

PAPER • OPEN ACCESS

Sustainability assessment and performance evaluation of a Ground Coupled Heat Pump system: coupling a model based on COMSOL Multiphysics and a MATLAB heat pump model

To cite this article: C Alimonti *et al* 2019 *J. Phys.: Conf. Ser.* **1224** 012023

View the [article online](#) for updates and enhancements.



IOP | ebooks™

Bringing you innovative digital publishing with leading voices to create your essential collection of books in STEM research.

Start exploring the collection - download the first chapter of every title for free.

Sustainability assessment and performance evaluation of a Ground Coupled Heat Pump system: coupling a model based on COMSOL Multiphysics and a MATLAB heat pump model.

C Alimonti¹, E Soldo¹, S Minniti² and MFM Speetjens³

¹Sapienza University of Rome, DICMA, Via Eudossiana 18 00184 Rome

²Eindhoven University of Technology, Electrical Engineering Dept. 5612 AZ Eindhoven

³Eindhoven University of Technology, Mechanical Engineering Dept. 5612 AZ Eindhoven

claudio.alimonti@uniroma1.it

Abstract. The present study investigates the sustainable use of a ground coupled heat pump (GCHP). In order to assess the performance of this type of installation, a computer model composed by two parts has been developed. The Borehole Heat Exchanger (BHE) model is developed in COMSOL Multiphysics, based on numerical methods. Part of the results are fed to the heat pump energy model, developed in MATLAB. A real case study has been used to validate the model: the Faculty of Engineering of La Sapienza University in Latina, undertaking a renewal project for an abandoned part of the building. After the renovation, the building will host a research center on the topic of low-enthalpy geothermal systems. The analysis have demonstrated that the modelled GCHP system can supply a significant share of the energy required from the future research center. This amount of energy can be provided keeping almost stable the thermal balance of the surrounding region in the subsoil, operating in a sustainable way. The range of variation of the ground temperature with respect to the average value is within the limit of 5°C, which is the cap set by the international legislation.

1. Introduction

Our primary challenge in the energy transition is the research of solid alternatives for the global energy system; alternatives that could be sustainable over a long time on our planet. The current energy supply system, mainly based on fossil fuels must gradually be replaced by another system, based on new innovative principles. The sustainability should be considered as important as the renewability in the evaluation of “green” energy sources.

Geothermal energy is one of the main opportunities for this purpose and it consists of the heat contained within the Earth’s crust and mantle. This resource is characterized by an enormous potential both for electricity production and direct use applications. The use of Ground Source Heat Pumps (GSHP) for building heating do not produce CO₂ emissions and do not require specific characteristics for the subsoil. Therefore, the GSHPs can be strategic in order to reach the environmental goals confirmed by the Conference of Parties in Paris (COP21). The growth in installed capacity of direct-use applications reflects the increasing international interest in this type of technology: according to



[1] the number of installed units is increased of a 52% respect to the data of 2010 and three times respect to the data of 2005.

The aim of this work is to build an overall model in order to carry out a first sustainability analysis of a ground source heat pump system. The analysis has two targets:

- understand in what extent the surrounding ground is influenced by the GSHP installation over a long-term period (10 years);
- on the other side, evaluate the energy performance of the system depending on the coupling between heat exchanger and surrounding ground.

As the sustainability of a geothermal source depends on a large number of variables, often interdependent and transient, an analytical approach is quite difficult. In this work, a two-dimensional (2D) transient model of a GSHP system is developed.

The general structure of the model is divided in two parts:

- the Borehole Heat Exchanger (BHE) model built in COMSOL Multiphysics, which simulates the interaction between the system and the ground;
- the heat pump (HP) model developed in MATLAB, which analyses the energy performance of the system.

There is a one-way coupling between the two models: part of the results obtained from the BHE model is fed into the HP energy model to calculate and assess the performance indicators of the system. The case-study provides the relevant information regarding the stratigraphy of the subsoil as well as the climatic characteristics of the location.

A case study is used to validate the model in a real situation, the Faculty of Engineering of La Sapienza University, located in Latina, which is undertaking a renewal project for an abandoned part of the building. After the renovation works the abandoned wing will host a research center on the topic of low-enthalpy geothermal systems.

2. Methodology

The schematic reported in figure 1 depicts the structure of the model. The general problem was divided in two models: the BHE model and the HP energy model.

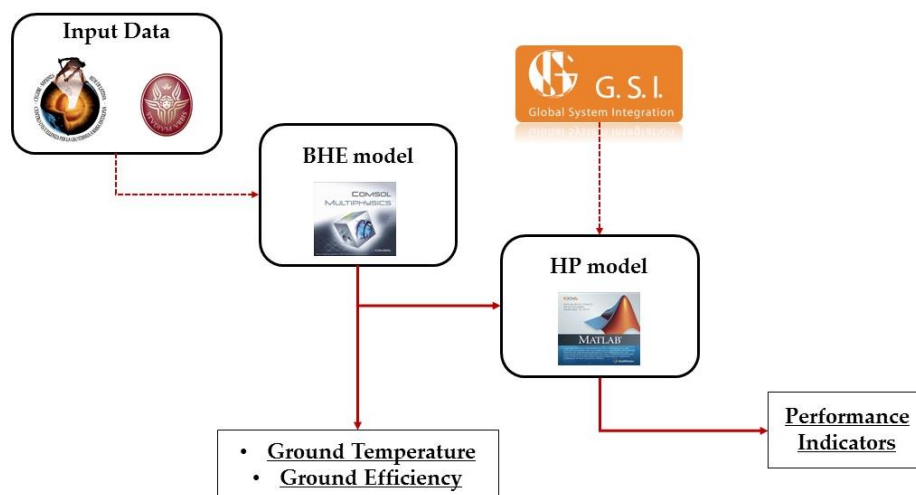


Figure 1. Structure of the model

The BHE model was developed in COMSOL Multiphysics, a modelling software based on numerical methods. A time simulation of 10 years has been used to study the effect of the borehole heat exchanger on the surrounding ground. The heat pump energy model was developed in MATLAB, starting from a catalogue data of a specific heat pump. The model used was the AQUA MAGIS

