FleXible user-CEntric Energy poSitive houseS

Deliverable 2.2: Design principles and test result of deep borehole collector

LC-EEB-03-2019

New developments in plus energy houses (IA),

Proposal No. 870157

Title	Document Version
D2.2 Design principles and test result of deep borehole collector	1.0

Project Number	Project Acronym	Project Title
H2020-870157	EXCESS	FleXible user-CEntric Energy poSitive houseS

Contractual Delivery Date	Actual Delivery Date	Deliverable Type*-Security**
November 2020	November 2020	R-PU

*Type: P: Prototype; R: Report; D: Demonstrator; O: Other.

Security Class: PU: Public; PP: Restricted to other programme participants (including the Commission); RE: Restricted to a group defined by the consortium (including the Commission); CO: **Confidential, only for members of the consortium (including the Commission).

Responsible	Organisation	Contributing WP
Adib Kalantar, Ph.D.	MuoviTech	WP2

Abstract
This report discusses design principles of deep drilling solutions and borehole collector technology. The work explores deep drilling solutions and borehole collector technology aiming at transferring the experiences of experimental deep drilling to business as usual procedure in the built environment. The report also reviews the methods and procedure for improving the economy of drilling, considering air and water-based drilling methods, and combination of these. The report addresses the identification of the most viable, reliable, cost-efficient methods and drilling technologies to drill deeper than current boreholes in densely built urban areas. The risk management procedures for tackling rock quality and installation of the coaxial collector are discussed, based on the large experience gained on the field in the recent years. The suggested collector is a closed loop coaxial collector, and among the advantages of using coaxial heat exchangers, reduced pressure loss compared to U-pipes is one of the most significant. The thermal performance is also improved respect to the U-pipe collectors, having a more balanced heat exchange of the fluid coming downwards and bedrock. The analytical approach was used to evaluate the hourly thermal loads for the Finnish demo site, for the fluid return temperature from the ground for 30 years of operation. The final performance evaluation of the borehole and collector integrated with heat pump, solar PVT panels and building energy systems will be done in the later phase in WP4; PEB implementation and monitoring.

Keywords
Positive Energy Buildings; PEBs; deep borehole drilling; drilling technologies; coaxial collector; multi source heat pump; ground heat exchangers

Revision	Date	Description	Author (Organisation)
V0.1	09.06.2020	*Report planning and writing*	Adib Kalantar (CTO MuoviTech group) with contribution from Mr. Ismo Heimonen (VTT)
V0.2	05.11.2020	*Manuscript to internal review*	Adib Kalantar, Ph.D., (CTO MuoviTech group) with contribution from Mr. Mika Manner (TAS) and Mr. Ismo Heimonen (VTT)
V1.0	27.11.2020	*Full report for coordinator and shared with interviewees*	Adib Kalantar, Ph.D., (CTO MuoviTech group) with contribution from and Mr. Ismo Heimonen (VTT)

This project has received funding from the
European Union's Horizon 2020 Research and Innovation Programme
under Grant Agreement № 870157.
More information available at https://positive-energy-buildings.eu/

EXECUTIVE SUMMARY

This report discusses the design principles of deep drilling solutions and borehole collector technology. The report is based on the study in the EXCESS (FleXible user-CEntric Energy poSitive houseS) project. Work Package 2 focuses on adjustments and integration of the technologies we aim to test in EXCESS and includes six Tasks. The Task 2.2 is focused on deep borehole development. This task explores deep drilling solutions and borehole collector technology aiming at transferring the experiences of experimental deep drilling to business as usual procedure in the built environment. This part of the project is dived into two subtasks:

- ✓ Deep drilling solutions and technology for the built environment
- ✓ Deep borehole heat exchangers.

The first part reviews the methods and procedure for improving the economy of drilling methods, considering air and water-based drilling methods, and a combination of both. Section 2 describes the methods and technologies for semi-deep borehole drilling exceeding the current typical drilling depth of 300-400 m. The target is to find out which method and technology, which tools and machines as well as which potential drilling operator will produce the desired effect, the semi-deep boreholes for the Finnish demo PEB building in Kalasatama, Helsinki. The desired outcome has to be achieved within a reasonable cost, and preferably with a competitive cost structure in comparison to the existing and proven methods. Such end result is expected to be replicable throughout the Nordic Climate cities, where hard crystalline rock, such as granite as primary bedrock material, is common in many places. The risk management procedures for tackling rock quality and installation of the coaxial collector are discussed, based on the large experience gained on the field in the recent years.

Section 3 of this report deals with deep borehole collectors where the coaxial collector is introduced. The study investigated the temperature range of the working fluid due to the thermal gradient effect in the ground, PVT ground recharge and multisource heat pump operations (cooling load supply and active recharging of the ground increases the fluid temperature causing degradation of commonly used ground collector materials) for selecting appropriate materials for the collector. The suggested collector is a closed loop coaxial collector, and the material properties and impact of the heat transfer fluid have been investigated to improve the thermal performance of the solution. Among the advantages of using coaxial heat exchangers, reduced pressure loss compared to single U-pipes or double U-pipes is one of the most significant. In addition, a closer contact with the borehole wall may lead to lower borehole thermal resistances. However, it must be considered that the coaxial configuration still faces considerable challenges mainly in the installation phases compared to the U-pipe heat exchanger. The requirement of placing the outer pipe as close as possible to the borehole wall sometimes leads to difficulties when the borehole is not exactly vertical but inclined, causing it getting stuck in these areas.

The validated novel borehole collector will be implemented in the PEB demonstration as a Case Study in Nordic Climate, located at Kalasatama, Helsinki in Finland. The final performance evaluation of the borehole and collector integrated with the heat pump, solar PVT panels and building energy systems (space heating, domestic hot water DHW, ventilation) will be carried out in a later phase in WP4 PEB implementation and monitoring, as discussed in the section 4 of this report.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

TERMINOLOGY

BHE	Borehole heat exchanger
COP	Coefficient of performance
DTH	Down-the-hole drill/hammer
EED	Earth energy designer
GHE	Ground heat exchanger
GSHP	Ground source heat pump
PEB	Positive energy building
PV	Photovoltaic solar panel
PVT	Combined photovoltaic and thermal solar panel
ROP	Rate of progress

