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Energy and exergy analysis of ground thermal energy storage: optimal charging time in different operating conditions.

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Abstract:

Large attention in the last decade, has been focused on the best way to exploit renewable energy sources as solar and geothermal energy, using storage systems. An interesting thermal energy storage system is represented by the ground because it has high availability, it is a low-cost system since soil is free and it has good heat transfer characteristics. Boreholes thermal energy storage systems are investigated in this paper. These systems are characterized by a large number of boreholes, which operate in different and variable conditions. Charging time required to reach the design temperature level is evaluated for various design conditions. The analysis is performed through a parametric study aiming in finding the optimal charging time for different designs. The optimal conditions are defined in order to have the designed temperature in the ground and a constant internal energy in the ground between the operation seasons. Results show that the size influences significantly the duration of the charge stage and the efficiency of the system during the operation. These two parameters can be used to identify the best configuration of the plant during the design.

System operating in two years, is examined for the optimal summer charging time can further increase the efficiency of the system. This approach can be used during operation as a tool of improvement the efficiency.

Keywords:

Ground thermal energy storage; Boreholes thermal energy storage; Optimal design.

1. Introduction

Underground thermal energy storage (UTES) is a form of energy storage that provides large-scale seasonal storage of cold and heat in natural underground sites [1-3]. Energy storage can be proposed as a way to address mismatch between the availability of the renewables and the energy demand [3-4]. They can also be used in cogeneration and trigeneration systems making these systems more efficiently because the production of electricity and heat are uncoupled by using thermal energy storage: heat that is not needed during the production period as in the nighttime or in the summer is stored [5]. In general, storage systems allow one to reduce energy costs, primary energy consumption and increase flexibility of operation [6]. UTES are based on the mechanism of the sensible storage that is usually simpler and cheaper than their alternatives. It consists of storing heat, as internal energy, in the temperature increase of a medium that is generally a liquid or a solid [7]. In the case of storage in the soil, storage may be obtained through boreholes which results in a potentially low-cost system. In borehole thermal energy storage systems (BTES) heat con be stored in dry rocks by circulating a fluid through a borehole. The common BTESs are low temperature systems, usually linked with a ground source heat pump in which the working fluid absorbs heat circulating in the borehole heat exchanger [8-9]. Recently, various analytical and numerical studies have been conducted about BTES systems, mostly concerning with the modelling of pipe configurations, investigation of heat transfer characteristics, thermal response tests of different types of boreholes, etc. [10-15].

Several studies are available about the design and the performance of BTES in real plants. Ozgener et al. [16] carried out energetic and exergetic analysis of the Salihli geothermal district heating system with the actual thermal data. They applied the energy and exergy analysis to the system performance for determining improvement potentials of the system. Kizilkan et al. [17] performed a thermodynamic analysis of the BTES system located in UOIT in Ontario, Canada, and a parametric study to determine the effects of various system parameters and operating conditions on energy and exergy efficiencies. Lundh et al. [18] performed an evaluation of operation of the Swedish solar heated residential area with seasonal storage in rock after 2 years. Subbitt et al. [19] described a high solar fraction seasonal storage district heating system located in Canada and its operation; they presented 5 years of measured performance and compared those results against the TRNSYS predicted performance for the same period. Most of these works do not present a specific reference to the charge stage required by BTES systems that can represent an issue if it is too long. In fact BTES systems at high temperature require long times of charge before achieving a typical performance so that the surrounding ground could reach the designed temperature level [18] and this time also depends on the design of system.