(mod.110) made by the company Global System Integration. Some results were obtained directly from the BHE model such as the temperature field of the surrounding ground. The coupling between the BHE model and the heat pump model in MATLAB is a one-way coupling: the Leaving Fluid Temperature obtained from the BHE model was used as input data for the heat pump model, obtaining all the performance indicators for the specific case-study.

2.1. BHE model

The BHE model has been built with COMSOL Multiphysics®, general-purpose software based on advanced numerical methods for modelling and simulating physics-based problems. COMSOL is based on different modules, which model different physical problems such as the Structural Mechanics Module and the Computational Fluid Dynamics (CFD) Module. Another feature of the software is the presence of several Multiphysics Modules, built to couple different modules and different physics.

The computational power available was not enough to implement and simulate over a long period a 3-D model. Therefore, the proposed model was built in 2D, even considering that a high detail level was not relevant to determine with sufficient accuracy the performance of the heat pump. The long-term effect on the ground can be considered almost symmetric in every vertical plane passing through the center of the borehole.

The implemented geometry is a section made with a vertical plane passing through the axis of the two legs of the U-tube. A single U-tube configuration was considered for simplicity. In figure 2 the dimensions of the U-tube pipe inside the borehole are shown further in detail. The size of the hole is an average of typical values found in literature [2,3]. A pipe with a nominal diameter (and actual OD) of 40 mm is chosen and for the dimension ratio (DR) has been selected a DR11 (32,7 mm) which is the most common with nominal diameters lower than 63 mm.

The positioning of the pipe inside the borehole can be variable depending on the characteristic of the subsoil and the thermal properties of the grout. In the section implemented in the model, there is a 30-mm distance between the two legs of the U-tube pipe. The same distance is present between each leg and the borehole wall.

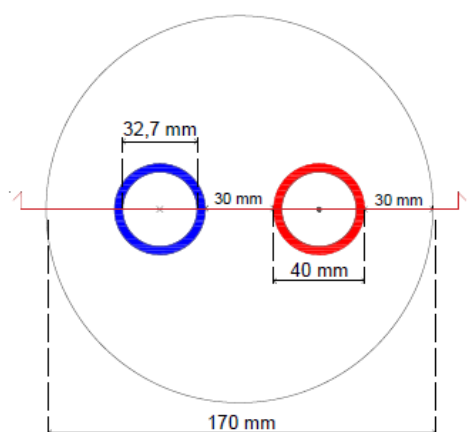


Figure 2. Horizontal section of the BHE model

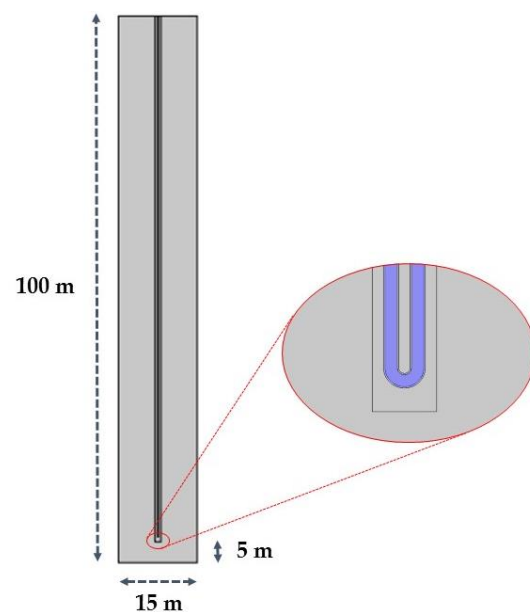


Figure 3. Dimensions of the BHE model implemented in Comsol

The overall dimensions of the model are shown in figure 3 from the Graphical User Interface (GUI) in COMSOL Multiphysics. The dimension of the lateral surrounding zone was selected considering the typical influence zone of this application.

The table 1 shows the materials implemented in the model.

Table 1. Materials of the model and their position

Material	Position in the model
Antifreeze Solution	Circulating in the pipe
Grout	Filling Material
HDPE	U-tube Pipe
Ground	Surrounding Region

The antifreeze solution is a mixture of water and Mono Ethylene Glycol (MEG), very common in this type of applications. Data sheets from the company MEGlobal [4] are used to evaluate temperature-varying properties such as viscosity, thermal conductivity and heat transfer coefficient at constant pressure. Regarding the share between MEG and water, a mixture with 30% of MEG (in weight, which means 27,7% of volume share) is chosen for the BHE model.

The High-Density Polyethylene (HDPE) has been selected for pipe material. The table 2 summarizes the average thermal properties of grout [5, 6] and of the HDPE [7, 8].

Table 2. Grout and HDPE thermal properties

Material	Density	Thermal conductivity	Heat capacity at constant pressure
Grout	1700 kg m ⁻³	1.5 W m ⁻¹ K ⁻¹	2000 J kg ⁻¹ K ⁻¹
HDPE	9500 kg m ⁻³	0.5 m ⁻¹ K ⁻¹	1900 J kg ⁻¹ K ⁻¹

The thermal properties of the subsoil are values that cannot be easily measured and stored. The values set in the model (figure 4) are an average of different references found in the literature [2, 9].