NOMENCLATURE

Symbol

C	Specific heat capacity [J/kg K]
D_h	Hydraulic diameter [m]
f	Friction factor [-]
h	Heat transfer coefficient [W/m^2 K]
k	Thermal conductivity [W/m K]
ΔP	Pressure drop [Pa]
r_1	Coaxial collector inner radius [m]
r_2	Coaxial collector outer radius [m]
r	Radius [m]
R	Thermal resistance [K m/W]
T	Temperature [K]
ν	Velocity [m/s]
ρ	Density [kg/m^3]
Re	Reynolds number [-]
Q	Volumetric flow rate [m^3/s]

1 INTRODUCTION

Following the Paris Agreement in December 12, 2015, most countries have already accepted plans to contribute to the reduction of the greenhouse gas emissions. Based on this road map, all new buildings in the European Union shall be nearly zero energy buildings (nZEB) by the year 2021 and globally, the concept of the net zero energy buildings should be implemented between 2020 and 2030. According to the EXCESS (FleXible user-CEntric Energy poSitive houseS) project, the next step solution would be positive energy buildings (PEB) and districts as an energy efficient building that produces more energy than it uses via renewable sources. [8] To achieve the set goals, sustainable energy production systems which mainly rely on renewable energy combined with energy efficiency must be implemented. Renewable energies could come from various energy sources such as wind, solar power, geothermal energy, waves, biomass, or hydropower.

Geothermal energy has a unique position among the renewable energy resources. In fact, we live right on top of the most affordable, sustainable and comfortable energy source on earth thanks to earth's relatively constant underground temperature. Therefore ground can be used as a heat source during the winter and as a heat sink during the summer to capture or dissipate heat from or into the rock.

Usually there are two ways of upscaling ground source heat pump systems installations, either by increasing the number of boreholes or by increasing the depths of the boreholes. Whereas the first alternative needs additional surface area, the deeper boreholes (beyond 600 m), which are more challenging than the conventional boreholes, can be applied when there is a lack of space, e.g. in dense living areas. The challenge of geothermal energy industry is to develop the geothermal systems integrated with other renewable energy sources, towards hybrid energy systems, and develop deeper borehole solutions requiring less space in dense built areas. For these solutions the development of the economic drilling and high performance geothermal collectors is needed.

Therefore, this study contributes to the design principles of deep drilling solutions and borehole collector technology. The report is based on the studies made in the EXCESS project. Work Package 2 focuses on adjustments and integration of the technologies we aim to test in EXCESS and includes six Tasks. The Task 2.2 is focused on deep borehole development. This task explores deep drilling solutions and borehole collector technology aiming at transferring the experiences of experimental deep drilling to a business as usual procedure in the built environment. This part of the project is dived into two subtasks:

- Deep drilling solutions and technology for the built environment
- Deep borehole heat exchangers.

The Finnish pilot in the EXCESS project in Kalasatama, Helsinki, is a typical example of a new city residential building project. The building plot is too small to facilitate a sufficient number of conventional 300 m deep boreholes with large enough distances between them, to prevent them affecting each other’s available thermal energy. Therefore, the need for deeper boreholes is highlighted.

1.1 Path/roadmap of WP2 results towards WP4 demo

The results from Task 2.2 (ST2.2.1 Deep drilling solutions and technology for the built environment and ST2.2.2 Deep borehole collectors) will be applied to the Finnish demo (WP4), the planned PEB house in Kalasatama, Helsinki. ST2.2.1 results define a reliable way to achieve a suitable drilling method and closely connect the results from ST2.2.2 collector development.

The required borehole depth and the number of boreholes, collector installation technique to the borehole development, are discusssed in order to come up with the desired end result: a well-functioning borehole plus collector combination to produce the sufficient heat energy for the pilot PEB building GSHPs as well as to function as a heat sink for the summertime excess heat energy. For the borehole to function these both ways, a collector with good thermal connection to the bedrock is required.

2 DEEP DRILLING SOLUTIONS AND TECHNOLOGY

2.1 Introduction to borehole systems

In the beginning, Ground Source Heat Pump (GSHP) systems were dominantly applied in single family homes and later in attached houses. However, in recent years, a very strong trend has been observed towards GSHPs in city areas. The challenge is to find technical solutions for GSHP systems in densely built city areas for multi-story buildings. This has brought along new requirements and has also exposed the need to further develop the proven GSHP installations to suit better to the new city environment. Primarily the need is to develop deeper borehole solutions for geothermal heat pump thermal energy collectors, as more heat energy is required, and less plot surface is available for them.

Drilling of boreholes in previously mentioned market segments has been ongoing for approximately the past 40 years. The progress in the methods and technology has been gradual and relatively slow, as no completely revolutionizing technologies and methods have emerged.

There has been gradual and continuous progress towards more efficient and productive processes and tools during Tom Allen Senera's company history. GSHP borehole efficiency has increased gradually, as more powerful and durable tools have become available. The dominant method is and has been throughout GSHP borehole drilling history "Down The Hole" (DTH) air hammers, which is shortly described as follows:

A down-the-hole drill (known as DTH by most professionals) is basically a mini jackhammer screwed on the bottom of a drill string. The fast hammer action breaks hard rock into small flakes and dust and is blown clear by the air exhaust from the DTH hammer. The DTH hammer is one of the fastest ways to drill hard rock. In DTH drilling, the percussion mechanism – commonly called the hammer – is located directly behind the drill bit. The drill pipes transmit the necessary feed force and rotation to hammer and bit plus compressed air or fluids for the hammer and flushing of cuttings. The extension pipes are added to the drill string successively behind the hammer as the drilling proceeds. The piston strikes the impact surface of the bit directly, while the hammer casing gives straight and stable guidance of the drill bit. This means that the impact energy does not have to pass through any joints at all. The impact energy therefore is not lost in joints allowing for much deeper percussion drilling. This is a great breakthrough for smaller portable water well drilling rigs, that before were limited. The DTH on smaller rigs now can provide comparable results with large heavy truck rigs. With recent advances in technology, DTH hammers and bits can now be operated to run at up to 35 bar, increasing the penetration speed (Source https://en.wikipedia.org/wiki/Down-the-hole_drill)[1]

Figure 1 illustrates the cross section of an air DTH hammer and bit (sometimes called crown) and the essential parts.[2]