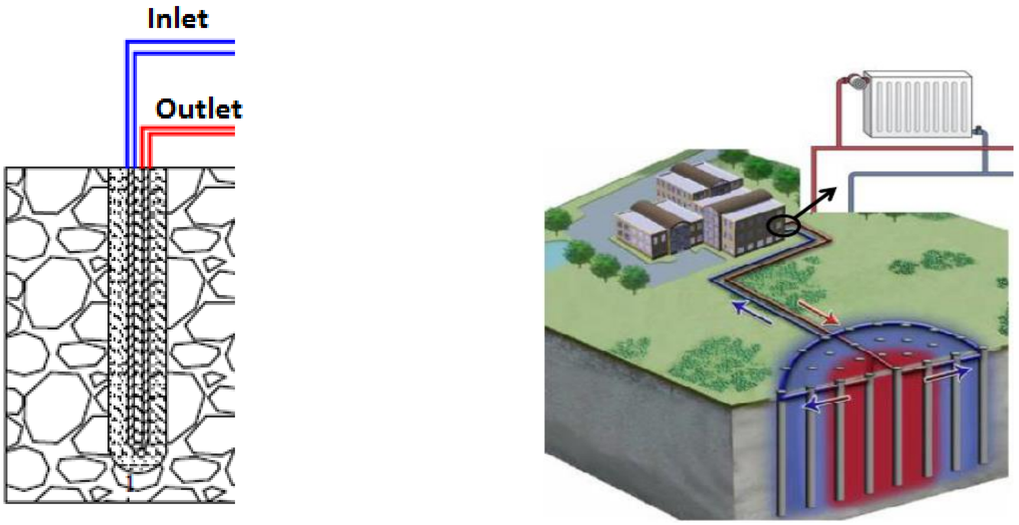
Because of the importance of charging time and of design, a parametric analysis is proposed in this study in order to investigate the optimal time required by BTES systems to reach the designed temperature and to maintain the internal energy in the ground constant after each year. The parametric study is performed in different operating conditions as different installation depths and different distances between boreholes. Each analyzed design is a high temperature store, thought to be used directly to supply radiators in the winter season. The single borehole is analyzed considering a 1-D multilayer cylindrical coaxial heat exchanger. Finite Difference Method is used to evaluate the temporal evolution of ground temperature around borehole, while the ε-NTU method is used to calculate the temporal evolution of the fluid in the borehole. The efficiency value for long operation period and the relative charging time can be considered two new indicators to take into account for selecting the type of plant during the design. The logic to maintain constant the internal energy in the ground during the years of operation can also represented a tool of optimization that maximizes the efficiency.

2. System description and operating conditions

The high temperature underground thermal energy storage considered in this article is constituted by boreholes heat exchangers. The inserted tubes work as heat exchangers between the heat transfer fluid (water) and the storage medium (soil). Each borehole is a vertical single U-tube, as represented in Fig 1(a), in polyethylene with an inner diameter of 0.029 m and an outer diameter of 0.033 m and k=0.33 W/(m K). The borehole is in saturated Sand with a diameter of 0.1 m and k=1.8 W/(m K) and is installed in a ground with a thermal conductivity of 2.5 W/(m K). The mass flow rate in each borehole is 0.9 kg/s.

Two stages characterize the operation of the system. The first one occurs after installation when the BTES system is subject to a charge stage before the effective operation. During the charge stage, the sensible heat is stored in the surrounding ground thanks to water at high temperature that flows in the boreholes. The inlet water from a district heating network is considered at 90°C. For this application, the Turin district heating network has been chosen. It is the largest network in Italy and it currently connects about 56 million m^3 of buildings with an annual thermal request of about 2000 GWh. The maximum thermal power is about 1.2 GW and the total length of the network is about 515 km [20].

The second stage is the effective operation during the heating season. The BTES system is designed to supply heat radiators and it is directly connected with the user without any heat pump. Figure 1(b) shows a schematic representation of BTES system and its connection with the user.



(a) (b)

Fig. 1. BTES system: a) the vertical single U-Tube borehole and b) the direct connection with radiators.

During seasonal operation, the system operates as a ground heat exchanger (GHE) and the inlet mass flow rate circulates in boreholes and gains heat from the ground up to reach 60°C. The average temperature in the radiators is about 55°C.

The energy requirement depends on the external temperature. A periodic function is considered to evaluate the annual variation of the external temperature [21]:

$$T_{air} = T_{mean} - T_{amp} * \cos(\frac{2p}{365}(t_{year} - t_{shift})) \quad (1)$$

where

T_{mean} is the annual mean temperature ;

T_{amp} is the amplitude of seasonal variation;

t_{year} is the current time (day);

t_{shift} is the day of the year with the minimum surface temperature (day).

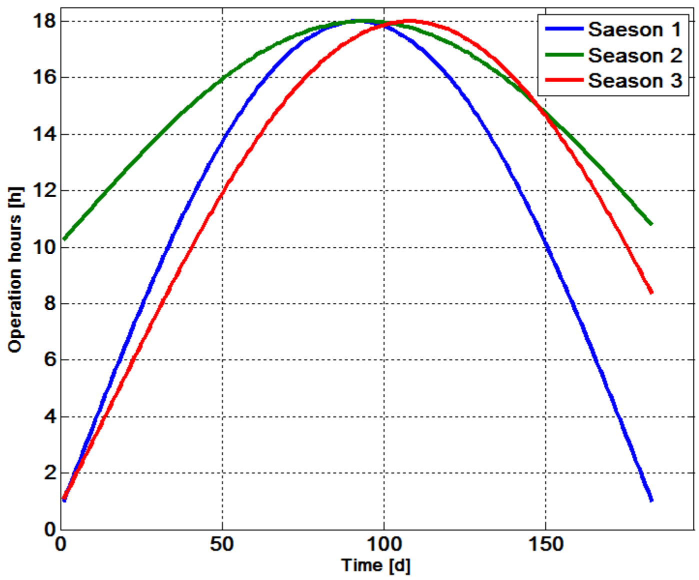


Fig. 2. Operation hours of the BTES system for three different winter seasons.