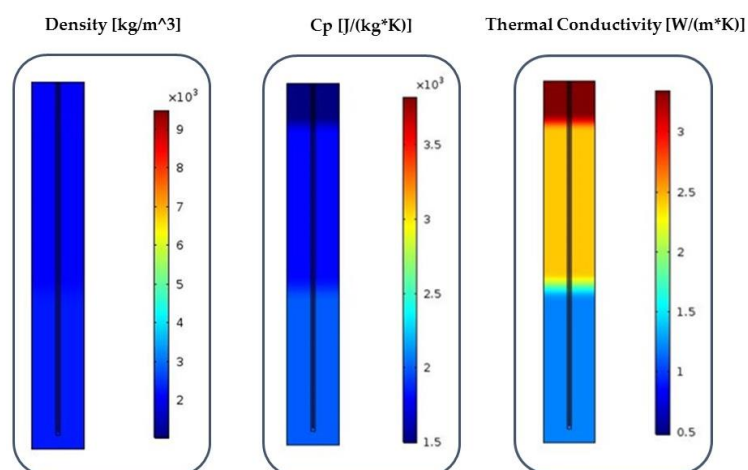


Figure 4. Thermal properties of the surrounding rock

It is easy to notice the change in thermal conductivity between different layers, passing from the value of 3,3 Wm⁻¹K⁻¹ to 1,2 Wm⁻¹K⁻¹ at deeper depths. The values in density are slightly different for

different layers, keeping the values around 2000 kg/m^3 . The heat capacity at constant pressure decreases from deeper to shallow depths, since the deeper is the depth the greater is the density and capacity to store heat limiting its movement throughout different layers.

The figure 5 describes the modules structure used to build the BHE model. The **Non-Isothermal Flow** is the used Multiphysics Interface to simulate a moving fluid exchanging heat with the surrounding materials. The **Heat Transfer Module** uses the heat equation to calculate the temperature field in the whole model: the **Heat Transfer in Solids** evaluates the temperature of the ground, the HDPE and the filling material of the BHE; the **Heat Transfer in Fluids** evaluates the temperature of the antifreeze solution. Inside the U-tube, the **Turbulent Flow** module uses the Reynolds-Averaged Navier-Stokes equations (RANS) equations for the conservation of momentum and the continuity equation for the conservation of mass.

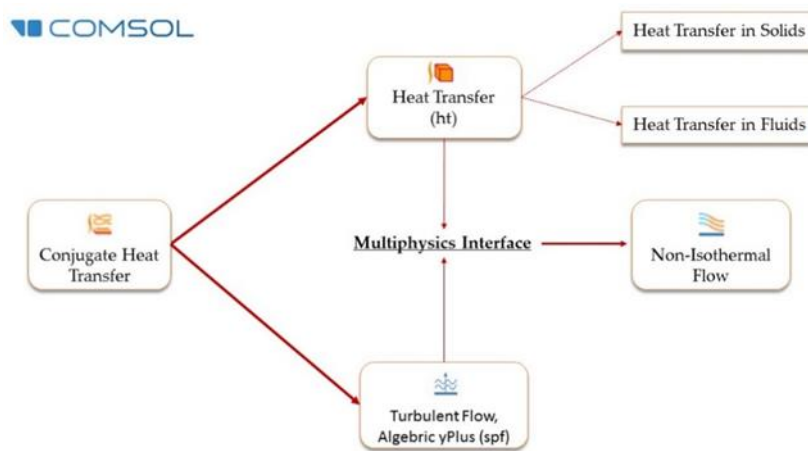


Figure 5. Modules framework in COMSOL multiphysics

Regarding the boundary conditions, a constant temperature is set on the external boundaries of the BHE model. The average monthly temperature of the case study's location is set on the upper boundary and it varies every month. The yearly average temperature of the subsoil is set on the lateral and on the lower boundaries of the model and it is constant for the entire simulation period. On the outlet boundary of the pipe a constant pressure is set, while in the inlet boundary a constant inlet velocity is set. The fluid has no slip along the walls because the vector field is equal to zero.

The output data obtained from the simulation are the ground temperature, the average linear heat flux and the fluid temperature.

The ground temperature data obtained from the BHE model are stored at 5, 40, 80 meters. Two values for every depth have been selected: at 2 meters left and 2 meters right from the BHE.

The average linear heat flux along the two legs of the U-tube pipe is representative of the heat exchange between the antifreeze solution and the ground. The average temperature of the heat transfer fluid is calculated along the outlet boundary of the pipe.

2.2. Heat pump energy model

The general structure of the heat pump energy model is reported in figure 6. The two inputs are the EFT derived from the BHE model, previously described, and the Fluid Temperature required on the building-side that depends from the type of distribution system within the building.

The heat pump is AQUA MAGIS unit, an high-efficiency water-to-water heat pump selected from the catalogue of Global System Integration (GSI).

Catalogue data are used as starting point to assess the energy performance of the heat pump. The Entering Fluid Temperature (EFT) is the independent variable, in function of which all the relevant parameters. The catalogue reports the evaluation only for 4-5 different values of EFT. A MATLAB

code was developed to determine the polynomial interpolation functions for each parameter in order to perform the calculation for every possible value of EFT.