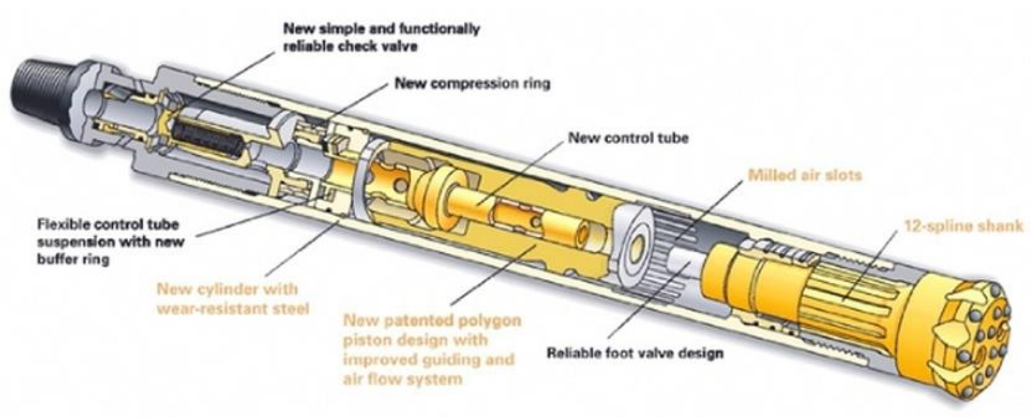

Figure 1 The cross section of an air DTH hammer and bit (sometimes called crown) and the essential parts

In order to drill boreholes for GSHP thermal energy collectors, a whole set of equipment is needed to run the DTH hammer. There needs to be a truck to transport the drilling air compressor and the drilling unit to the site, as well as a dust and cuttings collection container to prevent the environment from spreading the rock dust and particles. In city areas also an additional separation container is needed to let settle rock dust from the water coming from the borehole before allowing the water to flow into the municipal rainwater system. Only limited quantities of rock particles in the water is allowed in the rainwater system, thus constituting an important limiting factor for specifying the optimum drilling method. This requirement has emerged in Finland during the past few years as drilling has become more common in city areas.

Figure 2 presents the typical drilling equipment arriving at the drill site. The drilling unit is lowered from the truck (on the left), which is also carrying the compressor for drilling air. The drilling unit, with mast vertically (on the right), is drilling the GSHP collector borehole.[3]

Figure 2 Typical drilling equipment arriving at the drill site

Within the past 10 years, the efficiency of the borehole drilling process has improved due to the increased use of more powerful 35 bar air compressors. Previously the compressors ranged from 20 to 30 bar. The higher pressure allows drilling to proceed to approximately 300 m depth in conditions where there is some groundwater entering the borehole from the cracks in the bedrock. More powerful compressors have the drawback of increased energy consumption: Water entering into the borehole causes hydrostatic pressure outside of the drilling shaft, which creates the problem of air not exiting from the DTH hammer fast enough, therefore reducing the drilling speed and efficiency. In order to compensate this, the need to run the hammer at higher air pressure and volume emerged, causing a remarkable increase in the consumption of diesel oil powering the air compressor. This is of importance, since a typical 300 m borehole drilling can consume up to 1000 liters of diesel oil, thus exceeding a 10 % share of the total cost.

Another advancement in borehole production efficiency is the borehole diameter reduction from the previously prevalent 140 mm (5,5 inch) standard to the current 115 mm (4,5 inch) standard. This has reduced the quantity of crushed rock material by approx. 33 %, reducing the material and energy cost, as well as costs for transporting and discharging the rock material.

The most recent developments include also the new 45 mm single U pipe collector developed by MuoviTech to reduce the pressure loss in the ground heat exchangers. This collector can be installed in the smaller and more efficient drill of 115 mm boreholes, allowing the GSHP to run on boreholes exceeding the ‘standard’ depth of 300 m, to the approximate maximum depth of 350 m.

The current efficient drilling depth of 300 m allows the GSHP to be used in the majority of the attached houses. It also allows the GSHPs to be used in multi-story houses, where there is the exhaust air heat recovery option available as an additional heat source for the GSHP, thus constituting a hybrid system. In some city areas, where the typical 1970s houses with exhaust air fans exist, it is common practice to build systems combining GSHP boreholes with liquid based exhaust air heat recovery. The same heat carrier fluid can run through the boreholes and exhaust air heat recovery unit. The standard practice applied by TAS is to charge the ground with the excessive summertime heat form the exhaust air heat recovery units.

There are many multi-story houses in city areas where there is lack of sufficient space for drilling the required number of boreholes and no exhaust air heat recovery from buildings is available to be used as an additional source of heat energy. These two reasons are currently greatly limiting the use of GSHPs in densely built city areas, as well as in buildings with large heating energy needs. Therefore, there is a pressing need for drilling deeper boreholes to extract more energy from the bedrock in plots with limited available surface.

The Finnish pilot in the EXCESS project in Kalasatama, Helsinki, is a typical example of a new city residential building project. The building plot is too small to facilitate a sufficient number of conventional 300 m deep boreholes with large enough distances between them, to prevent them affecting each other’s available thermal energy. The building will be equipped with central mechanical supply/exhaust ventilation including efficient air to air heat recovery, thus there is very limited amount of remaining excess heat in exhaust air available to charge the boreholes. Therefore, the need for deeper boreholes is highlighted.

2.2 Research challenges and methodology for drilling methods research

The research challenge is to identify the most viable, reliable and cost-efficient methods and drilling technologies to drill deeper than existing / current boreholes in densely built urban areas. In order for deeper boreholes to become more common, the new drilling method and technology has to be:

1. Safe to the drill operator
2. Easy to operate, not needing highly specialized and trained work force
3. Safe to surrounding area and inhabitants
4. Reliable in capacity to drill the required depth
5. Applicable to various hard rock qualities and bedrock deviations
6. Allow predictable outcome and replication
7. An environmental friendly process
8. Not requiring exceptional water handling capacities
9. Efficient in time consumption
10. Efficient in fuel / energy consumption
11. Generally cost effective not requiring too many non-standard tools
12. Allow the easy installation of the thermal energy collector in the borehole

GSHP Borehole drilling beyond 300 m has not been investigated to a large extent due to the drilling operations being heavily operations based. Drilling companies receive their revenue mostly from the meters drilled and U-type collectors installed. Typically, the drilling companies acquire the air compressor technology from large compressor and drilling technology companies like Atlas Copco, the drilling units from manufacturers like Comacchio and the drilling tools like DTH hammers and bits (also called drill crowns) from the corresponding suppliers. Thereafter it is up to the drilling companies to run the drilling operations as efficiently as possible with components available on the market. Most of the information considering drilling efficiency and costs involved is not available from research papers, but from the drilling companies conducting the practical operations.

