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Contents

TECHNICAL BULLETIN 1/2025

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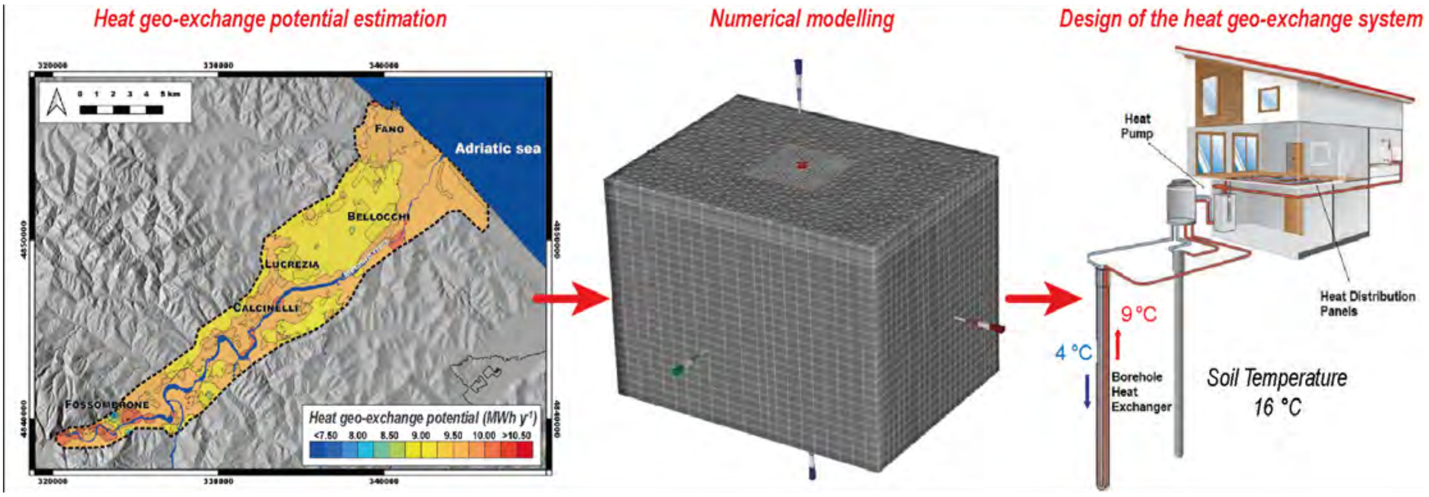
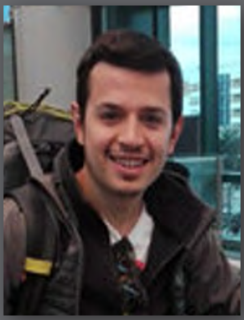
Maps of Shallow Ground Heat Exchange and numerical modelling for Thermal Energy Production



Introduction

The direct use of “geothermal resources” for heating and cooling indoor air conditioning systems, i.e. shallow ground heat exchange (hereafter heat geoexchange), represents one of the most promising solutions for reducing the greenhouse gas emissions produced by traditional fossil-fuel-based systems [1]. The heat geoexchange is a renewable energy, fundamentally based on the physical datum of the nearly steady-state temperature of the ground (rock and aquifer) just few metres below the Earth surface, i.e. a depth where the atmospheric temperature variation due to the seasons (solar radiation) and the cycle of day and night does not modify the ground temperature [2]. Based on the above physics principle, ground source heat exchangers (GSHEs) linked to heat pumps are becoming a common type of indoor air conditioning system, due to its very-low environment impact and null visual influence on the landscape. GSHEs can be associated with vertical or horizontal closed-loop systems, also known as Borehole Heat Exchangers (BHEs), generally made of high-density polyethylene (HDPI) pipes. The vector fluid circulating within the HDPI pipes and allowing the heat geoexchange is water, eventually with propylene glycol added, to prevent freezing of the liquid near the surface. Boreholes where the HDPI pipes are installed (normally with U or double U-shaped) should of course be grouted with an impermeable bentonite-rich cement and tested before collecting the inlet and outlet pipes to the heat pump [2]. Alternatively, heat geoexchange may be performed through open-loop systems, always coupled with heat pumps but directly exploiting groundwater. These systems are called groundwater heat exchangers (GWHEs) [2].