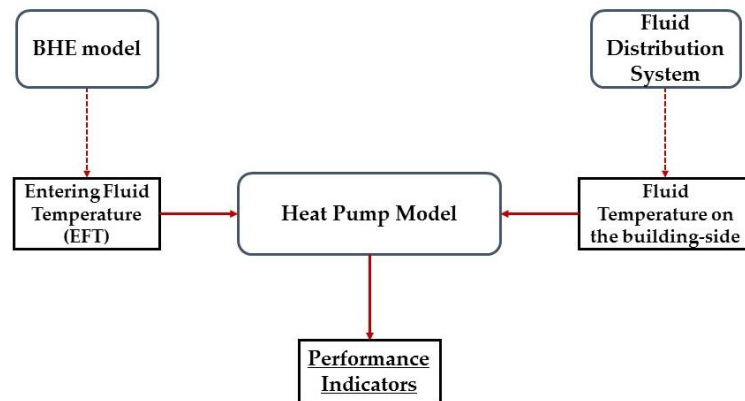


Figure 6. Modules framework in MATLAB

Regarding the building side, the code was developed considering the two possible distribution systems: the fan Coil units' system that requires temperature around 45°C in heating mode and around 7°C in cooling mode; the underfloor heating that requires temperature around 35°C in heating mode and around 15°C in cooling mode.

The catalogue data of the heat pump shows that the temperature difference (ΔT) of the antifreeze solution after the heat exchange with the refrigerant of the heat pump is nearly stable independently from the EFT. This justifies the use of a constant ΔT for the entire season.

The output data of the HP model are the power supplied to the building (output power), the Coefficient Of Performance (COP) while operating in the heating mode and the Energy Efficiency Ratio (EER) while operating in the cooling mode.

3. The case study: Faculty of Industrial Engineering in Latina

The project concerns the renovation works on one wing of the Faculty of Engineering in Latina, detached location of La Sapienza University.

The available wing (figure 7) is completely abandoned. A first step will be the renewal of the building to host a research center on the low-enthalpy geothermal systems (the first one in the central part of Italy). Secondly, a geothermal plant will be installed, to supply heating and cooling and to produce electricity to the research center. The additional value will be constituted by the installation of monitoring equipment to evaluate the performance of the system.

The space on the ground floor will be used as "Technical Room-Laboratory", where the internal unit of the geothermal plant and the Thermal Response Test equipment (TRT) will be hosted. The six rooms of the upper floor will be used for different purposes: a big conference room, which could be used also as lecture room; one room to control the performance parameters of the geothermal installation; a room for measurements and control for the ground parameters; one room for the researchers and the technical responsible; other two rooms will be used for design-consulting, support to design companies, software developments, geothermal databases, and technoeconomic feasibility studies.

Table 5. Stratigraphy of the case study

Depth [m]		Soil
0	10	Sand
10	60	Clayey sand
60	100	Clay

3.1. Simulation strategy

The simulation strategy was set considering 5 days (working days) of 24h operation and 2 days (weekend) of stop, according to the typical schedule of Italian universities, where no lectures are planned during the weekend. The two-days stop permits a recovery of the ground temperature surrounding the BHE and it allows to the heat transfer fluid to reach the external average temperature, improving the efficiency during operative days.

On the seasonal mode of operation, the simulation strategy was set considering 10 months of operations (5 in heating mode and 5 in cooling mode) and 2 months of stop (1 month for each operating period). This share was chosen considering the typical thermal load in Italy and considering also the results of the energy analysis of the site. This two months stop will also allow to the ground to spread the thermal load acquired/lost due to the heat injection/extraction of the BHE in a better way compared to the slight recovery in the weekends.

4. Results

4.1. Validation of the model

The BHE model was validate to verify the influence of the boundary effect on the BHE model. Therefore the total width of the lateral boundaries has been changed from 15 m to 30 m and a greater ΔT has been applied in the periodic boundary condition that links inlet and outlet of the U-tube pipe (4,6 °C during the heating mode and -5°C during the cooling season).

The figure 8 shows the effect of the modifications on the ground temperature at 5 km from the center of the BHE.

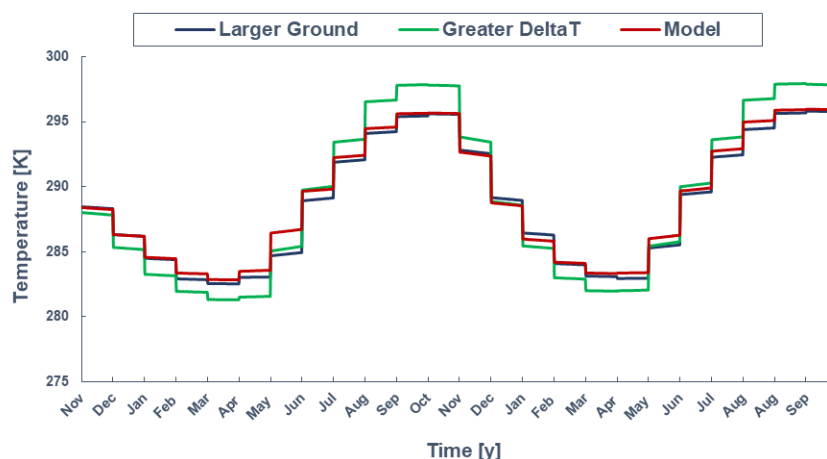


Figure 8. Ground temperature at 5m depth: comparison of the modified COMSOL models

Considering the model with larger lateral boundaries the temperature change of the ground is nearly equal to the normal model. This is enough to confirm that the boundary effect is not relevant for the evaluation of the ground temperature. The greater ΔT in the Periodic Boundary Condition between the inlet and the outlet of the pipe influences the change in temperature within the subsoil. A

larger range of variation is induced during the year. The influence of the geothermal installation is preponderant compared to the influence of the monthly fluctuations of the external temperature. The influence-zone of the installation is evaluated for the two deeper types of subsoil, the clayey sand (figure 9 - a) and the clay (figure 9 - b). The simulation time was set to 3 years. The average temperature has been calculated for lines parallel to the main dimension of the borehole at the end of each operational season (two values per year). The initial alteration of the subsoil is significant but after that, there is a stabilization: the influence zone at the end of the installation's lifetime is just under 8,5 m for clayey sand and about 7 m for clay.

