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The deeper the better? A thermogeological analysis of medium-deep borehole heat exchangers in low-enthalpy crystalline rocks

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Abstract

The energy sector is undergoing a fundamental transformation, with a significant investment in low-carbon technologies to replace fossil-based systems. In densely populated urban areas, deep boreholes offer an alternative over shallow geothermal systems, which demand extensive surface areas to attain large-scale heat production. This paper presents numerical calculations of the thermal energy that can be extracted from the medium-deep borehole heat exchangers in the low-enthalpy geothermal setting at depths ranging from 600 to 3000 m. We applied the thermogeological parameters of three locations across Finland and tested two types of coaxial borehole heat exchangers to understand better the variables that affect heat production in low-permeability crystalline rocks. For each depth, location, and heat collector type, we used a range of fluid flow rates to examine the correlation between thermal energy production and resulting outlet temperature. Our results indicate a trade-off between thermal energy production and outlet fluid temperature depending on the fluid flow rate, and that the vacuum-insulated tubing outperforms a high-density polyethylene pipe in energy and temperature production. In addition, the results suggest that the local thermogeological factors impact heat production. Maximum energy production from a 600-m-deep well achieved 170 MWh/a, increasing to 330 MWh/a from a 1000-m-deep well, 980 MWh/a from a 2-km-deep well, and up to 1880 MWh/a from a 3-km-deep well. We demonstrate that understanding the interplay of the local geology, heat exchanger materials, and fluid circulation rates is necessary to maximize the potential of medium-deep geothermal boreholes as a reliable long-term baseload energy source.

Keywords: Geothermal energy, Medium-deep, Low enthalpy, Borehole heat exchanger, Crystalline rock, COMSOL Multiphysics, Space heating

Introduction

The progressive displacement of fossil fuels by clean, affordable, and reliable energy sources requires implementation of low-carbon technologies that will meet large-scale commercial demands across all energy sectors. Renewable heat production at large scales is a challenging target for most cold climate countries, today accounting for only a minor proportion of the energy used for space heating worldwide (IEA, 2021). Whereas

countries like Finland and Denmark can provide over 50% of their space heating needs from renewables, petroleum-based sources are still taking the most significant shares of heat sectors of many nations (IRENA, 2017). Unlike the geothermal production of electricity that requires high-temperature fluids for power generation, unconventional low-enthalpy geothermal resources can provide energy to meet space and district heating applications (Jolie et al., 2021). Areas with low heat flux density have generally been overlooked in the geothermal prospecting due to their poor potential, but locally their contribution to the heating sector can be significant. Such low-temperature areas are found for example in the stable continental Archean–Precambrian settings like the Baltic Shield (Kukkonen et al., 2003), Canadian Shield (Guillou et al., 1994; Rolandone et al., 2002), the Kalahari craton in South Africa (Rudnick and Nyblade, 1999), the West African craton (Chapman and Pollack, 1974), the Western Shield of Australia (Neumann et al., 2000) and in the Siberian Craton (Duchkov, 1991).

In Finland, geothermal energy has been researched since the 1970s (Kukkonen, 2000), but the geothermal market in the Nordic countries has been dominated by the shallow geothermal energy systems (up to 300 m), mainly using borehole heat exchangers (BHEs) and ground-source heat pumps (GSHPs) to deliver space heating for single-family dwellings (Gehlin et al., 2016). In the last 10 years, the share of larger installations has been increasing, as more efficient BHEs and GSHP systems are supplying heat for offices, industrial buildings, and residential blocks (Statistics Finland, 2021). Whereas shallow geothermal wells are likely to take a good share of future heat spacing markets (IRENA, 2017), in the urban areas, the challenge of shallow geothermal heat production is the lack of available surface land area required by large BHE fields. Deeper BHEs are gaining the interest of energy companies because they use less land area and, with the use of heat pumps and the rapidly developing drilling technologies, may offer more extractable energy per area, with higher fluid temperature outcomes.

To date, there are only a few medium-deep single well geothermal boreholes in crystalline rocks in Europe. Commercial examples include two 1.5-km-deep boreholes installed to keep Oslo airport in Norway ice-free (Kvalsvik et al., 2019), and a medium-deep borehole operating in Weggis, Switzerland, which produces 220 MWh/a of heat for a residential area (Kohl et al., 2002). The highest peak power recorded for any medium-deep borehole produced near 400 kW of heat in a test of a 2-km-deep borehole in Cornwall, UK (Collins and Law, 2014). In Finland, there is one pilot 1300-m-deep well using a coaxial heat collector and five new projects are in the drilling phase across the country (Arola and Wiberg, 2022). Conversely, some commercial failures have also been reported, such as the Aachen SuperC project in Germany, which experienced several technical issues with plastic pipes, resulting in a maximum recovery temperature of 35 °C (Falcone et al., 2018).

In the scientific literature, the terms medium-deep and deep borehole heat exchanger are used interchangeably, typically corresponding to an arbitrary depth of geothermal production. For example, in China and Central Europe, the depth limit for shallow borehole heat exchangers is defined as 200 m (e.g., Pan et al., 2020; Welsch, 2019), whereas in Northern Europe, conventional shallow borehole heat exchangers can reach depths of 400 m (Korhonen et al., 2019). For medium-deep geothermal boreholes, some authors have considered the depth of 3000 m (Chen et al., 2019; Pan et al., 2020), while

others have suggested 1000 m as the deep-end boundary (Holmberg, 2016; Schulte, 2016; Welsch, 2019). Here, we use the term medium-deep to describe geothermal systems with a range of depths of 600–3000 m, based on our experience dealing with the emerging geothermal heat industry in Nordic countries. Irrespective of these depth markers, a common feature of medium-deep borehole technology is the integration of a coaxial heat collector to exchange heat from the host rock to the fluid in the borehole (Cai et al., 2019; Kohl et al., 2002, 2000; Pan et al., 2020). The BHEs are designed to extract geothermal energy from the host rock by circulating the working fluid in a well without necessarily extracting fluids from the enclosing rock formation (Renaud et al., 2019). BHE systems have been modelled analytically, semi-analytically and numerically over the past four decades, as early as Horne (1980) and Eskilson and Claesson (1988) and numerous models are reviewed by Li and Lai (2015) and Zhao et al. (2020). The advantage of the analytical models is their computational speed and that they are not limited by the softwares or licence expenses. Numerical models, on the other hand, can be easier modified to have more complex geometries and boundary conditions.

Here, we investigate the effects of geological and engineering variables on the heat outcome of medium-deep geothermal boreholes. We apply a numerical finite element method to model how the interplay of thermogeological, climatological and engineering parameters affect the geothermal well performance. The input data rely on verified measurements and best practices of energy and drilling companies. We selected three locations in different parts of Finland to estimate how their geological and climatological parameters influence the productivity of geothermal energy wells at different depths. Our work aims to answer three fundamental questions that will leverage the exploration of geothermal systems in crystalline rocks in Finland and globally: (i) How medium-deep low-enthalpy geothermal energy production is affected by the underlying geological and climatological conditions? (ii) What are the outlet temperatures of medium-deep BHE systems with increasing drilling depths compared to the production of shallow BHEs systems? and (iii) Is there a relevant performance difference between heat collector types? Although the current drilling costs are slowing down the development of the medium-deep geothermal in crystalline rocks, our resulting models will increase the likelihood of locating and designing profitable systems, scaling-up the existing low-carbon solutions for the heating sector.