The primary method of this research is based on conducting analysis of the available research papers on drilling efficiency on hard, crystalline rock and interviewing the most professional and experienced drilling operators and individuals in the Nordic / Finnish market. An overview of the interviewed persons:

1. Tom Allen, GSHP borehole drilling experience starting from year 1991, has performed experimental drilling pilot projects, the latest for Rototec, the leading borehole drilling operator in the Nordic market.
2. Mikko Ojanne, development director, former CEO and founder of Rototec, the leading Northern European drilling contractor.
3. Christian Savela, CEO of ST1 GSHP solutions business. Currently St1 is the only provider of boreholes exceeding 500 m in the Nordic market (according to TAS knowledge). St1 has performed several borehole deliveries exceeding 500 m in depth.
4. Christian Sarkala, GSHP expert and former CEO of Tom Allen Oy

In addition to the review of research papers and expert interviews, a thorough examination of the Internet searches has resulted in a multitude of tool and method descriptions from drilling tool and machine manufactures such as:

- Epiroc (former Atlas Copco)
- Hanjin DNB (South Korean test site)
- Robit Rocktools (Finnish rock drilling tool manufacturer)
- Mincon (Rock drilling tool manufacturer)
- Wassara (Water drilling tool manufacturer, part of LKAB, the Swedish iron ore mining company)
-

This information has been analyzed and absorbed to provide deeper understanding of the challenge.

2.3 Drilling

2.3.1 Challenges and possibilities of drilling with air DTH

Challenges and possibilities of the air based DTH drilling method are well known due to their wide use. These challenges and possibilities are also well presented in the research paper[4]*where it is stated that*Down-the-hole hammers (DTH) using compressed air have successfully been proven for decades in shallow drilling < 400 m depth." And that: "Here, downhole hammer drilling, based on compressed air down-the-hole (DTH) hammer BHAs, has very successfully been used in shallow drilling applications for many years now. They have proven their rather high rate of progress ROP compared to PDC or tricone bits numerous times. These tools have shown a tremendous increase in ROP, especially in hard rock. Thus, this is the kind of tool to potentially make the deep drilling industry much more efficient."[19]
Figure 3 illustrates Epiroc (former Atlas Copco) air DTH hammers and crowns[2]:

Figure 3 Epiroc (former Atlas Copco) air DTH hammers and crowns

Due to the compressibility of air, the quantity and pressure of air needs to increase according to the depth of the borehole. Water entering the borehole causes hydrostatic counter pressure, which needs to be compensated for by increased air pressure and volume. As a result, the drilling progress slows down with depth since the pneumatic power of the air compressor is limited. Deep boreholes, when drilled with air DTH, become exponentially more expensive with increasing depth. Air has, on the other hand, proven to be an efficient method for lifting the rock cuttings up to the surface.

Case example: Based on the interview of Christian Savela, CEO of ST1 geothermal business, drilling down to the depth of 600m is possible to achieve with a currently available four-inch hammer and 115mm drill crown. Beyond the depth of 600m the air flow needs to be increased in order to lift the cuttings. The airflow is limited in a four-inch hammer, and a five-inch hammer is needed to provide sufficient air flow. Going beyond 600 m therefore creates the need to switch to a five-inch hammer, which in turn requires the use of 152 mm drill crowns. A 152 mm borehole in turn increases the crushed rock volume by 75 % in comparison with 115 mm drill crowns / borehole dimension. Drilling beyond 600 m depth typically requires the additional air pressure only achievable through a booster which is connected in series with a regular 35 bar compressor to achieve the higher air pressures needed in deeper boreholes. Typically, the cost for using a booster exceeds 2000 €/day in rental cost, in addition to that comes the added fuel consumption to run the booster.

Figure 4 illustrates the Atlas Copco booster on the left side of a compressor. [1]

Figure 4 The Atlas Copco booster on the left side of a compressor

Case example: The importance of a proper lift of cuttings from borehole is experienced in multiple TAS drill sites, where the airflow has not been sufficient. This becomes clearly observable, when despite the air compressor running, no rock cuttings or water exit from the borehole. This type of incident requires immediate shutting of the supply air valve. If the air flow is not shut, the borehole volume accumulates pressurized air below the rock cuttings block, the block can break uncontrollably and shoot the rock cuttings and pressurized air and water from the borehole. The release of pressure comes with such a force that the dust hose may detach from its fastenings, spraying rock particles and water with a force dangerous to the surroundings. This case illustrates one of the possible hazards and required safety regulations associated with the application of air DTH drilling in densely built city areas.

Case example: Pressurized air can cause danger in conditions where the bedrock has multiple channels or fractures, running horizontally: Pressurized air can escape from the borehole via horizontal channels in the bedrock to nearby boreholes. The pressurized air can escape to the surface via a neighbouring GSHP borehole, sometimes hundreds of meters from the actual drill site, throwing possibly tiles, rock material and water in the air. This case illustrates the safety challenges in borehole drilling with pressurized air in areas where bedrock is not solid and uniform. This illustrates that there clearly is a need for safer drilling methods in city areas.

Case example: GSHP borehole straightness deviations in a TAS geothermal heating system project (Christian Sarkala as a project manager) in Munkkiniemi, Helsinki, Finland. The air DTH drilling requires a rather large space between the hammer and the borehole wall to allow fast enough air stream to carry the rock particles upwards. This space allows the hammer to deviate in angle, resulting in a deviation of the borehole straightnessfrom the planned direction and angle. Also, the drilling shaft, which is typically 76mm in diameter, can bend in 115mm boreholes, contributing to such deviations. Deviations have not yet resulted in major legal or technical issues, but it is expected that the growing borehole density in city areas will result in more strict requirements for the borehole straightness and related deviations in the future. Currently, discussions are ongoing between the industry and the regulatory authorities.

Figure 5 illustrates a 400m borehole bending and deviating from its drill site, 12 boreholes x 400 m were drilled, the deviations varied between 30 m and the illustrated maximum deviation of 90,73m.[5]

Depth	Distance to target (m)
0	0,00
10	0,08
20	0,12
30	0,25
40	0,49
50	0,80
60	1,20
70	1,72
80	2,28
90	2,84
100	3,41
110	4,04
120	4,72
130	5,51
140	6,50
150	7,72
160	9,20
170	10,76
180	12,38
190	14,10
200	15,89
210	17,84
220	20,11
230	22,92
240	26,18
250	29,70
260	33,35
270	37,13
280	41,14
290	45,34
300	49,87
310	54,69
320	59,46
330	64,11
340	68,81
350	73,67
360	78,56
370	83,33
380	88,20
385	90,73