If, on one hand the GWHEs requires suitable hydrogeological characteristics of the specific site (i.e. a productive aquifer), on the other hand the closed-loop systems based on BHEs can be developed virtually anywhere [3], and, if the ex-



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ploitation of the ground thermal reservoir during winter and summer seasons is balanced, the longevity of the system can be achieved [4]. Nonetheless, despite this versatility, the installation of BHEs needs the knowledge of the main geological, hydrogeological and thermophysical features of the ground, since the efficiency of the closed-loop systems, and its sustainability, heavily depend on the thermal properties of the ground and its ability to exchange heat (thermal conductivity, porosity and water permeability of the rocks). Besides fundamental knowledge of geology, petrophysics and hydrogeology these features can be further understood thanks to the use of advanced numerical models, which are critical for the simulation and optimization of heat geoexchange systems [5]. In fact, they allow the simulation of the ground's thermal behaviour in response to continuous operation of the closed- or open-loop systems, permitting the optimal balance between heating and cooling seasons, thus avoiding any long-term depletion of the ground thermal reservoir.

In this framework, the availability of thematic maps of the thermal properties of the ground and numerical models at the finite elements play a crucial role in territorial planning, enabling the optimization of geoexchange systems and ensuring energy production that is both efficient and environmentally friendly.

Heat Geoexchange Maps for Territorial Planning

Heat geoexchange maps (Fig. 1), which represent the distribution of thermal properties of the ground (such as thermal conductivity and heat capacity), are essential tools in planning indoor air conditioning systems based on closed-loop GSHEs.

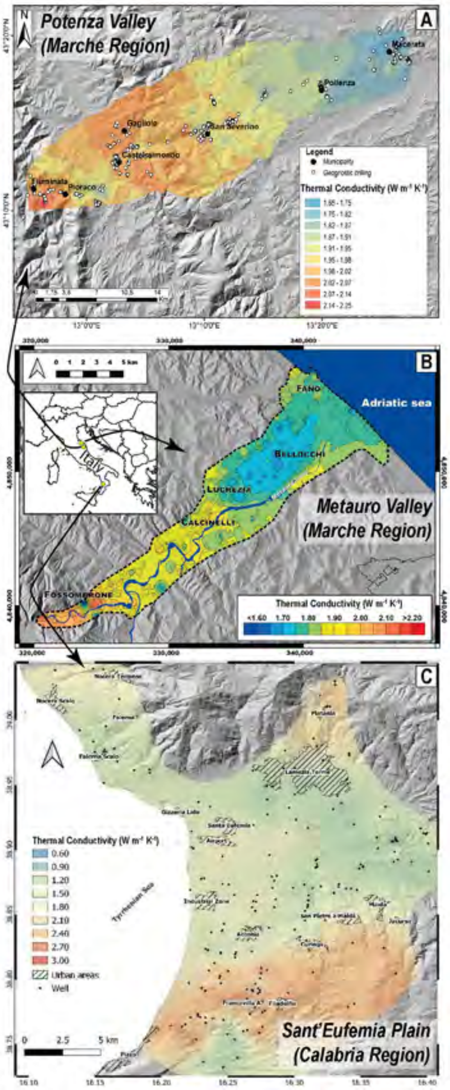

Figure 1 - Examples of thermal conductivity maps in the a) Potenza River valley (Marche Region [modified from 6]), b) Metauro River valley (Marche Region; [modified from 3]), and c) Sant'Eufemia Coastal Plain (Calabria Region; [modified from 7]) averaged over 100 meters of depth from the surface.

These maps allow to identify areas with high potential for installing heat geoexchange systems, which usually have depths of the BHEs comprised between 50 and 200 m. The data extracted from these maps provides information on the depth and thicknesses of the various geological layers, and on the heat transfer capacity of the ground [e.g., 3,6,7,8], all of which are of paramount importance to optimise the system design (i.e., the number of, and distance between BHEs based on the energy demand of the building/s).