Geological and geothermal setting

Finland is located in the central Fennoscandian Shield, characterized by a cold and thick (150–250 km) lithosphere (Artemieva, 2019; Grad et al., 2014; Kukkonen et al., 2003) with a mean heat flux density of $42 \pm 4 \text{ mWm}^{-2}$ (Veikkolainen and Kukkonen, 2019). The age of the crystalline bedrock varies from Archean (3100–2500 Ma) to Proterozoic (2500–1200 Ma), comprising rocks formed by multiple tectonic plate collisions and continental terrain accretions (Nironen et al., 2017). The Precambrian bedrock of Finland is covered by a continuous, thin layer of glacial and postglacial sediment deposited during the Weichselian glacial stage and the Holocene, varying in thickness from a few metres to some tens of metres (Lahermo et al., 1990; Lunkka et al., 2004). Typically, the average thermal conductivity of crystalline rocks in Finland is around $3.2 \text{ W/(m}\cdot\text{K)}$, depending mainly on their mineral composition (Peltoniemi and Kukkonen, 1995). The geothermal

gradient of Finland varies between 8 and 17 K/km and the mean annual ground temperature is controlled by climatological conditions, varying from +7 °C in Southern Finland to +1 °C in the northern parts of the country (Aalto et al., 2016).

Our study focuses on three areas across Finland: (i) Vantaa, (ii) Jyväskylä, and (iii) Rovaniemi, aiming to obtain information on the potential of medium-deep geothermal heat production in different geothermal settings in the southern, central, and northern Finland, respectively (Fig. 1). Vantaa area comprises Paleo-to-Mesoproterozoic granitoids and high-grade metamorphic rocks, much of which has experienced intense partial melting (i.e., migmatization) during the Svecofennian Orogeny (Korsman et al., 1997). Granitic rocks in Vantaa often have a high percentage of microcline minerals, conferring a potassium-rich composition and consequently high radiogenic heat production properties. However, remanent of older felsic and ultramafic rocks also occur, forming a heterogeneous crustal block (Nironen, 2005). Jyväskylä area, like Vantaa, also sets within the Svecofennian tectonic province. Most rocks in the Jyväskylä region are part of the Central Finland Granitoid Complex, a crustal block characterized by syn- and post-kinematic tonalites, granodiorites, quartz monzonites and granites that provide the lowest radiogenic heat production properties examined in this study. In contrast, Rovaniemi area is part of the Karelian tectonic province, characterized by the Central Lapland Granite Complex in the north and

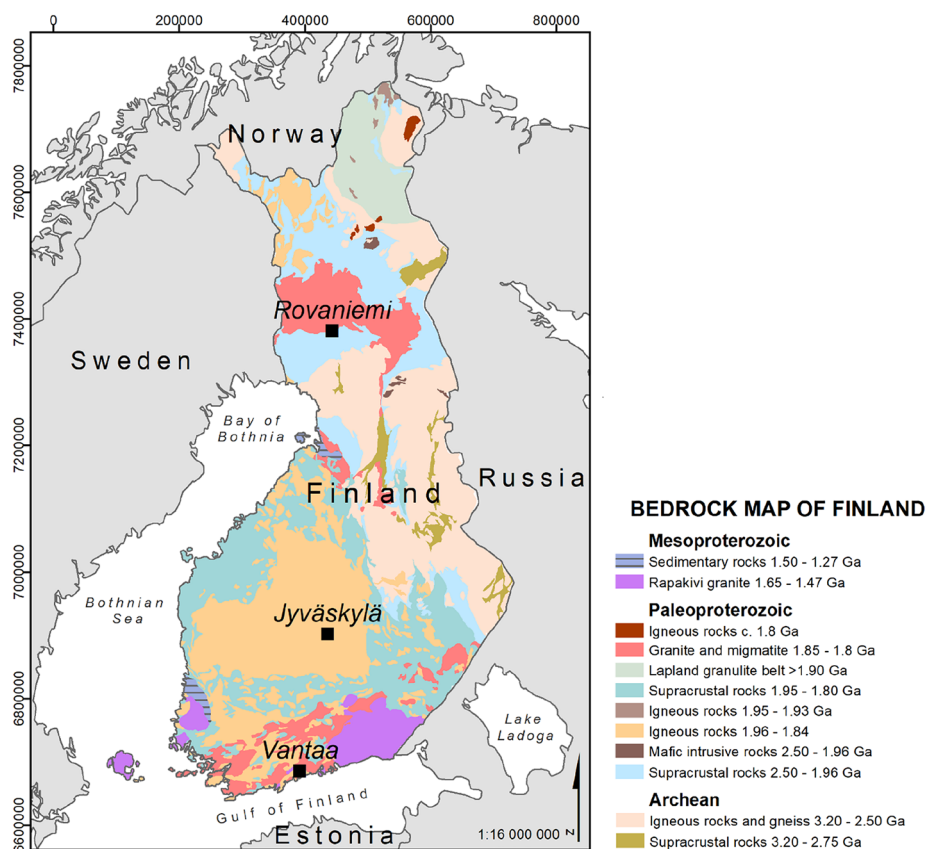


Fig. 1 Simplified geological map of Finland and the study area locations. Bedrock of Finland 1:5 000 000 © Geological Survey of Finland

by the Paleoproterozoic Peräpohja Schist Belt in the south (Nironen, 2005). Rocks in Rovaniemi have a complex interrelationship between porphyritic granites, granodiorites, gneissic inclusions and various migmatitic bodies that have relatively high radiogenic heat production properties (Nironen et al., 2017).

Materials and methods

Thermogeological parameters

To estimate the potential of medium-deep geothermal systems in Finland, we use data primarily obtained from the literature and information derived from these original datasets (Table 1). The mean annual ground temperatures (T_g) were calculated using the relationship suggested by Kukkonen (1986):

$$T_g = 0.71 \cdot T_a + 2.93, \quad (1)$$

where T_a is the mean annual air temperature for the climatological normal period 1931–1960 from the data of the Finnish Meteorological Institute (Aalto et al., 2016). The cell size of the mean annual air temperature data is 1 km². The geological map is adapted from the digital Bedrock map of Finland at the scale of 1:5 M (Fig. 1). Each lithological unit was assigned a thermal conductivity value based on laboratory measurements presented by Peltoniemi and Kukkonen (1995). Radiogenic heat production rates (A_0) were compiled from Veikkolainen and Kukkonen (2019). Radiogenic heat production rate is based on equation from Rybach (1973):

$$A_0 = \rho \cdot (9.52 \cdot c_U + 2.56 \cdot c_{Th} + 3.48 \cdot c_K) \cdot 10^{-5}, \quad (2)$$

where ρ is rock density and c the concentration of U, K and Th. Further, we estimated the geothermal heat flux from the radiogenic heat production rates described above, using Birch's law:

$$q = q_0 + DA_0, \quad (3)$$

Table 1 Thermogeological parameters of each location investigated in this study

	Vantaa	Jyväskylä	Rovaniemi	Source
Mean annual air temperature (°C)	4.51	3.38	0.89	Aalto et al., 2016
Mean annual ground temperature (°C)	6.1	5.3	3.6	Calculated from air temperatures using Eq. (1)
Rock type	Microcline granite	Granodiorite	Porphyritic granite	Digital geological map of Finland 5 M (GTK database)
Thermal conductivity of bedrock [W/(m·K)]	3.30	3.19	3.30	Peltoniemi and Kukkonen, 1995
Radiogenic heat production (μ W/m ³)	2.96	1.33	2.56	Veikkolainen and Kukkonen, 2019
Geothermal heat flux (mW/m ²)	44.5	44.0	42.8	See text for calculations
Geothermal gradient (K/km)	13.5	13.9	13.0	Calculated by dividing the geothermal heat flux density by the rock thermal conductivity

where q_0 is the reduced heat flux density (the heat flux density below the heat-producing crustal layer), D is the thickness of the heat-producing crustal layer, and A_0 is the near-surface radiogenic heat production rate (Eppelbaum et al., 2014). Veikkolainen and Kukkonen (2019) calculated the coefficients q_0 and D by fitting Eq. (3) to paleoclimatically corrected heat flux data, resulting in the reduced heat flux density of 33.79 mW/m² and the thickness of the heat-producing crustal layer of 5.919 km.

Rock density was assigned a constant value of 2725 kg/m³ based on the averaging lithology of the study areas, as constrained density calculated by Pirttijärvi et al. (2013) and specific heat capacity of the rock at each location was assigned a constant value of 728 J/kg·K based on laboratory measurements conducted on Finnish rock samples by Kukkonen (2015).

Borehole design, heat exchangers, and heat collector pipes

We modelled borehole heat exchangers of four lengths: 600, 1000, 2000, and 3000 m (Fig. 2). In the 600 m U-tube model, the working fluid was an ethanol–water mixture with 28 wt% ethanol. In the coaxial BHE models, water was used as the heat carrier fluid. The topmost 300 m of the boreholes were cased to avoid any fluid exchange with the shallow environment. Typically, crystalline rocks have low natural permeability, and the groundwater can only enter a borehole if it intersects a fracture zone. We assume that the boreholes do not intersect any permeable zones deeper than 300 m, so the deeper part of the borehole was left uncased, and the working fluid of the coaxial models was in direct contact with the rock below the casing. Casing the top part of the borehole prevents cool groundwater from entering the borehole, but the low thermal conductivity of the concrete casing acts as an insulator, so leaving most of the borehole uncased allows more efficient heat transfer between the rock and the working fluid. Fluid flow direction was set to be down the annulus and up the central pipe as optimized by, e.g., Horne (1980) and Holmberg et al. (2016). The present modelling options, including the casing procedure, are based on the suggestions and the interest of industry and companies operating in Finland.

We compared two types of collector pipes: vacuum-insulated tubing (VIT) and standard high-density polyethylene (HDPE) pipe. The most important parameter that distinguishes these two pipe types is their thermal conductivity. VIT consists of two concentric steel pipes separated from each other by vacuumed-air space. Effective thermal conductivity of 0.02 W/m·K was used for the VIT in this study (Śliwa et al., 2018; Zhou et al., 2015). As an industrial standard, HDPE pipes have a higher thermal conductivity of 0.42 W/m·K. However, HDPE is still in use because of its significantly lower price (Chen et al., 2019; Saaly et al., 2014). The efficiency of the VIT was experimentally tested in, for example, Weggis, Switzerland (Kohl et al., 2002), and HDPE pipes have been modelled by Wang et al., (2017).

For the 1- to 3-km-deep BHEs, we considered the boreholes to have a diameter of 8.5 in. (215.9 mm). The topmost 300 m of the wellbores was 12.25 in. (311 mm) in diameter and cased with 33-mm-thick cement casing. The 600-m-deep coaxial BHE was uncased, and its diameter was 160 mm. For the 600-m-deep BHEs, two diameter options for the

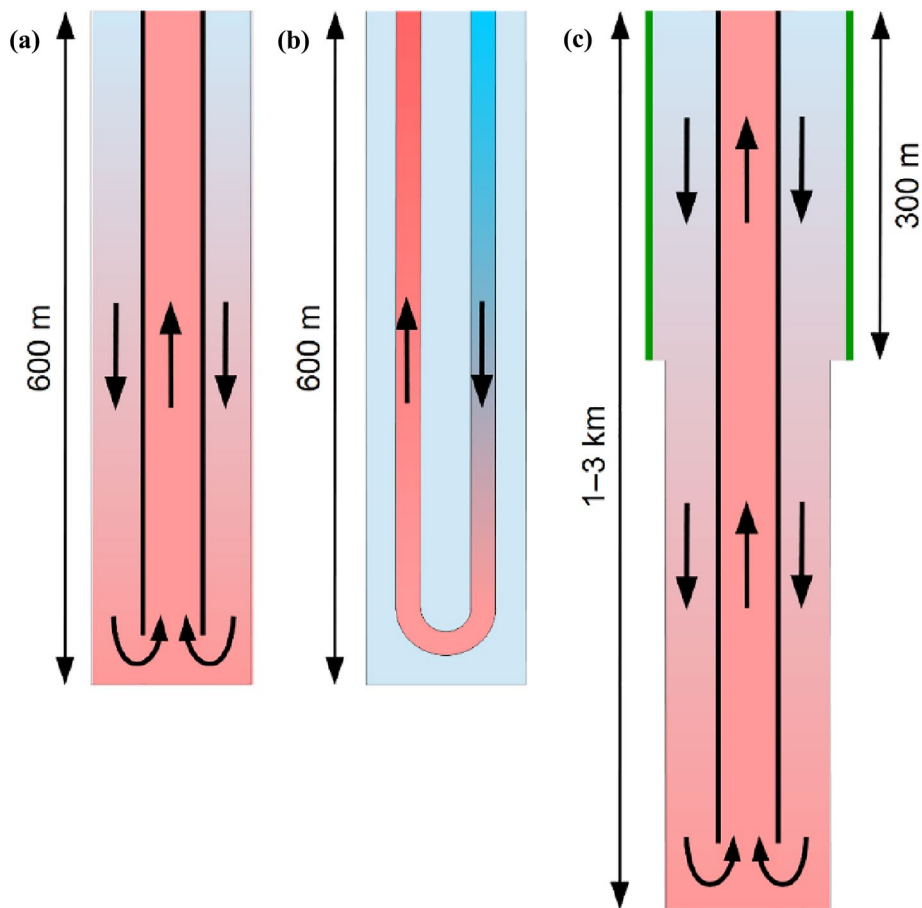


Fig. 2 The borehole heat exchangers modelled in this study. **a** A 600-m-deep open-loop coaxial borehole heat exchanger, **b** a 600-m-deep U-tube borehole heat exchanger, and **c** a 1- to 3-km-deep open-loop coaxial borehole heat exchanger with casing in the topmost 300 m (green). Arrows indicate the direction of working fluid circulation

VIT and one for the HDPE pipe were considered. As a comparison, we also modelled a standard U-tube BHE with a HDPE collector, an existing and tested BHE system. All BHE parameters were chosen based on existing or planned pilot experiments in Finland, and the parameters are summarized in Table 2.