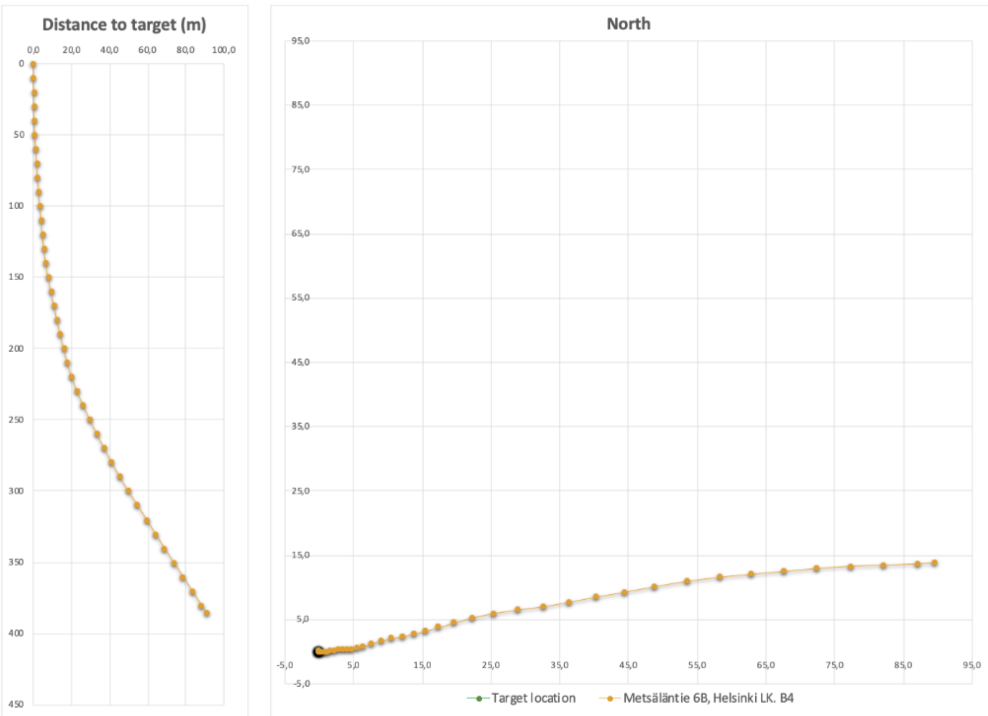

Figure 5 Borehole bending and deviating from its drill site

As concluded in the research paper[4]: *"DTH air hammers, however, will not work in greater depths due to air being compressible and, more important, having a specific density much lower than water or rock, respectively."*

As a conclusion, considering the air DTH method, air is proven to be very efficient in depths up to approximately 300-400 m. Beyond that depth, air-based drilling is becoming very inefficient and costly. Specifically going beyond 600 m increases the cost of air DTH drilling exponentially, due to an increase in air pressure, air volume and the need to crush 75% more rock. Borehole straightness issues may limit the use of air DTH method.

2.3.2 Challenges and possibilities of water based DTH drilling:

Water is incompressible, therefore enabling very efficient transfer of power from the surface water compressor to the DTH drilling hammer. These benefits are highlighted in the already mentioned research paper[4]:

In contrast with air DTH, hydraulic water / liquid powered hammers are more efficient at breaking rock, even at greater, virtually unlimited depth. For over 20 years now DTH water hammers have been produced and commercially available and have been used and intensely tested at GZB in Bochum. Furthermore, a Swedish manufacturer has used and marketed his product for production drilling in mineral mines as well as for special applications in shallow to medium deep drilling. One major issue with these hammers so far was the rather important requirement for water quality, requiring virtually clean tap water to function properly.

Figure 6 illustrates the Swedish Wassara water DTH hammer and a crown[6]. As clearly visible in the picture, the crown and hammer are very close to the same diameter, not allowing the hammer to deviate in direction as much as the air DTH hammers. Therefore, water DTH hammers have the advantage of producing more precisely straight boreholes.

Figure 6 Swedish Wassara water DTH hammer and a crown

The GTZ paper[4] clearly illustrates the overall efficiency as well as the fuel efficiency of water based DTH in shallow depths. On the other hand, the excessive consumption of pure water and the time needed for flushing the rock cuttings from the borehole is also highlighted. Excessive consumption of clean water in drilling operations poses another problem, which is very difficult and costly to solve: How to evacuate the drilling water away from the drilling site in a cost-efficient way. If drilling produces hundreds or even thousands of cubic meters of water mixed with rock dust, there is currently no commercially available and cost-efficient method to clean the water on site. Cleaning is necessary in order for the water to be released to the rainwater system or, when filtered to a very low particulate level, to be recirculated in the drilling process.

Case Example: Based on the interviews of Mikko Ojanne, development director of Rototec, the challenge of water drilling is the flushing of the borehole while drilling. This is in good accordance with the GTZ paper. According to Mikko, based on experience gained from multiple drilling sites in Sweden, the first 50 to 100 m of drilling with water based DTH can be controlled quite well, having low noise emissions, no loose dust etc. After the initial 50 or 100 m the drilling operation comes often to an abrupt halt due to the drilling shaft, hammer and crown being stuck in the borehole by densely packed rock cuttings. This can result in a situation where the crown, hammer and shaft have to be abandoned in the unfinished borehole. In effect this particular problem has resulted in a situation that no driller has continued using water DTH method in the production work of GSHP boreholes.

A probable cause of rock cuttings not being flushed from the borehole after the first 50 to 100m is that the bedrock contains multiple cracks providing the upwards flowing water the escape passages, thus leaving less water flow to carry away the cuttings up to the surface. Since the water pressure in the borehole is higher than in the surrounding ground water, it is only natural that some water does escape from the borehole. If the bedrock was free from cracks, exactly the same water flow which flows downward inside the drilling shaft would return to the surface, and the upward water flow speed in the annulus would remain constant and efficiently lift the rock particles. The occurrence of the rock cuttings blocking the borehole only after the DTH hammer has gained some depth, islogical, because the probability of encountering some cracks increases by the increasing depth. It could well be the case that the borehole gets blocked at the first major crack allowing the water to leak away from the borehole, thus leaving only the accumulating rock cuttings in the annulus that after some time blocks the borehole.

A conclusion of the water DTH method is that it is an efficient, proven method in drilling in iron ore mines etc. sites, where the drilling depths are limited or the borehole is horizontal or drilled upwards, making it easier for the water with cuttings to flow away from the borehole. The water DTH method is less noisy, more energy efficient and clean, not suffering from similar safety related issues as the air DTH method. The critical downfall of the water DTH method is that the quantity of water exiting from the crown is not sufficient for flushing the borehole while drilling, and the problem only gets worse with depth. Consequently, more time has to be spent on the extensive flushing of the borehole. This results in lower productivity and excessive consumption of clean water which in turn creates the need for expensive and space consuming drilling water separation or cleaning containers and technology.