The minimum external temperature during the season is considered as the design temperature. In this condition, the BTES system is used for 18 hours. The operation hours in all design are evaluated taking into account the difference between the design temperature and the external temperature. Figure 2 reports the operation hours of the plant during the winter operation for three different seasons each one with different mean temperature, amplitude and day of the year with the minimum temperature.

After winter operation, the ground is recharged using water at 90°C until for a certain time called summer charging time.

3. Mathematical model

3.1 Thermal Model

In this work each vertical single U-tube borehole is considered as a cylindrical coaxial heat exchanger and it is analyzed using a one-dimensional model. The one-dimensional model includes the fluid bulk flow, an equivalent convective resistance layer, the tube layer and the grout layer that is surrounded by the ground. Consequently, four radiuses are identified: r_i (inner u-tube radius), r_{ex} (outer u-tube radius), r_g (borehole radius) and r_s (soil). Figure 3 shows the domain and the various radiuses.

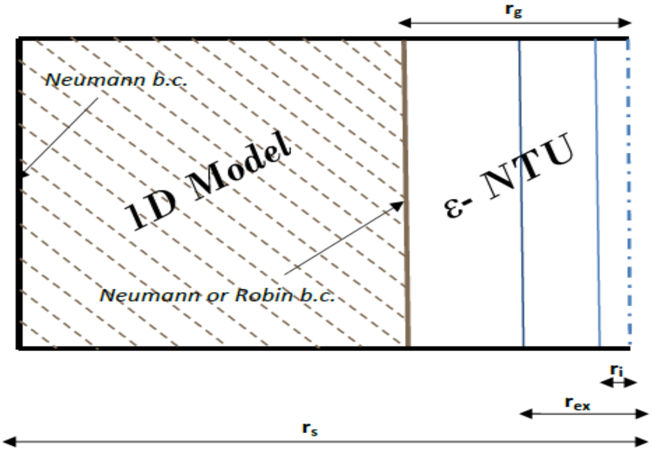


Fig. 3. System representation.

The ground radius is half pitch between two boreholes. The temperature distribution in the soil around the vertical U-tube GHE is obtained solving the 1D transient heat conduction equation in cylindrical coordinates:

$$\rho_s c_{ps}\frac{\partial T}{\partial t}=\frac{1}{r}\frac{\partial}{\partial r}\left(k_s r\frac{\partial T}{\partial r}\right) \tag{2}$$

Central finite difference is used to discretize spatial derivatives while implicit backward Euler scheme is adopted for time integration. The 1D model is applied in the region of the soil surrounding the borehole ($r_s \le r \le r_g$).

The initial condition is given by undisturbed soil temperature:

$$T(0,r)=T_s \tag{3}$$

For this application, the undisturbed soil temperature is assumed as 15°C. The type of boundary condition on the inner surface ($r=r_g$) depends on the operating condition: when domestic users need thermal energy or when the system is recharged, the boundary condition is given by Robin boundary condition (Eq. 4).

$$k_s \left.\frac{\partial T(t,r)}{\partial r}\right|_{r=r_g} = \pm h_w (T - T_{av}) \tag{4}$$

where T_{av} is the mean temperature of water in the vertical U-tube GHE.

In the case of no energy demand the system is considered adiabatic and the relative boundary condition is given by Neumann boundary condition (Eq. 5).

$$k_s \left.\frac{\partial T(t,r)}{\partial r}\right|_{r=r_g} = 0 \tag{5}$$

On the outer surface ($r=r_s$), the adiabatic condition is prescribed (Eq.5). In the thermal model, the heat losses are not taken into account directly. At the end of each season of operation, the thermal energy that has not been used, can be considered in part as a residual thermal energy and in part as exergy destroyed. This is due to the choice of the domain because the outer surface is sufficiently distant from the boundary where the heat exchange occurs.

Figure 3 shows also where the boundary conditions are applied.

The temporal distribution of soil temperature at borehole interface is evaluated by Eq.2. This value represents the source temperature, with infinite specific heat, that exchanges heat with the inlet fluid in the borehole. The heat flux and the temporal evolution of outlet fluid in borehole are calculated applying the ε-NTU method in the region on the borehole ($r_g \leq r \leq r_{in}$). The heat transfer coefficient referred to inner surface is expressed as:

$$R^{-1} = \frac{1}{\frac{1}{h_w} + \ln\left(\frac{r_{ex}}{r_i}\right)\frac{r_i}{k_p} + \ln\left(\frac{r_g}{r_{ex}}\right)\frac{r_i}{k_g} + \ln\left(\frac{r_s}{r_g}\right)\frac{r_i}{k_s}} \tag{6}$$

The accuracy of the 1-D model is tested comparing it with a 2-D model [22] where the U-tube GHE is discretized along its entire length (equal to twice the borehole depth) and Eq.2 is solved for each element of the discretization.