The maximum volumetric flow rate was separately determined for each borehole depth based on the pressure loss in the well calculated with Moody friction factor approximation for smooth pipes,

$$f = \begin{cases} 0.316 \cdot Re^{-1/4} & \text{if } Re \leq 20,000 \\ 0.184 \cdot Re^{-1/5} & \text{if } Re > 20,000 \end{cases}, \tag{4}$$

where Re is the Reynolds number, calculated as $Re = uD/\nu$, where u is the mean fluid velocity in the pipe, D is the inner pipe diameter and ν is the kinematic viscosity of the fluid (Incropera and DeWitt, 1996). The pressure loss in the pipe was calculated using

$$\Delta p = \frac{fLu^2}{2D}, \tag{5}$$

Table 2 Summary of borehole heat exchanger parameters adopted in this study

1. Borehole depth (m) and type	600, U-tube	600, coaxial	1000, coaxial	2000, coaxial	3000, coaxial
2. Borehole diameter (mm)	160	160	0–300 m: 311; 300–1000 m: 215.9	0–300 m: 311; 300–2000 m: 215.9	0–300 m: 311; 300–3000 m: 215.9
3. Collector thermal conductivity [W/(m*K)]	HDPE, $k=0.42$	VIT, $k=0.02$ HDPE, $k=0.42$	VIT, $k=0.02$ HDPE, $k=0.42$	VIT, $k=0.02$ HDPE, $k=0.42$	VIT, $k=0.02$ HDPE, $k=0.42$
4. Collector inner/outer diameter (mm)	51.4/63	VIT, 50/89 VIT, 76/114 HDPE, 80/100	VIT, 76/114 HDPE, 100/120	VIT, 76/124 HDPE, 100/120	VIT, 76/124 HDPE, 100/120
5. Casing length and thickness	No	No	300 m, 33 mm	300 m, 33 mm	300 m, 33 mm
6. Flow rate (L/s)	1–3	1–3	1–5	VIT, 1–5 HDPE pipe, 2–10	VIT, 1–5 HDPE pipe, 2–10

All borehole and pipe diameter values are from the Drilling data handbook (Gabolde et al., 1999)

where L is the pipe length and u is the velocity of the fluid in the pipe. Pipe roughness and minor losses caused by velocity changes in the pipe diameter changes, well bottom, valves, etc., were considered to have little impact on the total pressure loss and consequently were not assessed in detail. The acceptable pressure drop was set as 2 bars for 1-km pipes, 4 bars for 2-km pipes and 5 bars for 3-km pipes. In the case of 600-m pipes, the increase in flow rate was dictated by temperature losses more than by pressure losses, and the maximum volumetric flow rate was therefore set to 3 L/s.

Numerical modelling

The finite element modelling and simulation platform COMSOL Multiphysics® was used to construct the models of the BHEs illustrated in Fig. 2 and to simulate their operation. The open-loop coaxial BHEs were modelled using two-dimensional axisymmetric models and the U-tube BHE was modelled using a three-dimensional model. The equation used to describe the temperature field T was

$$\rho C_p \frac{\partial T}{\partial t} - k \nabla^2 T + \rho C_p \mathbf{u} \cdot \nabla T - A_0 = 0, \tag{6}$$

where t is time, ρ is density, C_p is the specific heat capacity, k is thermal conductivity, \mathbf{u} is velocity vector, and A_0 is the radiogenic heat production rate. All models comprised domains representing the piping, working fluid, and rock, together with casing when included. Furthermore, the working fluid was assumed to instantaneously conduct heat horizontally to simulate turbulent flow.

The boundary conditions applied to the model were the surface geothermal heat flux density estimated using Birch’s law (Eq. 3) at the ground surface boundary and the reduced geothermal heat flux density at the bottom boundary of the model. Heat extraction was assumed to be constant throughout the year, which corresponded to a heat pump dropping the entering water temperature (T_{ewt}) by

$$\Delta T = \frac{E_{\text{ann}}}{H} \cdot \frac{1}{\rho C_p Q}, \tag{7}$$

where E_{ann} is the amount of heat annually extracted from the ground, H is the number of hours in a year (8760 h), rC_p is the volumetric heat capacity of the working fluid, and Q is its flow rate. Thus, the leaving water temperature was $T_{\text{lwt}} = T_{\text{ewt}} - DT$ and was imposed as a temperature boundary condition on the BHE inlet.

Solving maximal annual energy yield

COMSOL Multiphysics[®] was used to simulate 25 years of operation of the BHEs systems. A COMSOL simulation was expressed as

$$f(\boldsymbol{\theta}; E_{\text{ann}}) = T_{\text{min}}, \quad (8)$$

where f is a function that maps the vector of model parameters \mathbf{q} and annually extracted energy E_{ann} to T_{min} , which is the minimum temperature at the borehole wall at the end of the simulation. The maximal amount of thermal energy E_{max} that can be extracted annually from the ground using a BHE without dropping the borehole outer boundary temperature below the freezing point of 0 °C was determined by solving

$$E_{\text{max}} = \arg \min_{E_{\text{ann}}} |f(\boldsymbol{\theta}; E_{\text{ann}})|. \quad (9)$$

The minimization problem in Eq. (9) was solved for each location, borehole length, collector type, and volumetric fluid flow rate using MATLAB[®] and COMSOL through LiveLink[™] for MATLAB. In this study, the energy values are pure geothermal heat from the subsurface, and additional energy from running the heat pumps is not assessed. Therefore, our results provide a first-order estimation of the amount of thermal energy from each location, informing the decision-makers and investors about the options for drilling deeper in low-enthalpy crystalline settings in Finland and elsewhere.

Model validation

We validated our model with an analytical model of coaxial borehole heat exchanger of Beier et al. (2014) with a Matlab code written by Chen et al. (2019). The model calculates the transient heat conduction in the BHE and as a result, provides temperature profiles along the inner pipe, annulus and grout. The analytical model does not include parameters for the geothermal gradient, heat flux and radiogenic heat production, so for the model validation we simplified our COMSOL model to reproduce the results. We used a model with a constant temperature value of the temperature at the centre of the borehole across the entire borehole length.

Results

Energy production estimation

The energy production estimation was based on different geological and borehole designing parameters (Tables 1, 2). Our models indicate that the thermal energy yield is highest in the southernmost Vantaa area (up to 1880 MWh/a), slightly lower in central Finland Jyväskylä (up to 1830 MWh/a), and lowest in the northernmost Rovaniemi location (up to 1590 MWh/a) (Table 3). In Rovaniemi, the thermal energy yield is 15–26% lower than in Vantaa, and 13–18% lower than in Jyväskylä. In addition, the thermal energy yield of each location is directly proportional to the borehole depth. We observe

Table 3 Maximum thermal energy production (MWh/a) from three locations with VIT pipe and a flow rate of 3 L/s with a 600-m-deep well and 5L/s with well depths of 1000 m, 2000 m, and 3000 m

Well depth (m)	Vantaa (MWh/a)	Jyväskylä (MWh/a)	Rovaniemi (MWh/a)
600	170	150	125
1000	330	310	270
2000	980	950	830
3000	1880	1830	1590

that as the BHE depth increases from 600 to 1000 m, the thermal energy yield roughly doubled, nearly tripled from 1000 to 2000 m, and almost doubled when increasing the depth from 2000 to 3000 m. These results show that the BHE energy production can increase over tenfold from 600 to 3000-m-depth boreholes.