2.3.3 Combination methods

Dictated by the analysis of the different drilling technologies it is quite apparent that an optimal deep drilling method would combine the advantages of both water and air DHT methods. Water should be used for conducting energy to the DTH hammer, as water does not compress, does not suffer from the groundwater hydrostatic counterpressure and consumes approximately only one fourth of the energy of the air DTH method in shallow depths. The energy consumption difference between the methods could well double or triple when proceeding to greater depths. This could result in the water DTH method consuming 1/12 - 1/8 of the energy of the air DTH method thus providing a clear advantage over air DTH drilling.

Figure 7 illustrates the comparison of the fuel and water consumption of air and water DTH methods in relatively shallow depths, less than 200m. [4]

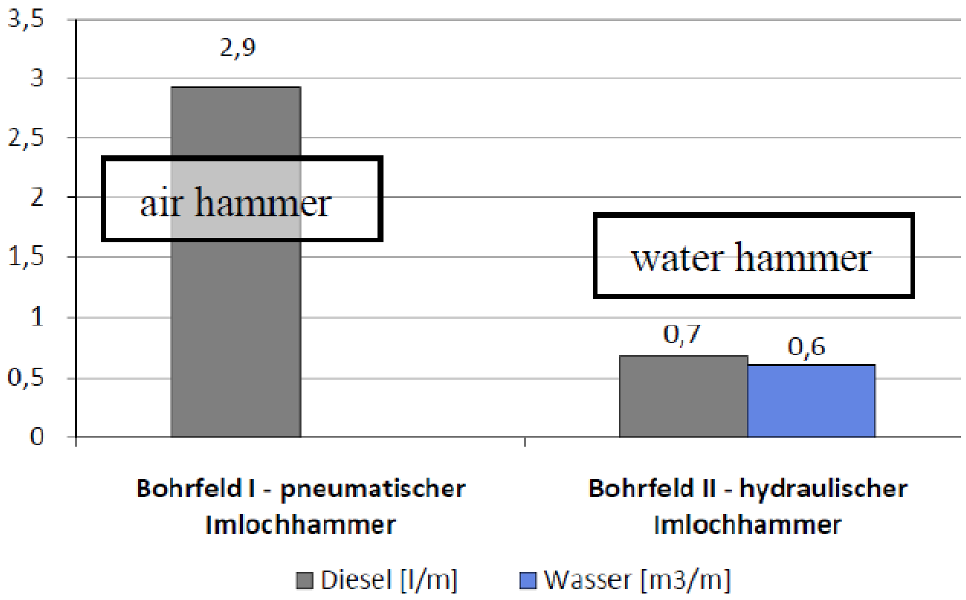

Figure 7 Comparison of the fuel and water consumption of air and water DTH methods

The GZB paper[4] provides some discussion in regard to combining air and water drilling. Particularly the deep drilling case in South Korea is discussed, where the drilling water is intensified with pressurized air. The same case included some polymer additives in the drilling water helping to lift the cuttings. The South Korea project showed promising results in drilling performance all the way to the depth of 5000 m in hard granite, which is also a typical mineral in the Finnish bedrock.

From TAS and the Finnish pilot perspective polymer addition to the drill water is not a desired nor an attractive option, because that would force to use the onsite water cleaning equipment, which would add cost and reduce the mobility and method applicability and replicability on small plots in the cities.

It appears that there is (at least) one important finding in GZB paper[4] which could be utilized in the limited city spaces and in drilling hard crystalline rock in Scandinavia: ”In terms of hole cleaning while drilling, the tests in South Korea did show very impressive results. When borehole stability is not a problem, like in granites etc., the air lift effect of small volumes of compressed air mixed into the fluid does improve cutting transport tremendously, further improving hammer performance. However, hammer and especially the pump have to be set up for that.”

According to TAS’s knowledge, currently there are no pumps commercially available allowing mixing air with water in quantities applicable for drilling. Neither is there a commercially available water DTH hammer designed for drilling water with mixed air. Using intensified water with pressurized air would pose another probable risk; the cavitation induced wearing out the hammer / crown. In order to proceed with intensified water drilling with air as a carrier to speed up the flushing of the cuttings to the surface, further development of the waterpump is needed as well as hammer testing to ensure air does not hinder the hammer action.

The currently available Wassara water DTH hammers have been designed for the minimum water consumption, thus making water treatment easier. The currently available Wassara water DTH hammers have been designed for the minimum water consumption, thus making water treatment or disposing of easier. Currently with DTH air drilling technology, the excess water issue takes place when the groundwater enters the borehole and is blown to the surface caused by air pressure. Depending on the ground water flow to the borehole in air DHT drilling method, the quantities of water in air DTH may even exceed the quantity of water based DTH drilling. Therefore the current Wassara water flow quantities do not pose any more significant problem as current ground water flows in air DTH methos Also, the consumption level of clean water is not an issue, since water consumption of drilling is, according to Wassara, 70-270 l/m. In an 800m borehole the water consumption would be 56 m^3 – 216 m^3, which at a current Helsinki price of 4 €/m^3 would only be roughly 200€-1000 €, just a few percent of the total drilling cost. Also this quantity of water would be disposable in the city rainwater system.

2.4 Impact of bedrock quality on drilling, proposed method of risk alleviation

The bedrock quality greatly affects the borehole drilling. If the DTH drill encounters cracks or frctures which feed plenty of water into the borehole, a depth of 300 or 350 m may not be reached. This is due to the added hydrostatic pressure of the groundwater column in the borehole. This problem is dealt with already in the planning stage, where positions for spare boreholes are planned and utilized if necessary. This may not be available in smaller city plots, where each boreholehas to be successfully drilled to the target depth, or otherwise the GSHP heating system will not function as planned. Therefore, the reliability of drilling through these groundwater feeding cracks is essential. The planned water DTH drilling is a much better method for clearing this issue, as groundwater pressure outside of the shaft is not affecting significantly the drilling performance because the hydrostatic pressure inside the shaft helps to win the groundwater pressure outside the shaft. But there are occasionally some other issues affecting the successful completion of a borehole: There may be more extensive cracks, crushed bedrock, gravel and sand pockets that cannot be drilled through as more sand, gravel and loose rocks block the borehole. This type of deformations can sometimes be filled with cement or concrete pumped to the borehole with high pressure and after it has hardened, the drilling continues through the hardened cement or concrete.