Figure 4 reports the average ground temperature for one operation year with the two models. Because the differences and the relative error are irrelevant, 1-D is chosen for the reduced CPU-Time.

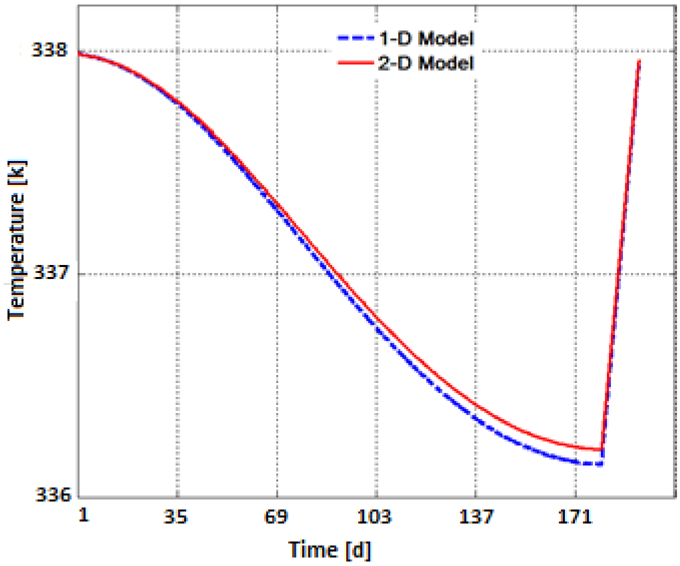


Fig. 4. Average Ground Temperature during one seasonal operation and during the summer recharge.

3.2 Parametric analysis

The parametric analysis is conducted simulating the operation of the BTES system. Different pitches between the boreholes (3-7 m with a space step of 1) and different installation depths of boreholes (25m, 50m, 75m, 100m and 125m) are investigated. The various combinations of pitch-depth selected for the analysis result in 25 different BTES designs, each one with a proper length and a proper thermal extraction capacity. For borehole heat exchangers that operate annually from 1800 to 2400 hours in normal rocky underground with k=1.5-3.0 W/(m·K), the specific heat extraction rate is in the range of 50-60 W/m [23]. Therefore a vertical borehole has a heat extraction rate about 1.8 kW at 30 m of depth and it can achieve about 6 kW at 100 m. For the same installed power, the different designs investigated are distinguished by the number of boreholes that is greater for shorter drilling.

The system is assumed to operate according to the curve of the operation hours called *Season 1* reported in the Figure 2. The operation curve represents the amount of energy to extract and it influences both the system efficiency and the choice of the design variables as the ground temperature at the end of the charging stage. The latter must be sufficiently high to guarantee the coverage of the energy requirement for the entire season without penalizing the efficiency of the system. In fact a ground at too high temperature could be not advantage from a thermodynamic point of view because the efficiency of BTES is higher if the energy stored is fully exploited during the winter operation. The optimal charging time is chosen as the operational parameter in each scenario. It is evaluated in order to have the average temperature of the ground at 65°C and the same internal energy between two consecutive operation seasons. The parametric analysis also includes the calculation of the internal energy of the ground at the end of the operation season:

$$U = mcT_{av} \tag{7}$$

The optimal summer recharging ensures the same U value and it has been performed under the hypothesis that the operation hours are equal for the two operation periods considered.

The Figure 5 report the logic used for the parametric analysis. The recharge stage (t_1^*) is increased (t_1) until to U_1 and U_2 are about the same.

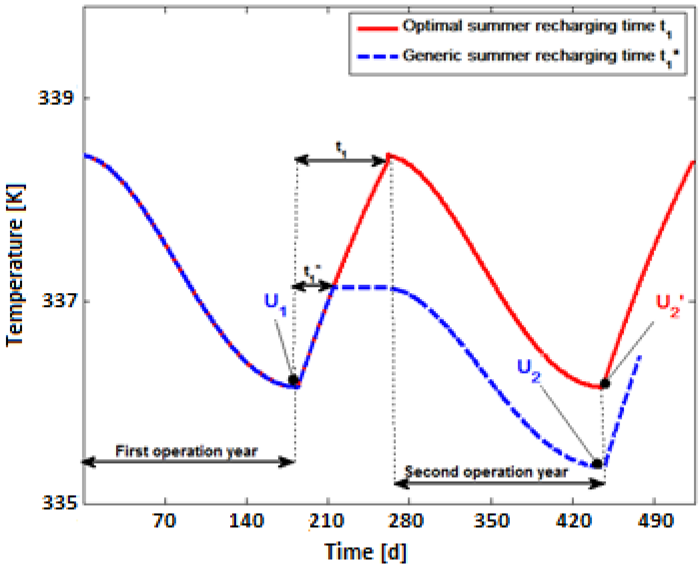


Fig. 5.Average Ground Temperature with two different summer recharging times

For each scenario, the first-law efficiency and second-law efficiency are evaluated considering 10 and 20 operation years, under the hypothesis that the winter seasons and the relative energy demands are exactly the same.