At the highest used volumetric flow rates, the energy yield does not depend on the pipe type (Fig. 3a). With 600–1000 m deep wells, the working fluid outlet temperature is 1.2–2 °C (northern to southern location) regardless of the collector type (Fig. 3b). As the borehole depth increases to 2 and 3 km, outlet temperatures attained with VIT are twice as high as those with HDPE pipes. At a depth of 3 km, the VIT temperatures achieved 8.7–10 °C, whereas HDPE pipes can only produce 4.2–5 °C, i.e., half of the VIT heat outcome. With an increase in borehole depth from 1 to 2 km, the specific heat rate increases from 31 to 35% with VIT and 30–50% with HDPE pipe, depending on the location (Fig. 3c). The specific heat rate of both collectors grows around 14–20% when the borehole depth increases from 600 m to 1 km, and 20% when the borehole depth increases from 2 to 3 km.

At the lowest modelled volumetric flow rates, the increase in the energy yield as a function of depth is linear with VIT, which rises by a factor of 1.8 between 600 m and 1 km, 2.4 between 1 and 2 km, and 1.5 between 2 and 3 km (Fig. 3d). With HDPE pipe, the energy yield remains practically the same between 600 m and 1 km, but increases by a factor of 3.3 when the borehole depth increases from 1 to 2 km, and again by only 1.2 when deepening the borehole from 2 to 3 km. Differences in the working fluid outlet temperature depending on the collector type are more evident at low flow rates. In the VIT case, the 600-m-deep well outlet temperature increases linearly from 3 to 3.9 °C (northern to southern), and, respectively, from 23 to 27 °C using a 3-km-deep borehole. With HDPE pipe, the 600-m-deep well outlet temperature increases linearly from 2.4–3 °C, and to 6.6–7.9 °C in a 3-km-deep well (Fig. 3e). With VIT, the specific heat rate increases by 7–15% between 600 m and 1 km, 13–20% between 1 and 2 km, and less than 10% between 2 and 3 km. With HDPE pipe, the specific heat rate decreases by 28–36% between 600 and 1000 m, increases 40% between 1 and 2 km, and decreases again 20% between 2 and 3 km (Fig. 3f).

Effect of thermal short-circuiting

The effects of the pipe material and fluid flow rate circulation are crucial for understanding the performance of medium-deep BHEs. We observe that a 2-km-deep well with VIT produces 980 MWh/a at highest circulation rates (5 L/s). To obtain the same amount of thermal energy, the flow rate in HDPE pipe needs to be doubled. With these

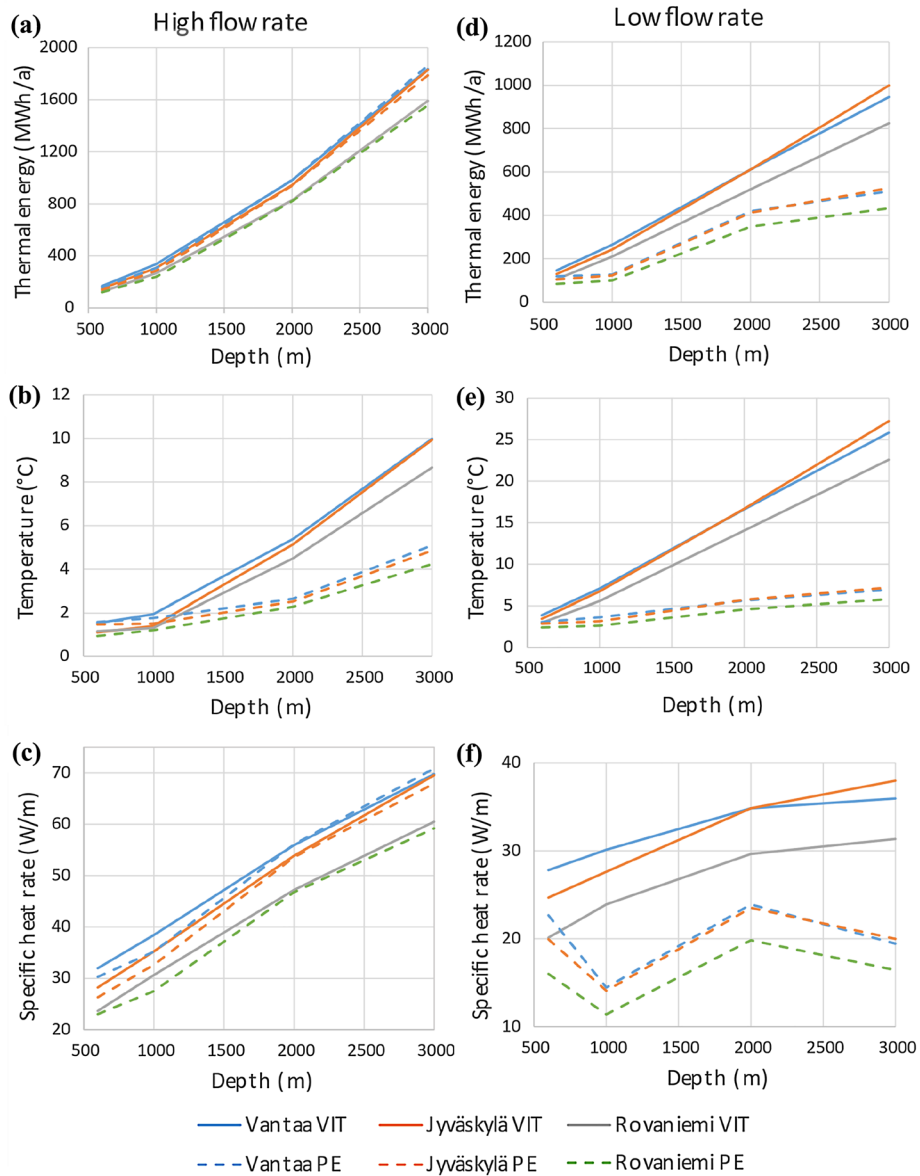


Fig. 3 Comparison of thermal energy produced by constant heat extraction over 25 years, with the outlet temperature and specific heat rate at high and low flow rates for each modelled depth, location, and two collector pipe types. The highest flow rates for VIT are 5 L/s at all pipe lengths, while for HDPE pipe they are 5 L/s at 1 km and 10 L/s at 2 km and 3 km. The lowest flow rates are 1 L/s for VIT at all pipe lengths and for 1 km of HDPE pipe, and 2 L/s for 2 km and 3 km HDPE pipe. Because flow rate is not similar in all cases, the solid and dashed lines do not represent interpolation

energy production values, VIT yields an outlet temperature of 5.4 °C, while HDPE pipe yields 2.6 °C. The vertical profiles of a 2-km-deep BHE from Vantaa from the 25-year production simulation at different flow rates are presented in Fig. 4. As a comparison, if the flow rate in HDPE pipe is lower, the temperature increases towards the bottom of the borehole and decreases again as fluid returns to the surface (Fig. 4, blue, green, and red lines). This temperature difference reflects the thermal short-circuiting effect, and the lower the volume flow is, the greater the effect. Thermal short-circuiting is observed