Furthermore, heat geoexchange maps enable the long-term assessment of the ground thermal reservoir potential. Since the efficiency of an indoor air conditioning GSHEs system largely depends on the ability of the ground to regenerate itself from a thermal point of view, having a clear understanding of the thermal properties distribution within the subsurface helps to prevent thermal overloads and ensures that systems operate over time in a sustainable manner [8]. The integration of these maps into territorial planning policies also promotes a more rational management of natural resources, reducing the likelihood of installations in unsuitable areas or regions with high thermal depletion risks. Thus, by knowing the thermal characteristics of the ground in different areas, decision-makers can prioritize installations where the heat geoexchange potential is higher, thus maximizing the system's efficiency and minimizing costs.

Numerical Models for the Sustainability of the Indoor Air Conditioning Systems based on GSHEs and GWHEs

The adoption of advanced numerical models is critical for the simulation and optimization of heat geoexchange systems. These models allow the simulation of the ground's thermal behaviour in response to continuous operation of a closed- or open-loop system [5]. Analysing the heat flow in the ground, managing long-term temperature profiles, and assessing potential thermal load scenarios are all activities that greatly benefit from numerical models.

Recent studies [5,6,9] highlight the importance of advanced models in predicting and optimizing the performance of indoor air conditioning systems operating through GSHEs or GWHEs. These models, based on differential equations that describe heat conduction, convection, and radiation, provide insights into local geological-hydrogeological conditions, climate variability, and rock properties that influence the behaviour, through time, of the ground thermal reservoir exploited for the energy demand. These numerical models can thus enhance the accuracy of predictions regarding the thermal wave and interference of the single BHE on the ground in short (Fig. 2) or long term (Fig. 3) periods, the thermal recovery times, and the energy efficiency through time of the GSHEs or GWHEs indoor air conditioning systems [9].