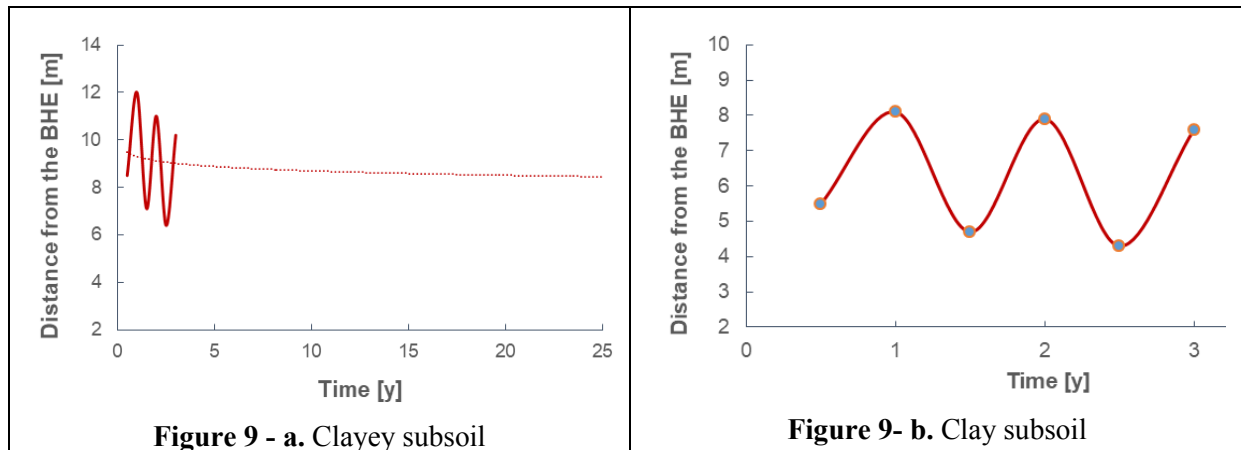


Figure 9. Influence zone of the GCHP installation

The figure 10 above shows the temperature distribution in the BHE model at the end of the Heating/Cooling season of the 3rd year. This is the larger model used to evaluate the influence of the boundary effect.

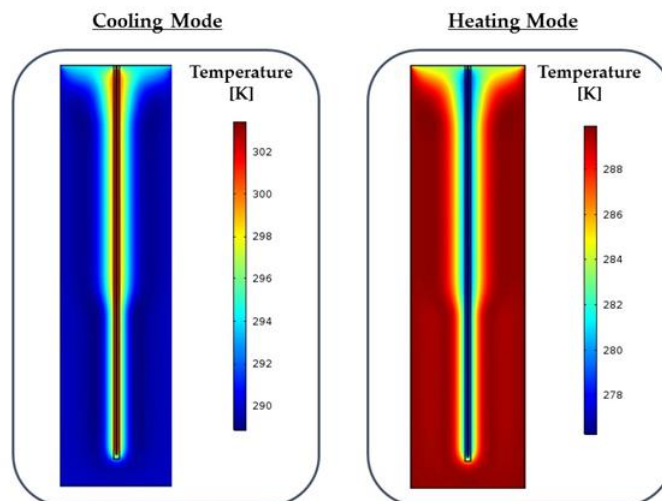


Figure 10. Temperature distribution for the larger model in the 3rd year of simulation

4.2. BHE model results

The figure 11 illustrates the fluctuation of the ground temperature in time at different depths. At the 10th year of operation, the yearly average temperature at 5 m of depth is 16,9°C while at the end of the

lifetime (25 years) of the installation the yearly average temperature is 290,6 K (17,45°C). The overall increase amounts to 2,3°C.

At 40m depth, the range of variation of the temperature is between 285 K (12°C) and 294,5 (21,6 °C). The yearly average temperature has an overall increase of 2,2°C at the end of the 25 years of operation with a final average temperature of 290,49°C (18,55°C). the overall trend has a larger increase in the first two years due to the modification of the undisturbed ground temperature. After that the trend is quite stable with a slight yearly increase.

Considerably different is the result at 80m depth where the type of subsoil is completely different (clay) and with lower thermal conductivity. The range of variation of the temperature is much tighter: between 287 K (14°C) and 292 K (19°C). Here, there is a larger increase in the first year (yearly rate of 0,24°C/y) and a lower increase in the next years. The temperature reaches the value of 290,05 K (16,9°C) after 25 years of operation.