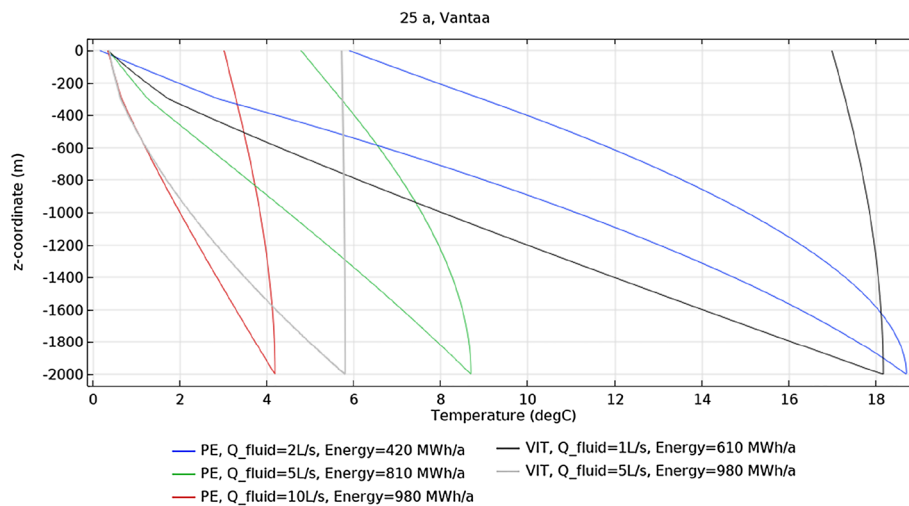


Fig. 4 Vertical temperature profiles of a 2000-m BHE with a VIT or HDPE pipe collector and different volumetric flow rates

at a much smaller scale in the vertical profile of VIT with a flow rate of 1 L/s (Fig. 4, black line), while at a high flow rate, there are practically no heat losses in the inner pipe (Fig. 4, grey line).

System efficiency as a function of production time

Our models show that the outlet temperature drastically drops during the first days of utilization of the geothermal systems, and then slowly decreases over time (Fig. 5). After one year (close-up in Fig. 5), we see that after the initial drop, temperature begins to stabilize but is still 2–5 °C higher after the first year of production than at the 25th production year. For all flow rates and collector cases, inlet temperatures drop to 0 °C after 25 years, as the model optimization parameters require.

600-m-deep wells

Parametrization of the 600-m-deep BHE was conducted with four different collector pipes, so the results for thermal energy production and the outlet temperature as a function of flow rate are presented here separately, only including results from the southernmost Vantaa area. The smaller diameter VIT pipe outperforms the other pipes in thermal energy production, regardless of the flow rate, but HDPE pipe performs better in terms of the outlet temperature at the highest flow rate of 3 L/s (Fig. 6). The thermal energy yield is low with the U-tube, but the poorest yield and lowest outlet temperature are obtained with a larger diameter VIT.

Model validation

Our results are in good agreement with the analytical solution at all times and depths. The results are presented as annual inlet and outlet temperatures of the well and vertical profiles of inner pipe and annulus. The results show that the analytical model with the same calculation parameters yields approximately 4% lower outlet temperature than the COMSOL model (Fig. 7). The solid line of the vertical profile (Fig. 7b) is analogous

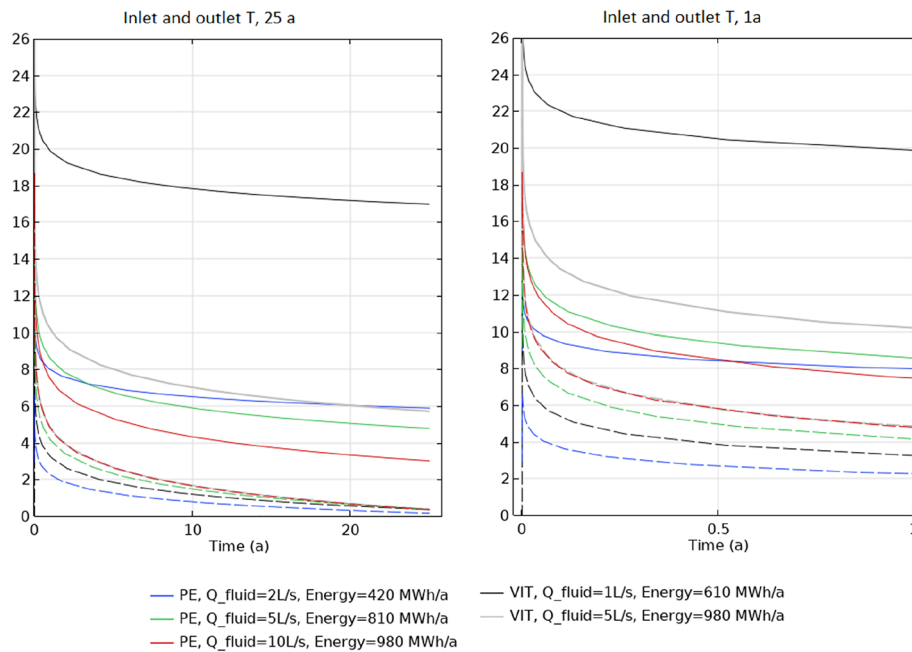


Fig. 5 Outlet (solid line) and inlet (dashed line) temperatures of a 2000-m BHE with VIT or HDPE pipe and different volumetric rates. The left figure presents temperature development over 25 years of simulation and the figure on the right is a close-up of the first year of production

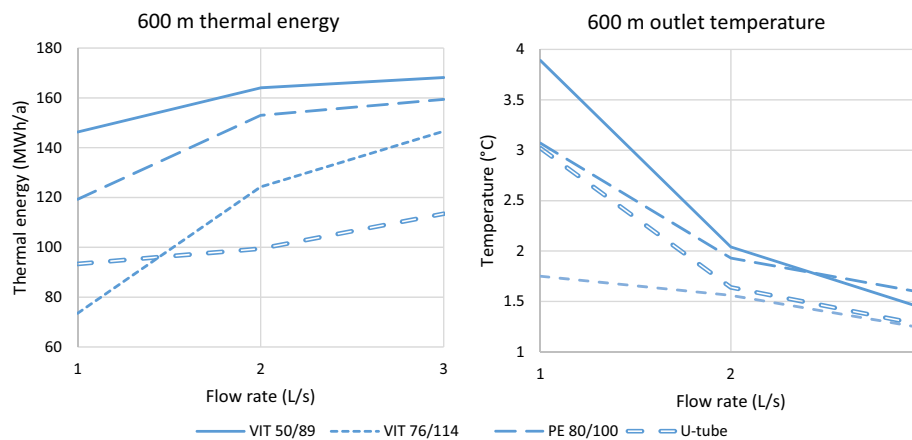


Fig. 6 Thermal energy and outlet temperature from 600-m wells as a function of flow rate with four different collectors

to the grey profile of Fig. 5. The differences in the profile shape and temperature are due to replacement of geothermal gradient value with a constant temperature, and omitting boundary heat fluxes and radiogenic heat production.