$$\varepsilon_I = \frac{\sum_{i=1}^{N_{seasons}} E_{Ext,i}}{E_{I,Ch} + \sum_{i=1}^{N_{season}-1} E_{Rech,i}} \qquad (8)$$

$$\varepsilon_{II} = \frac{\sum_{i=1}^{N_{seasons}} Ex_{Ext,i}}{Ex_{I,Ch} + \sum_{i=1}^{N_{season}-1} Ex_{Rech,i}} \qquad (9)$$

The comparison of the efficiency values at two different instants allows understanding how the considerable initial cost of the energy resource ($E_{I,ch}$) is amortized during the operation.

4. Results

4.1 Parametric analysis results

Figure 6 shows the results of parametric analysis: the optimal charging time has been evaluated for each system defined by the installation depth and boreholes pitch. For the system with a pitch of 3 m, the charging time to have the ground at 65°C varies from 30 to 86 days depending on the pipe length. An increase in the pitch between boreholes and of installation depth determines a higher charging time. On equal depth of installation, the charging time with a pitch of 7 m results eight times the one with pitch of 3 m. Such a long time before to reach the designed temperature level, reduces drastically the feasibility of the system itself.

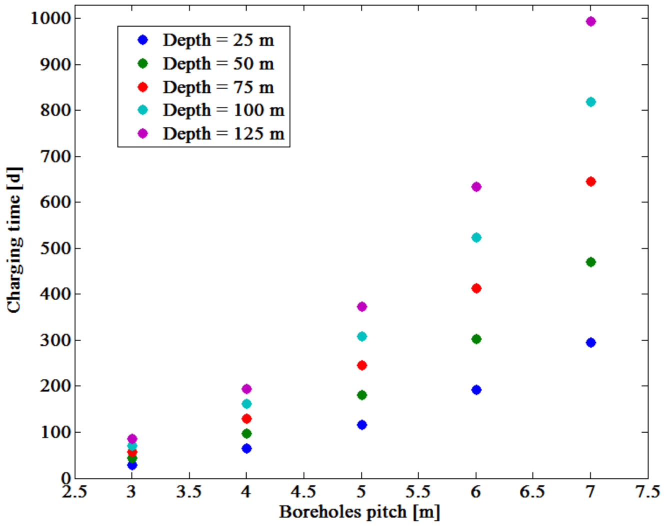
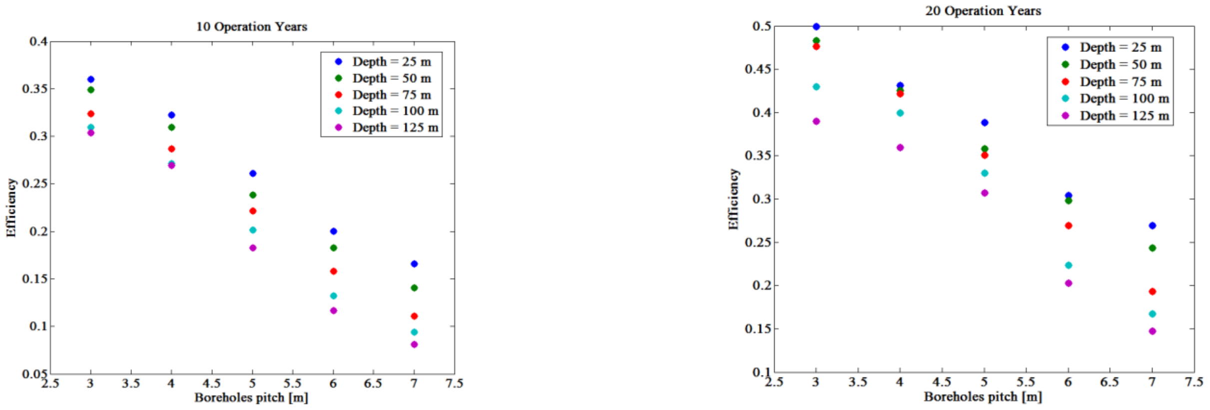


Fig. 6. Optimal charging time for different BTES systems.