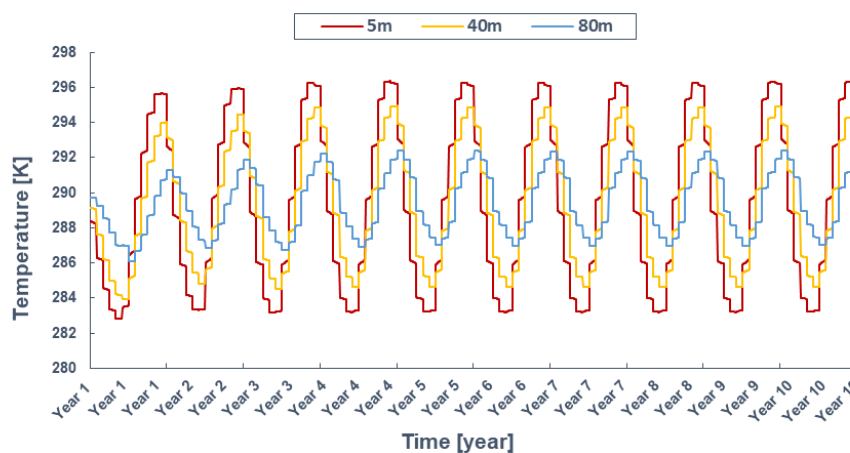


Figure 11. Comparison of ground temperature at different depths

In figure 12 the ground efficiency in the inlet leg (negative during the heating mode and positive during the cooling mode) is showed. The results show that 4 years are needed for the stabilization of the heat transfer process between the probe and the ground. The efficiency in the first heating season is lower because the ground is undisturbed. Afterwards, there is a stabilization because of the alternation of cooling and heating seasons that results in efficiency improving. The asymptotic value in the heating season is over 44 W/m, for the cooling season, the asymptotic value (around 47,5 W/m) is reached through more fluctuations. Furthermore, the amount of the heat transferred from the heat pump to the sink during the cooling season is higher than the one extracted during the heating season.

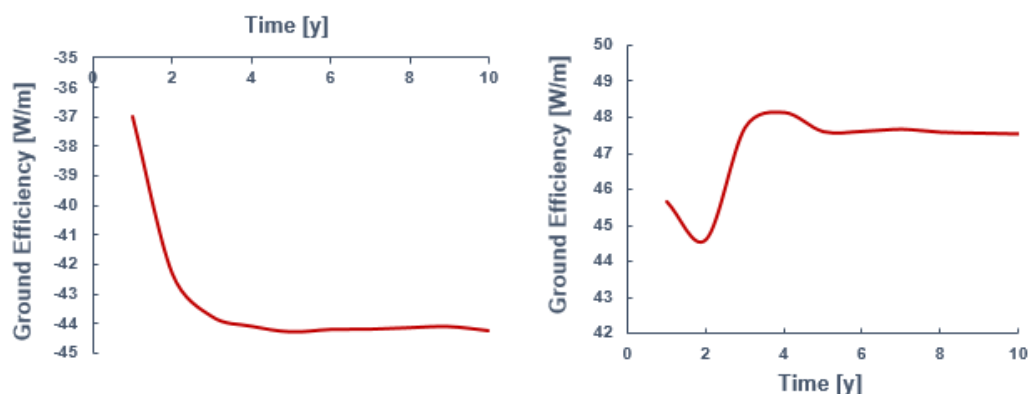


Figure 12. Average ground efficiency along the inlet leg. Left: heating mode - right: cooling mode

The situation is similar in the outlet leg (figure 13) because the system is almost symmetric with respect to a vertical line passing through the centre of the model. The only difference is the ΔT between the antifreeze solution and the subsoil. In the second part of U-tube pipe the fluid has already gained almost half of the total heat and the temperature has changed consequently. For this reason, the difference of temperature is lower and the ground efficiency is reduced. After the first 4 years, the value stabilises for the heating mode near 34 W/m, while for the cooling mode just under 37 W/m.

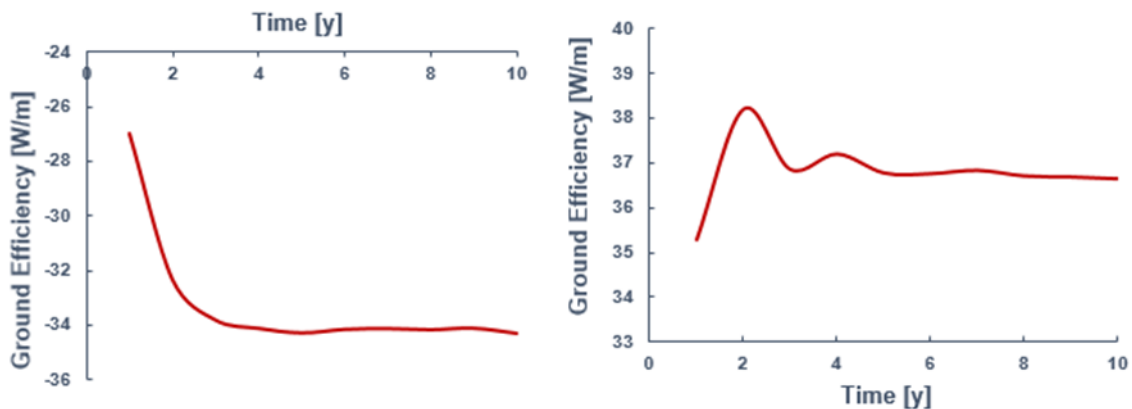


Figure 13. Average ground efficiency along the outlet leg. Left: heating mode - right: cooling mode

The entering fluid temperature (EFT) in the heat pump is the average of the temperature of the fluid along the upper boundary of the outlet leg of the U-tube pipe.

The figure 14 reports the trend of the EFT of the antifreeze solution during the 10 months of operation, for a total time of 10 years. After the first 2 years of stabilization, the variation range of the temperature is nearly stable: the range of variation is 2-12 °C for the heating mode, 18-33 °C for the cooling mode.