Bedrock quality and its deformations play a vital role in the success rate of deep borehole developments and thermal collector installation. It would be beneficial to know in advance whether there are some broken bedrock, gravel or sand pockets at certain depths. Information on the bedrock quality could then be considered in the decision-making process whether to proceed with a conventional depth or aim for deeper boreholes. In order to obtain information on the bedrock quality, a system has been proposed by TAS to drill the planned boreholes only to the depth where bedrock is reached with a conventional steel tube drilling. The drilling will sink the steel tubes approx. 2 m into the bedrock and the steel tubes are cemented in place as done conventionally. Before continuing with drilling, an acoustic transmitter / receiver is positioned at the bottom of each of these boreholes, and an acoustic test program is run. The results are analysed in order to locate the possible cracks, deformations, sand and gravel pockets. If the bedrock is of good enough quality, then deeper boreholes are recommended to the client. If too many deformations appear at critical depth, then more shallow boreholes are recommended. If the number of borehole quantity is too large resulting in too close proximity, then the energy system can be designed with heat energy charging to the bedrock via air to water heat pumps, exhaust air heat recovery or PVT panels, to name a few relevant options.

The proposed acoustic probing system does not yet exist (to TAS knowledge) but may be worth considering as an enabling technology and method to eliminate unsuccessful deep borehole drilling attempts. This is of importance since positive and successful projects lead to rapid adoption of GSHPs, negative ones slowing down the process. The acoustic probing could also be incorporated in more advanced GSHP borehole field design work for respective engineering companies.

As it is quite probable that acoustic probing methods will not be available in the Finnish pilot site in Kalasatama, Helsinki, the drilling of deeper boreholes will contain some risk. The risk can be mitigated by planning a few additional positions for boreholes, in case the targeted depth cannot be reached. The method to find this out is testing one borehole drilling at a time.

2.5 Decision/planning process/procedure on selecting the drilling method

The decision on how to plan and select the method of drilling has primarily two available options:

- Drill with readily available technology air DTH
- Develop water DTH hammer drilling with some features of using air as lifting propellant

The air DTH drilling option has some sub options:

- 4-inch hammer and 115mm crown (borehole diameter starting at 115mm and reducing by 5 to 10mm towards the bottom of the borehole)
- 4-inch hammer and approx. 125mm diameter crown (with reducing diameter of borehole in deeper sections)
- 5-inch hammer with 152mm crown

The water DTH drilling method will be developed further and depending on the results and available tools and machinery the final decision will be based on whether the technology will be ready and available within the construction schedule of the Finnish PEB pilot.

TAS has received information on the cost structure of drilling the boreholes with air DTH. The cost information is from the St1 geothermal drilling business unit. Based on this cost information, the total drilling cost can be accurately specified up to the depth of 600m. At greater depth borehole cost is not well predictable, as the pricing is based on the spent hours, materials and energy plus a project leadership fee. Figure 8 illustrates the drilling machinery it the drill site in Malmö.

Figure 8 Drilling machinery in drill site in Malmö, (source: St1 geothermal)

3 DEEP BOREHOLE COLLECTORS

Geothermal energy has a unique position among the renewable energy resources. In fact, we live right on top of the most affordable, sustainable and comfortable energy source on earth thanks to earth's relatively constant underground temperature. Therefore the ground can be used as a heat source during the winter and as a heat sink during the summer. In order to capture or dissipate heat from or into the rock, a ground heat exchanger (BHE) is installed.

This section deals with the design principle of the deep borehole collector technology, including a thermomechanical characterization of the BHE material and a thermo-fluid dynamic characterization of the heat transfer properties of the collector along its vertical development. Tests results and discussions will be also included.

Usually there are two ways of upscaling ground source heat pump systems installations, either by increasing the number of boreholes or by increasing the depths of the boreholes. Whereas the first alternative needs additional surface area, the deeper boreholes (beyond 600 m), which are more expensive than the conventional boreholes (as discussed in section 2), can be applied when there is a lack of space, e.g. in dense living areas. In the North part of Europe, the temperature in the rock increases with about 1–3 K/100 m, thus the thermal potential for heat extraction increases with increased depth.

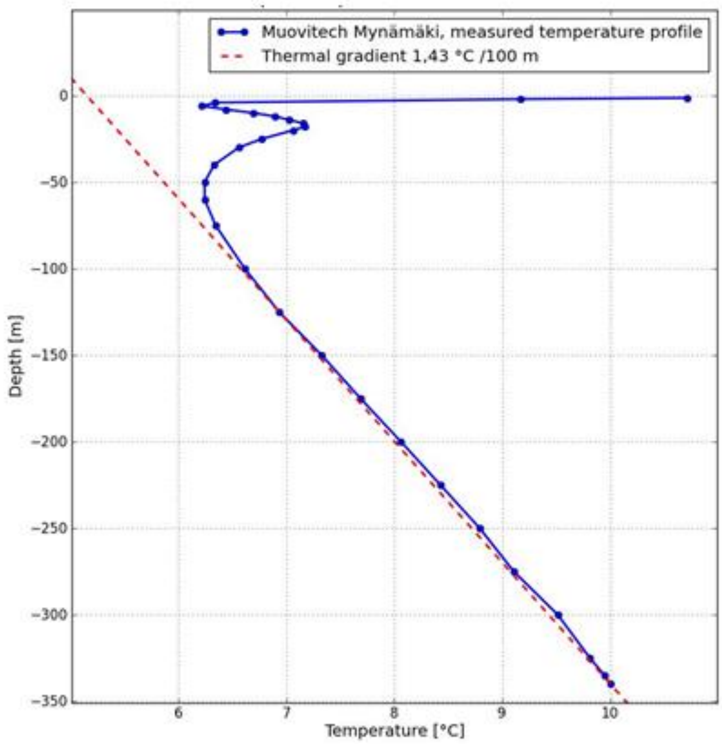

Figure 9 Undisturbed ground temperature and temperature evolution with depth in a borehole

Figure 9 shows a typical temperature profile along a borehole in Mynämäki, Finland. [7] This measurement was done in the test borehole facility (350 m depth) in the R&D department of MouviTech. As can be seen, the temperature variation near the ground surface caused by weather conditions is quite vast. It is generally accepted that the variation affects the temperature levels down to 15 meters below the surface. At that level, the temperature of the bedrock is not affected by weather conditions and is almost equal to the average annual temperature of the surface, which in the Finnish case is typically 6–7 °C. The coldest point (6.2 °C) is at about 50 meters depth, and the temperature starts to rise linearly after 125 meters. The thermal gradient in the borehole is about 1.43 K/100 m. In fact, geothermal energy utilizes the heat stored in the ground due to activities in the core of the earth (thermal gradient) or due to the absorbed energy from the sun. Any attempts to utilize the higher temperatures in the source combined with any solutions to reduce the temperature in the demand side can improve the efficiency of the whole system, e.g. reduced temperature in the demand side improves the COP of the heat pump. One important parameter in the source side is the borehole thermal resistance, which depends on the conductive and convective resistance of the fluid, the properties of ground heat exchanger GHE, and the backfilling material.