The optimal summer recharging time that ensures the same internal energy in the ground between two equal operation seasons is about 20 days for each scenario.

For the efficiency evaluation, the optimal charging and recharging time have been considered. The first low efficiency is calculated for 10 and 20 years of operation and it includes all of the summer recharges. The efficiency values are represented in Figure 7.

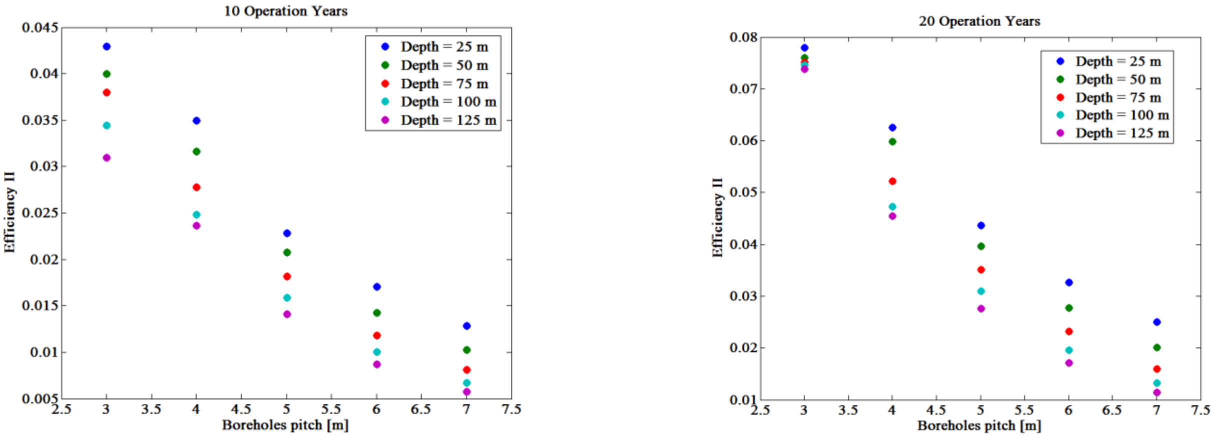


a) b)

Fig. 7. First law efficiency: a) for 10 years of operation and b) for 20 years of operation.

The efficiency results higher in the case of small lengths and of short pitches. After 10 years of operation, ε_I is about 36% for a system with pitch=3 m and depth=25 m, but it decreases of .about 52% when the boreholes are distant 7 m. The efficiency reduction that occurs when the boreholes are farther, is more significant in the case of deeper installation. Indeed a system with depth=125m and p=7 m is affected by a reduction of the first low efficiency of about 76% compared with the case of p=3 m.

The evaluation of ε_I in the time allows to understand how the energy stored in the charing stage, is exploited. After 20 operation years there is an increase of the efficiency for each design investigated. For a system with pitch=3 m and depth=25 m, ε_I achieves 50% in 20 years with percentage increase of about 38%. Instead a system with depth=125 m and p=7 m achieves 15% but it has an increase of about 81.4%. The thermal energy stored in the charging stage seems to be better exploited in time in systems with more distant boreholes and deeper ones. However these systems present too low efficiency even after 20 years of operation.



a) b)

Fig. 8. Second law efficiency: a) for 10 years of operation and b) for 20 years of operation.

Figure 8 shows the second law efficiency or exergy efficiency after 10 and 20 years of operation. The exergy efficiency results higher in the case of short installation depth and brief pitch: for the smallest system it is about 4.4% in a period of 10 achieving 7.8% in 20 years. As in the case of the first law efficiency, ε_{II} decreases for systems with more distant boreholes and deeper ones; also in this case these systems have a higher percentage increase of the exergy efficiency in the time. The ratio between ε_{II} and ε_{I} does not depend on the pitch but only on the tubes length and results greater for deeper boreholes. In this latter case, the average temperature achieved by the ground is higher.

The parametric analysis allows concluding that system designs with short pitches between boreholes and shallow installations require lower charging time and result higher performance. The results obtained are strictly linked to the operation hours selected for this application. At constant charging time, a larger number of hours of operation means more energy extracted, with a consequent increase of the system efficiency.

4.2 Application of the parametric analysis to different years of operation

The hypothesis assumed in the parametric analysis that winter seasons are exactly the same is far from the real seasonal trend. For this reason, the last analysis is conducted simulating 6 years of operation where every season is different. In this case, the study is aimed to find the optimal summer recharge that allows maintaining the internal energy of the ground constant. At the beginning of each winter season the internal energy is maintained equal to that at the beginning of the previous season.