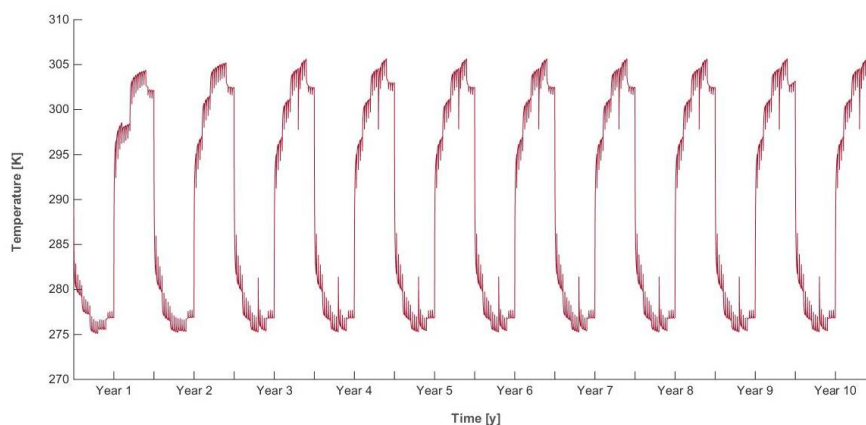


Figure 14. Entering fluid temperature for the 10 years of simulation

The figure 15 shows the yearly trend of EFT. During the 5 days of 24hours operation, the temperature varies logarithmically (it decreases in heating mode, it increases in cooling mode) but it does not reach the complete stabilization. Then, there are 2 days of stop where the heat transfer fluid is idle, and it reaches again the outside temperature. So the temperature in every month is slightly different to the monthly average temperature of the external environment, resulting in an efficient heat exchange.

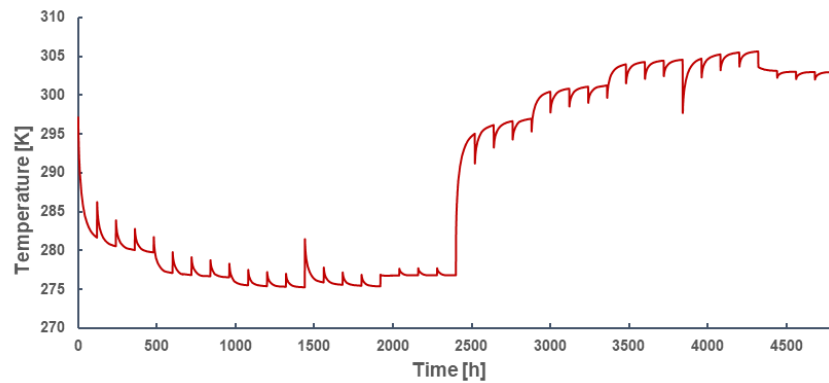


Figure 15. Entering fluid temperature for the 4th year

4.3. Heat Pump performance

Two types of distribution system are investigated because they are possible solution for the case-study: fan-coil units' system (figure 16) and underfloor heating system (figure 17).

Both of the solution can satisfy the peak heating request of the building (10.5 kW), but none of them is able to supply the peak load of cooling mode (17,32 kW). The average output power in the cooling mode is 10,98 kw for fan-coil units' system and 13,92 for underfloor heating system.

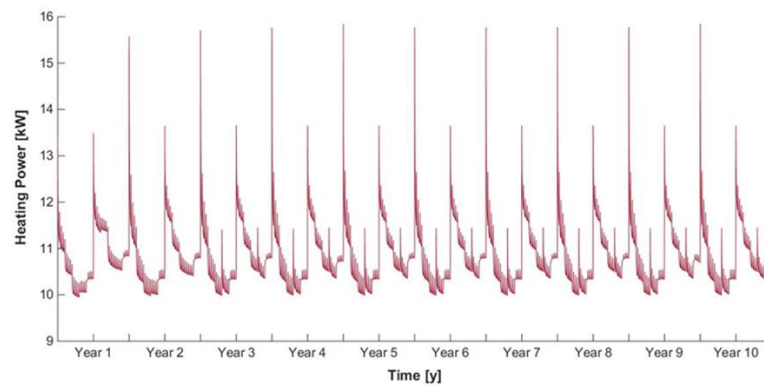


Figure 16. Output power with the fan-coil units' system

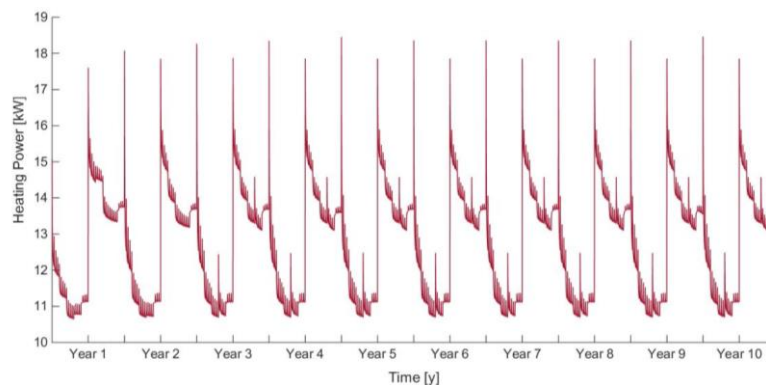


Figure 17. Output power with the underfloor heating system

Higher performance indicators are calculated for the underfloor heating system (figure 18) respect to the fan-coil distribution system. The stabilization of the COP is faster than the EER. The stabilized value of the COP is around 3,53 for fan coil system and 4,8 for underfloor heating system. The EER reaches the value of 5,3 for fan coil system and 6,44 for underfloor heating system.