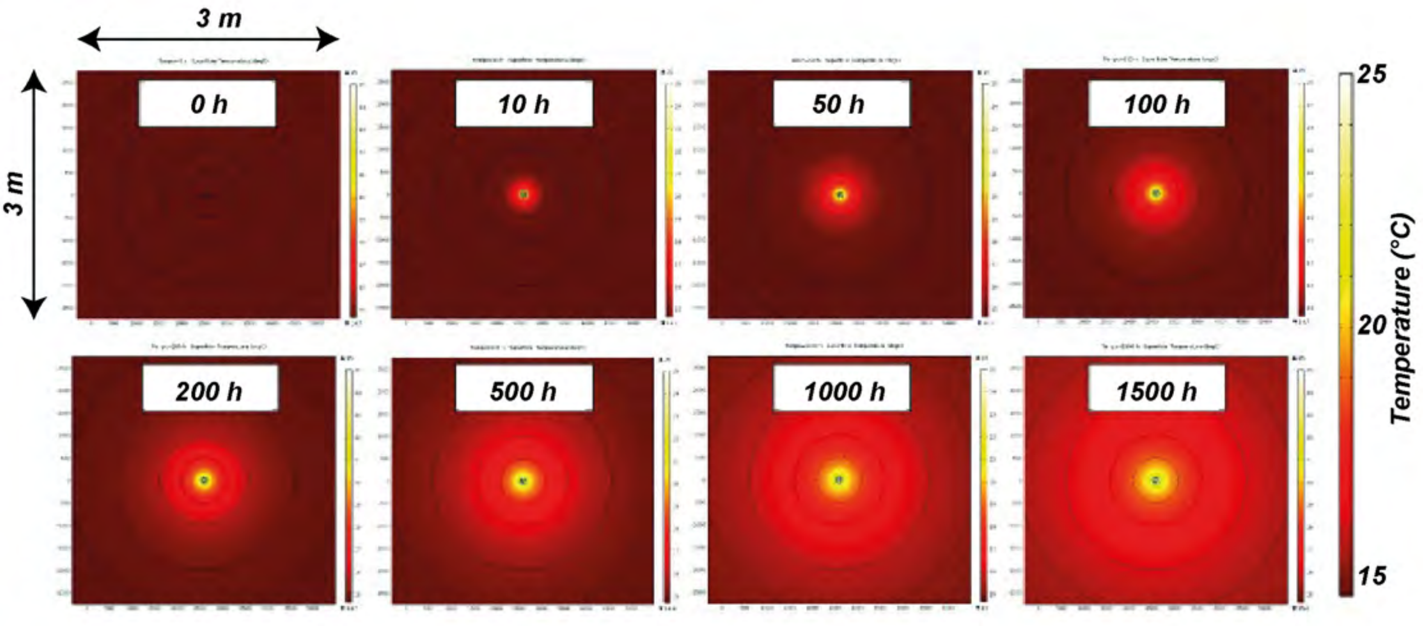

Figure 2 - Propagation of the ground thermal wave in short-time (up to 1500 hours), from the heat transfer fluid (water) inside the BHE pipe to the adjacent ground obtained by means of COMSOL Multiphysics Analyzer (software based on finite elements) [modified from 10], taken at 25 meters of depth.

Moreover, numerical models can be used to simulate the integration of various energy sources and design hybrid systems that combine heat geoexchange with other renewables, such as solar thermal energy and photovoltaic panels and, possibly, ground heat storage during summer season [11] as well. This integration among renewables not only increases the sustainability and resilience of the systems but also enhances energy efficiency and reduces operational costs over time. Nonetheless, hybrid models can offer the potential to significantly reduce the carbon footprint of heating and cooling systems, especially in areas with variable energy needs or where ground conditions are less favourable for GSHEs or GWHEs.

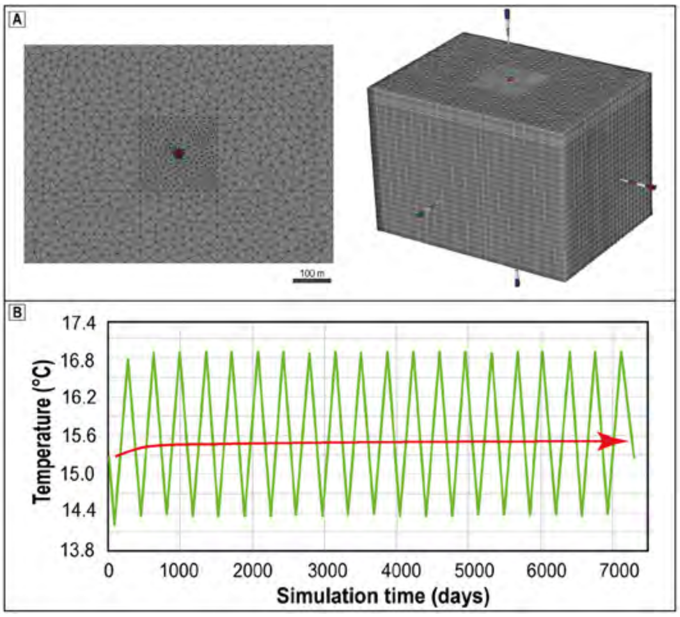

Figure 3 - a) Mesh performed within the calculation domain using FEFLOW software and example of a 3D layer configuration built according to hydraulic and thermal properties, the BHEs depth, and the calculation conditions; b) seasonal variation of the ground average temperature within 20 years (7000 days) in a simulated, 100 meters-depth, closed-loop BHEs system operating in heating and cooling mode [modified from 6]

Conclusions

The integration of heat geoexchange maps and numerical models in the design and management of indoor air conditioning systems based on GSHEs or GWHEs coupled with heat pumps is a key step toward promoting renewables and environmental sustainability. These maps provide a clear view of the potential of the ground thermal reservoir in different areas, enabling informed decisions regarding installation locations for BHEs, while numerical models ensure the continuous optimization of the indoor air conditioning system performances and operational efficiency over time, balancing the heating and cooling exploitation.

This integrated approach not only improves the economic competitiveness of heat geoexchange systems but also contributes significantly to reducing greenhouse gas emissions and advancing the transition to a more sustainable energy model.

By exploiting the synergies between heat geoexchange maps and numerical modelling, it will be possible to enhance the efficiency and sustainability of heating and cooling systems based on GSHEs (closed-loop) or GWHEs (open-loop), providing a crucial tool for sustainable energy planning.

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