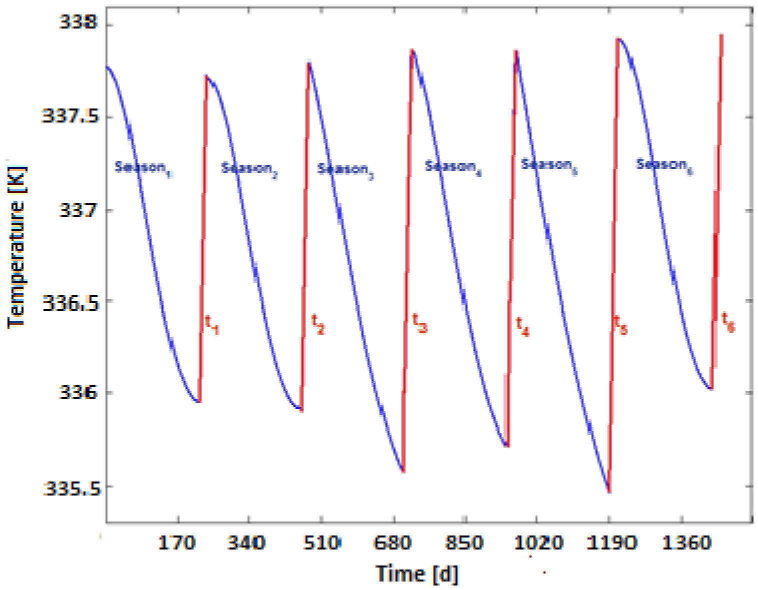


Fig. 9. Average temperature of the ground in 6 seasons of operation.

For this application the plant with a pitch between boreholes of 1m and installation depth of 30 m has been considered. Figure 9 reports the average temperature of the soil during the 6 years of operation. In particular the evolution of the temperature during the heating season (blue line) and the evolution of the temperature during the recharge stage (red line) are shown. The optimal recharging time will depend on the average temperature of the ground. For example, the 5th winter season is colder then 4th season and this causes a lower average temperature of the ground at the end of the season; for having the same internal energy, the summer recharging time (t_5) must be greater than the previous one (t_4). The summer recharging times obtained are respectively 15, 12 17, 20, 30 and 15 days. The first low efficiency at the end of the 6 years is about 30% against 27.7% when the recharging time is always 20 days; the exergy efficiency is about 18% against 16.8%. The variation is not so high but there are advantages in term of efficiency and the same amount of energy is assured for the next season bringing each time the soil at the same internal energy.

5. Conclusions

In this paper, a parametric analysis of borehole thermal energy storage systems has been proposed, considering various different designs obtained by varying the pitch between boreholes and the installation depth. The optimal charging time that allows one to achieve the design operating temperature and a periodically constant internal energy has been obtained.

Results show that the optimal charging time significantly depends on the design parameters. It varies from 30 to 86 days for boreholes with pitch of 3 m at the installation depth gradually increasing. The optimal charging time reaches the value of 994 days for the design with deepest and furthest boreholes. A summer recharging time of about 20 days is necessary for all designs to guarantee constant internal energy in the soil between two equal operation seasons.

Energy and exergy efficiencies have been calculated considering 10 years and 20 years of operation. For each design both efficiencies increase with increasing operation time. This means that the amount of energetic (or exergergetic) resource stored in the charge stage is used and so exploited during the operation. A system with shallow and near boreholes is characterized by an efficiency of about 36% after 10 years and about 40% after 20 years of operation. These values decrease with increasing depth and pitch up to about 15% after 20 operation years.

During the operation, the winter seasons are not the same and the efficiency of a BTES system can be maximized evaluating the optimal summer recharge that allows maintaining constant the internal energy of the ground. In this way the same amount of energy is assured for the next season bringing each time the soil at the same internal energy and the efficiency is about 30%, after the simulation of 6 different years of operation.

In conclusion BTES plants with small size result more advantage in term of charging time and efficiency, especially for a long period of plant operation. These results should be combined with an economic analysis. Installation costs depend on the number of perforations more than depth. From an economic point of view, this would lead to prefer a reduced number of boreholes but deeper contrasting the parametric analysis results. In addition, installation of boreholes at large depth and small pitch is technically difficult to perform, with high risk of drill crossing. Therefore, the proposed parametric analysis constitutes a first design map for the techno-economic analysis of borehole thermal storage systems.