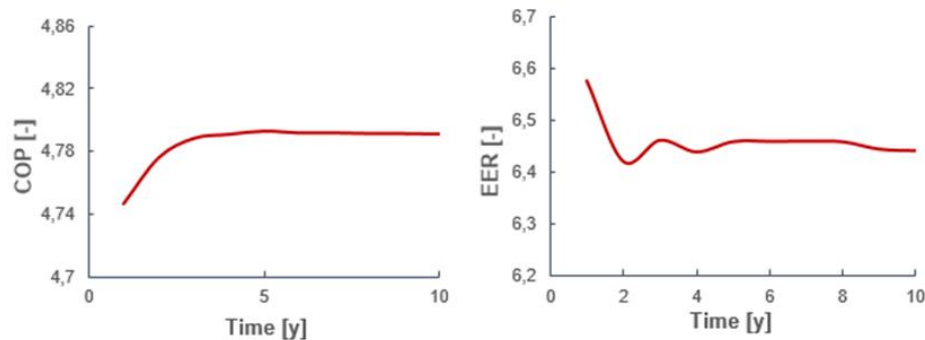


Figure 18. Seasonal performance indicators for the underfloor heating system

5. Conclusions

The present study investigates the sustainable use of a ground source heat pump applied to the Faculty of Industrial Engineering of La Sapienza University, located in Latina, which is undertaking a renewal project for an abandoned part of the building.

The analysis has been conducted with two main targets: understand in what extent the surrounding ground is influenced by the installation; evaluate the performance of the system during a long-term period of operation (at least 10 years).

Due to the number of coupled processes and variables involved The model has been divided in two parts: A 2-D Borehole Heat Exchanger (BHE) model is built on COMSOL to simulate the coupling between the system and the ground, and a heat pump energy model is developed on MATLAB using catalogue data as starting point.

The results of the simulations show that during 10 years of operation, the temperature change at a distance of 2 m from the center of the BHE, is around 1,5°C, reaching an increase of 1,9°C at the end of the 25 years of operation. This is the most relevant change, noticed at 5m depth from the surface. Going down in depth, there are different types of subsoil with lower thermal properties, which limit the temperature change. This is even lower at 40m and 80m depth. The thermal balance is almost maintained during the 10 years of operation because the plant is operating for the same time (5 months) both in the cooling and the heating season.

The stratigraphy of the subsoil in the location of Latina seems to be suitable for the application of a Ground Source Heat Pump system. The energy analysis illustrates that is not possible to meet the required peak load of the Faculty with just one single BHE, even with a length of 100m. The heating peak load can be reached with both types of distribution system but the output power is not enough during the cooling season. Highest output power and performance indicators are reached with the Underfloor heating system. The COP reaches an average value of 4,8 while the EER amounts to 6,4 in the cooling season. Those outputs confirm that geothermal heat pumps work more efficiently with distribution systems that do not require high temperature on the building side. By Lowering the lift between the two temperature levels, it results an increase of the overall efficiency of the system. On the other side, the Underfloor heating system is certainly the less cost-effective solution for the renewal of the faculty. A cost-benefit analysis should be performed to assess what is the best solution for supplying the energy demand of the research center.

Since the simulated BHE was not enough to satisfy the entire energy demand of the future research center, one option could be the installation of another BHE beside to the previous one. Considering this possibility, the influence-zone in the BHE model was evaluated, in order to avoid thermal interferences between different BHEs providing energy to the same building. The influence-zone amounts to 8,5 m from the center of the BHE. This means that the installation will modify the temperature field in the subsoil for 17 m in total.

Thus, in summary, the modelled GCHP system can supply a significant share of the energy required from the future research center. This amount of energy can be provided keeping almost stable the thermal balance of the surrounding region in the subsoil, operating in a sustainable way.

References

- [1] Lund J W and Boyd TL 2016 Direct utilization of geothermal energy 2015 worldwide review *Geoth.* **60** 66–93
- [2] Kavanaugh S and Rafferty K 2014 *Geothermal Heating and Cooling: Design of Ground-Source Heat Pump Systems* (Atlanta : ASHRAE)
- [3] Yang H, Cui P and Fang Z 2010 Vertical-borehole ground-coupled heat pumps: A review of models and systems *Appl. En.* **87** 16-27
- [4] MEGlobal. Ethylene Glycol - Product Guide . [Online] 2008. <http://www.meglobal.biz/>
- [5] GeoPro Inc. The importance of thermal grout conductivity . [Online] www.geoproinc.com.
- [6] CETCO. Geothermal Grout: Enhanced Thermally Conductive Grout. [Online] December 2013. http://www.cetco.com/DesktopModules/Bring2mind/DMX/Download.aspx?Command=Core_Download&PortalId=0&EntryId=4344
- [7] INEOS Olefins and Polymers USA. Typical Engineering Properties of High Density Polyethylene. [Online] <http://www.ineos.com/globalassets/ineos-group/businesses/ineos-olefins-and-polymers-usa/products/technical-information--patents/ineos-typical-engineering-properties-of-hdpe.pdf>.
- [8] Professional Plastics. Thermal Properties of Plastic Materials. [Online] <http://www.professionalplastics.com/professionalplastics/ThermalPropertiesofPlasticMaterials.pdf>.
- [9] Hamdan I and Clarke B 2010 Determination of Conductivity of Coarse and Fine Sand Soils Proc. World Geoth. Congr. 2010 Bali, Indonesia