Discussion

Geological and climatological influence on geothermal production

The lowest ground temperature levels and consequently the lowest thermal energy yield is observed in Rovaniemi, the northernmost location. The highest thermal energy yield

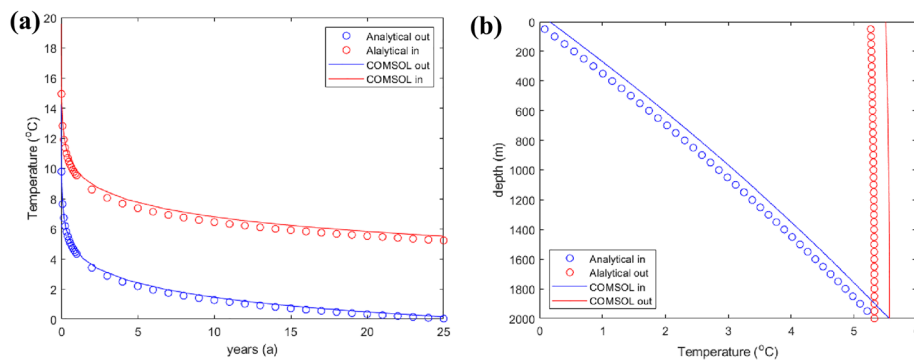


Fig. 7 Comparison of the analytical and numerical models: **a** annual inlet and outlet temperatures and **b** vertical temperature profile from the 25th production year. Both results are of a 2000 m BHE with a VIT collector

is observed in the southernmost location, Vantaa, as a result of the three factors: the highest ground surface temperature, high geothermal heat flux density, and high radiogenic heat production values due to the presence of microcline granites. The geothermal gradient in Jyväskylä is higher than in the two other locations due to the lower thermal conductivity and radiogenic heat production, so in both Jyväskylä and Vantaa, the temperature reaches 13.4 °C at a depth of 600 m, while at greater depths, the temperature is higher in Jyväskylä than in Vantaa. Regardless of the higher geothermal gradient in Jyväskylä, the outlet temperatures and thermal energy yield are mainly lower than in Vantaa. This difference in outlet temperature is attributed to the lower thermal conductivity of the granodiorite than microcline granite and consequently less efficient heat exchange between the host rock and the fluid.

Compared to other locations where deep geothermal wells have been drilled or modelled, Finland typically has lower heat flow and geothermal gradient, and therefore our models generally result in either lower outlet temperatures or thermal power. Chen et al. (2019) modelled a 2.6-km borehole in the “standard” and “elevated” geothermal gradient of 30 and 40 K/km, respectively, and their models resulted in a specific heat rate of 125–200 W/m. Correspondingly, our specific rates for a geothermal gradient of 13–14 K/km are 50 W/m for a 2-km well and 70 W/m for a 3-km well—approximately 0.4 times of the values reported by Chen et al. (2019). The simulated values of 886–1129 MWh/a for the 2.1-km-deep well in Weggis, Switzerland (Kohl et al., 2002) correlate with our results for a 2-km-deep borehole. In Weggis, the temperature recorded at the bottom of the 2.3-km-deep well was 73 °C (Kohl et al., 2002), which is roughly double than that in Jyväskylä, but their simulated energy yield values correlate with our results because the volumetric flow rate used in Weggis was lower than in our study.

As a conclusion, we observe that initial ground surface temperature and consequently the geothermal gradient have a significant impact on geothermal energy yield, while thermal conductivity of the local rock type has a more complex impact that depends on the production properties such as fluid flow rate. This is apparent from the comparison of the results obtained in thermogeological settings of Switzerland and Finland, as well as from the results of our study comparing thermogeological variations across Finland. Another essential finding is that, as the borehole depth increases from 600 to 1000 m,

the thermal energy yield roughly doubled, nearly tripled from 1000 to 2000 m, and almost doubled when increasing the depth from 2000 to 3000 m.

Collector type and flow rate

Our models suggest that the efficient insulation of VIT pipes result in the thermal energy production comparable with HDPE pipes with a larger hydraulic diameter and consequently higher flow rates (Fig. 3, Table 2). This relationship between flow rate and types of pipes is an essential finding if we consider that HDPE pipe is significantly lower in price than VIT. However, the fluid temperatures produced with HDPE pipe are relatively low at all flow rates and borehole lengths due to the thermal short-circuiting effect, being at their highest around 8 °C from a 3-km-deep well at a low volumetric flow rate (2 L/s). On the other hand, fluid outlet temperatures produced with VIT at low flow rates are 2.5–3 times higher than temperatures produced with either HDPE pipe or VIT with high flow rates.

The results of this study are similar to those in previous publications based on medium-deep wells in Nordic countries. Holmberg (2016) observed that borehole depth significantly affects the heating power, with the yield increasing by eightfold when borehole length was increased from 300 to 900 m. The power produced from a 600-m-deep well was on average 30 kW and that from a 1000-m-deep well was on average 65 kW (Holmberg, 2016), corresponding to 263 MWh/a and 569 MWh/a, respectively. In addition, the energy yield from a reference 2-km-deep borehole was 1 GWh/a over 25 years (Lund, 2019). We estimate that the energy yields presented in Holmberg (2016) are higher due to the short simulation time of 5000 h (208 days). When heat outtake is optimized for a more extended period, less annual heat production is expected. This reduction in extractable heat as a function of time was demonstrated by Lund (2019), in which energy extracted during the first 5 years was 1.2 GWh/a, dropping to 1 GWh/a when averaged over 25 years. The main reason for the higher yield in the latter case is the higher volumetric flow rate.

We arrive at the same conclusion as Nalla et al. (2005) that either the thermal power production or the outlet temperature of working fluid can be individually maximized. Alternatively, they can be simultaneously optimized so that reasonable temperatures for heat pump(s) as well as a reasonable heat production rate can be expected, as suggested by Horne (1980). The slower the fluid flows in the borehole, the higher temperature can be achieved, although less heat can be extracted, as observed by Acuña (2013). This effect is apparent in all the HDPE pipe results: the outlet temperature is generally lower and does not decrease as drastically with an increase in flow rate compared with VIT. Besides the correct flow rate parametrization and efficient insulation of the heat collector, the selection of suitable BHE parameters are essential features of coaxial collectors in the geothermal systems (Horne, 1980; Pan et al., 2020).

Comparison of medium-deep and shallow geothermal energy utilization

A common misconception of medium-deep wells is that they can produce long-term heating with high working fluid temperatures. Our models show that fluid outlet temperatures from 2 km boreholes can be up to 17 °C and from 3 km boreholes up to 27 °C (Fig. 3e). In Finland, the typical outlet temperature from conventional shallow

geothermal wells is around 0–4 °C (Korhonen et al., 2019), depending on the location and subsurface properties. In such small-scale closed-loop systems, the ethanol-based heat carrier fluid heats up by 1°–3° on average during heat extraction. By drilling deeper, we reach higher ground temperature levels, and the heat carrier fluid is consequently expected to warm up more. The advantages sought from medium-deep wells over shallow geothermal wells are related to two scenarios: (1) maximizing heat production with high flow rates and lower ground area requirements compared with conventional BHE fields; or (2) obtaining a higher return fluid temperature with low flow rates, which allows heat production coupled with a heat pump having good efficiency and thus heat distribution at a higher temperature than conventional BHE systems.