Nomenclature

		av	Average
c_p	Specific heat, J/kg K	*ch*	Charge
h	Heat transfer coefficient, W/m^2 K	*d*	Borehole depth
k	Thermal conductivity, W/m K	*ex*	Outer radius of U-tube
r	Radial Coordinate, m	*ext*	Extraction
t	Time	*g*	Grout
E	Energy, J	*i*	Inner radius of U-tube
Ex	Exergy, J	*in*	Inlet of U-tube
L	Length, m	*out*	Outlet of U-tube
R^{-1}	Global heat transfer coefficient, W/m^2 K	*p*	Pipe
T	Temperature, K	*rech*	Recharge
U	Internal Energy, J	*s*	Soil
Greek symbols		*w*	Water
ρ	Density, Kg/m^3		
ε	Efficiency		
Subscript			
I	First law		
II	Second law		

References

[1] Gao Q., Li M., Yu M., Spitler J.D., Yan Y.Y., Review of development from GSHP to UTES in China and other countries. Renew. Sust. Energ 2008; 1383-13394.

[2] Nordell B., Large-scale Thermal energy storage. Lulea University of Technology 2000.

[3] Nordell B., Grein M., Kharseh M., Large-scale utilisation of renewable energy requires energy storage. Lulea University of Technology 2007.

[4] Paksoy H.O., Thermal energy storage for sustainable energy consumption: fundamentals, case studies and design. Springer 2007.

[5] Sala J.M., Thermal energy storage (TES) systems for cogeneration and trigeneration systems. Advances in thermal energy storage systems: methods and applications 2015; 493–509.

[6]Caliskan H, Dincer I, Hepbasli A. Thermoeconomic analysis of a building energy system integrated with energy storage options. Energy Convers Manage 2013;76:274-81.

[7] Pinel P., Cruickshank C.A., Beausoleil-Morrison I., Wills A., A review of available methods for seasonal storage of solar thermal energy in residential applications. Renewable and Sustainable Energy Reviews 2011;15: 3341-3359.

[9] Wu W., You T., Wang B., Shi W., Li X., Evaluation of ground source absorption heat pumps combined with borehole free cooling. Energy Convers Manage 2014; 79:334-43.

[9] Zhai X.Q., Yang Y., Experience on the application of a ground source heat pump system in an archives building. Energy and Buildings 2011;43: 3263-3270

[10] Zeng H. Y.,Diao N. R., Fang Z. H., A finite line-source model for boreholes in geothermal heat exchangers. Heat Transfer-Asian Research 2002; 31:558-567.

[11] Bernier, M. A., Ground-coupled heat pump system simulation. ASHRAE Transactions 1986; 107:605-616.

[12] Zeng H., Diao N., Fang Z., Heat transfer analysis of boreholes in vertical ground heat exchangers. International Journal of Heat and Mass Transfer 2003; 46: 4467-4481.

[13] Florides G., Kalogirou S., Ground heat exchangers-A review of systems, models and applications. Renewable Energy 2007**;** 32:2461-2478.

[14] Ingersoll LR, Plass HJ., Theory of the ground pipe source for the heat pump. ASHRAE Trans 1948;54:339-48.

[15] Sharqawy MH, Mokheimer EM, Habib MA, Badr HM, Said SA, Al-Shayea NA., Energy, exergy and uncertainty analyses of the thermal response test for a ground heat exchanger. Int J Energy Res 2009;33:582-92.

[16] Ozgener L, Hepbasli A, Dincer I., Energy and exergy analysis of Salihli geothermal district heating system in Manisa, Turkey. Int J Energy Res 2005;29:393-408.

[17] Kizilkan O., Dincer I., Borehole thermal energy storage system for heating applications: Thermodynamic performance assessment. Energy Conversion and Management 2015; 90:53-61.

[18] Lundh M., Dalenback, J.O. Swedish solar heated residential area with seasonal storage in rock: initial evaluation. Renewable Energy 2008;33:703-711.

[19] Sibbitt B., McClenahan D., Djebbar R., Thornton J., Wong B., Carriere J., Kokko J., The performance of a high solar fraction seasonal storage district heating system five years of operation.

Energy Procedia 2012;33:856-865.

[20] Cosentino S., Guelpa E., Melli R., Sciacovelli A., Sciubba E., Toro C., Verda V., Identification of the optimal operational strategy of a large district heating network through POD modelling. Proceedings of ECOS 2014 27th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems; 2014 June 15-19; Turku, Finland

[21] Kasuda T., Archenbach P.R., Earth temperature and thermal diffusivity at selected stations on the United States. ASHRAE Transactions 1965.

[22] Cosentino S., Sciacovelli A., Verda V., Optimal operation of small geothermal systems through entropy generation analysis, Proceedings of the ASME 2014 12th Biennial Conference on Engineering Systems Design and Analysis; 2014 June 25-27; Copenhagen, Denmark.

[23]Sanner, B., Overview shallow geothermal systems. 05: Basics on geology – what engineers and drillers need to know. GeoTrainet Course for designers and drillers; 2010 March 17-19, Peine, Germany.