved in the heat extraction and injection and thus experiencing more pronounced temperature variations. In agreement with literature values reported in section 1.2, thresholds equal to $\Delta T_p = 1°C$ and $\Delta T_e = 3°C$ are set, as values consistent with common practice and physical sense.

The resulting perturbation and exploitation distances are reported in Figure 8 as a function of the Energy Imbalance, both as absolute values and normalized to the borehole spacing d. The perturbation distance ranges from about d/2 when EI = 0 to about 4d when EI = 60%. Therefore, in order to keep the perturbation distance within d the Energy Imbalance should be kept to a maximum of 20%. The exploitation distance is clearly much smaller than the perturbation one and less sensitive to the EI, although it tends to raise more rapidly for EI larger than 30%. Only for EI = 60% the exploitation distance exceeds d/2, proving that the occupied area A_{BHE} defined in Equation 7 can reasonably represent the exploitation area. In Figure 8 the impact of the ±10% variation in ground thermal diffusivity and Energy Density when EI = 40% is also shown.

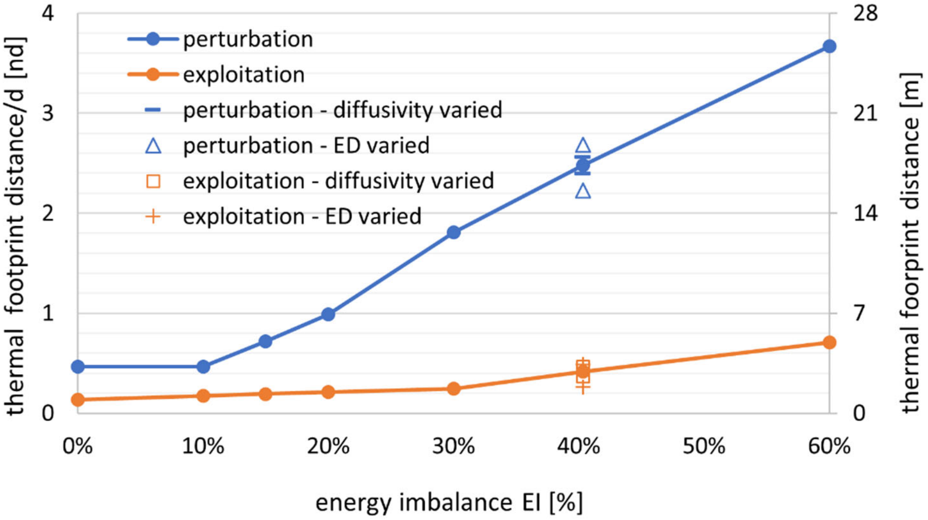

Fig. 8 - Thermal perturbation and exploitation distance as a function of the Energy Imbalance for the different cases, in absolute values (right axis) and in relative terms i.e. divided by the borehole-to-borehole distance d (left axis)

4 Conclusions

In the present study, the issue of the long-term sustainable operation of GSHP systems is investigated, with a special focus on what we called "external sustainability", namely ensuring no harm to the environment and fair access to the geothermal source for neighbour and future users. Through a simulation case study, the role of the annual energy balance in the ground, summarized by the Energy Imbalance metric, has been highlighted. The Energy Imbalance drives the thermal drift and the thermal footprint of the borefield and therefore it should be used as the main sustainability indicator. The case study shows that, in order to limit the thermal perturbation distance to the borehole-to-borehole distance, the energy imbalance could be limited to 20%.

Building loads are likely to evolve in the next years due to the climate change, leading to increasing summer loads and decreasing winter ones. From a practical point of view then, it is recommended that the GSHP system design includes an estimation of the Energy Imbalance based on present and future building loads. Moreover, energy monitoring should be encouraged, at least for large scale applications, so that the systems operation can be adjusted with time if an excessive energy imbalance is detected. Possible interventions may include switching to free cooling, hybrid solutions exploiting more sources, aggregation of buildings on a community scale.

At the same time the simulations showed that even in a perfectly balanced borefield the exploitation area experiences significant temperature variations. The amplitude of such variations is driven by the ground thermal diffusivity and by the intensity of exploitation, measured here through the Energy Density metric. If the ground is rich in groundwater, such temperature fluctuations will also affect it. Further efforts are thus necessary to understand to what extent cyclic variations in groundwater temperature can cause significant environmental concerns.

Future developments of the present study will consider more extended case studies, with different ground typologies and building demands. Moreover, by implementing the proper analytical solutions, the effect of regional groundwater flow will be addressed: a thermal plume extending downstream is expected in this case, and the maximum perturbation distance has to be identified in the flow direction.

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