Related to the first scenario, we can subsequently compare the specific heat rate between medium-deep and shallow boreholes from the potential of shallow geothermal energy reported by Arola et al. (2019). According to a shallow geothermal energy potential dataset produced by the Geological Survey of Finland, a single 300-m-deep borehole has a constant thermal power of 7632 W (25 W/m) in Vantaa, 5887 W (20 W/m) in Jyväskylä and 5320 W (18 W/m) in Rovaniemi. A 1-km-deep borehole with VIT at a high flow rate can produce a specific heat rate of 30–38 W/m, while the respective figures for a 2- and 3-km-deep borehole are 47–56 W/m and 60–70 W/m (Fig. 3). The achievable specific heat rate of a medium-deep borehole is therefore higher than what can be extracted from the conventional shallow BHE systems, but this is predominantly valid at high flow rates. At low flow rates, the increase in the specific heat rate is smaller. With HDPE pipe, the specific heat rate is highest with 2-km-deep wells, where it is between 20 and 25 W/m, thus corresponding to the energy extractable from conventional shallow systems. With 1- and 3-km-deep wells, the specific heat rate is lower than conventional shallow systems. When comparing the specific heat rates between medium-deep and shallow boreholes, one must bear in mind that in shallow closed-loop systems, U-tubes are the dominant technology, and the volumetric flow rates are lower.

Further considerations

Considering the temperature levels presented in this study, a heat pump is needed to raise the resulting temperature to the level required by the property or district heating system. District heating can be realized as low-temperature heating, to which medium-deep geothermal energy is well suited (Schmidt et al., 2017). A constant energy outtake was chosen to calculate the baseload that geothermal heat could provide, but intermittent energy outtake could provide a higher peak power (e.g., Kohl et al., 2002), while the recharging of wells with, for example, waste or solar heat could not only provide a higher yield, but also prolong the well lifetime. Therefore, further optimization of any geothermal system should be done taking into considerations case-specific characteristics, such as the end use (local or district heating), required peak power and availability of rechargeable heat.

Questions that must be investigated in further work include a sensitivity study on a wider range of subsurface properties and BHE parameters, such as borehole and collector dimensions and the impact of different casing materials. Moreover, the surface infrastructure is a factor that guides the parameter choices. The parameters for the present study were purely based on the geographical location and pipe parameters used in

pilot projects or considered as industrial alternatives presently available in the market. The next step is to validate the model results with pilot projects in suitable geological conditions.

Besides the highest thermal energy yield and highest possible production temperature, the CAPEX and OPEX costs of medium-deep geothermal systems are another essential factor to consider among stakeholders. Most essentially, the installation and drilling costs of deeper boreholes are significantly higher, as the costs do not increase linearly and possible risks for complications along the borehole increase with depth (Gehlin et al., 2016). However, the drilling technology is a rapidly developing field and technological innovations can bring the price down in the future. While VIT outperforms HDPE pipes in temperature production and the economics depend on the delivered temperature level (Gehlin et al., 2016) and pumping costs, it might still be more cost-effective to use HDPE or new innovative material solutions in the collector pipe. More detailed cost information may help estimate the amount of governmental financial support possibly needed to enable the geothermal industry to replace heating with fossil fuels with geothermal heat.

Furthermore, an important task is to assess the accuracy of a model that only considers conductive heat transfer in the rock matrix, because it is likely that a well will intersect fracture zones that will impact heat transfer in the formation and consequently in the borehole. Lastly, it is important to examine whether a seismic risk or other environmental risks are posed when installing medium-deep geothermal systems.

Conclusions

Exploration and production of medium-deep geothermal systems can significantly accelerate the transition away from fossil fuels by providing a clean and reliable energy source for residential and industrial heating. The results of this study indicate that: (1) the deeper the borehole is, the better is its thermal energy production and specific heat rate; (2) the higher the subsurface temperature, the better is the energy yield, when considering minor variations in thermogeological parameters; (3) VIT outperforms HDPE pipe in terms of energy and temperature production, and (4) with an increasing flow rate, we obtain more thermal energy but a significantly lower outlet fluid temperature. All these variables should be taken into consideration during the design and operation phases of medium-deep geothermal systems.

Our results indicate that drilling deep (from 600 to 3000 m) in low-enthalpy crystalline rocks can increase the yield of geothermal boreholes by one order of magnitude. This is a substantial increase in the energy yield in these low-temperature areas, and could help to offset the burning of fossil fuels in the unconventional low-temperature geothermal systems in the district heating sector. Compared to the shallow geothermal BHEs, medium-deep geothermal systems offer higher fluid outlet temperature that enables a higher coefficient of performance (COP) with a heat pump. Another advantage of deeper geothermal systems is that in densely populated areas, fewer wells will be needed to supply the same amount of heat, consequently having a smaller land surface impact than shallow geothermal systems. However, the current upfront cost of drilling can prevent the full expansion of this technology. Nevertheless, our results show that understanding the interplay of thermogeological and

engineering parameters is critical to up-scale sustainable low-carbon geothermal systems in Finland and in the areas where low-permeability crystalline rocks and low heat flow dominate the geological setting.

List of symbols

Roman letters

A	Radiogenic heat production (W/m^3)
C_p	Specific heat capacity at constant pressure [$\text{J}/(\text{kg}\cdot\text{K})$]
c	Concentration (ppm/‰)
D	Thickness (m)
E	Energy (MWh)
f	Moody friction factor (dimensionless)
H	Number of hours in a year (dimensionless)
k	Thermal conductivity [$\text{W}/(\text{m}\cdot\text{K})$]
L	Length (m)
p	Pressure (Pa)
q	Geothermal heat flux density (W/m^2)
Q	Volumetric flow rate (L/s)
Re	Reynolds number (dimensionless)
t	Time (s)
T	Temperature ($^{\circ}\text{C}$)
u	Velocity (m/s)
z	Depth (m)

Greek letters

ρ	Density (kg/m^3)
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Subscripts

a	Air
ann	Annual
g	Ground
in	Inlet
K	Potassium
max	Maximum
min	Minimum
out	Outlet
Th	Thorium
U	Uranium
0	Initial

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Author contributions

KP created the COMSOL model, ran necessary computations and wrote the sections on borehole parameters, results, and co-wrote the introduction, discussion, and conclusion sections. AM wrote the sections on geology and co-wrote discussion and conclusion sections. KK wrote the sections on numerical modelling and solving for maximum annual energy yield, created the initial Matlab code applied in this study and worked on the model validation. SV and NL co-wrote the introduction and made valuable comments on the manuscript. TA and AB supervised the work and made valuable comments on the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials

The datasets used and/or analysed during the current study are available from the corresponding author on request.

Declarations

Competing interests

The authors declare that they have no competing interests.

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