3.1 Introduction and current technologies

Geothermal energy has a unique position, among renewable energy resources. Near surface or shallow ground maintains an almost constant temperature during the seasons, so it can be used as a heat source during the wintertime and as heat sink during the summertime. A geothermal heat pump system or ground source heat pump system (GSHP) consists of a heat pump which is connected to the delivery system and a ground heat exchanger (GHE). A GHE is a loop or system of pipes buried horizontally in the ground or vertically inside of a borehole, to collect/reject heat from/into the surrounding. A fluid (e.g. ethanol/water mixture) circulating in the pipes transfers the heat from the ground to the heating system. GSHP systems have an average life expectancy of 50 years for the underground infrastructure (GHE).

Two design parameters i.e. ground thermal conductivity, and borehole thermal resistance are required for the sizing of GSHP systems. Ground thermal conductivity is a physical property of the ground surrounding the boreholes, and borehole thermal resistance is defined as the thermal resistance between the heat carrier fluid in the GHE and the borehole wall and should be kept as small as possible. It determines the temperature difference between the fluid in the GHE and the temperature at the borehole wall and is typically given per unit length of the borehole (K/W m).[9,10] The borehole thermal resistance depends on the conductive and convective resistance of the fluid, the thermal resistance of the GHE pipes, and the physical properties of the backfilling material.[11,12] Most common GHEs configurations installed in boreholes are single-U pipes or double-U pipes in the range of 30-300 m of the borehole depth. Therefore, these configurations, with different diameters and shapes, were intensively investigated in the literature to compare thermogeological and hydraulic parameters and the impact they have on heat rejection/extraction rates. However, in certain cases, the plot surface area may be limited and therefore there is a need for deeper boreholes. Single U pipes and double U pipes collectors cannot be used in deep geothermal layers due to the hydronic limitations. Coaxial collectors utilize the available borehole cross-section space more efficiently, allowing for a higher flow rate given a similar borehole diameter with a rather lower pressure drop. Therefore, this section discusses different aspects of cutting edge coaxial GHE for deep boreholes.

The main categories of possible GHE types are a) closed loop coaxial system b) open loop coaxial system. This report focuses on closed loop solutions.

3.2 Challenges & limitations for deep boreholes in GSHP

The exploitation of shallow ground geothermal energy is often carried out with a heat pump and a closed loop system, where a circulating fluid extracts or rejects heat in the surrounding soil. The closed loop acts as a ground heat exchanger (GHE). The single U-pipe and double U-pipe are the most common configuration of GHE in the range of 10-300 m depth boreholes. They consist of two/ four parallel pipes where the fluid moves downwards through one/two of them and upwards through the other. In this design, the pipes are connected at the bottom. It is worth to mention that in Scandinavia, the borehole is water filled however, in the rest of Europe grouting is obligatory as shown in Figure 10. Water fill or grouting is needed to improve the heat transfer between the collector system and bedrock.

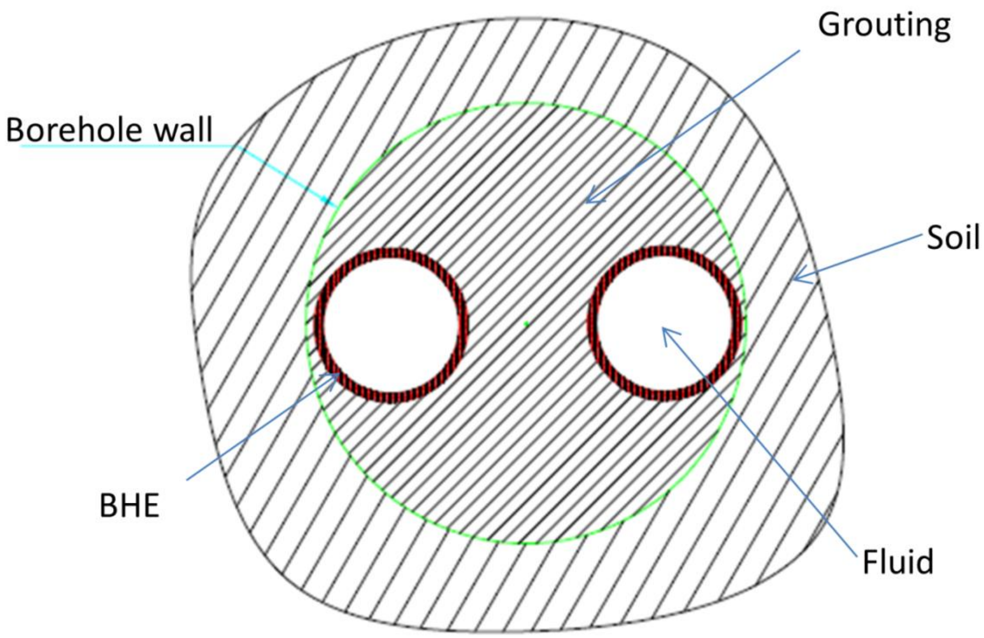

Figure 10 Schematic of a single U- pipe and cross section of a borehole with different components

Most common U pipe GHEs installed are in the range of 30-300 m of the borehole depth. However, in certain cases, the surface area may be limited and therefore there is a need to use this technology for deeper boreholes. The amount of heat that can be transferred from /to surrounding ground and heat carrier fluid depends on the two thermal properties: the thermal conductivity of the soil and thermal resistance of the borehole. The soil quality is usually related to the local geological situation which cannot be changed by designers; however, borehole thermal resistance can be engineered. The overall borehole thermal resistance has a significant effect on the system performance and therefore it should be as low as possible. The borehole thermal resistance itself depends on many factors such as borehole diameter, type of backfilling, convective heat transfer between fluid and heat exchangers, fluid characteristics, position and type of heat exchanger in the borehole, flow rate and so forth. The electrical consumption by circulation pumps plays an important role in the total efficiency of the system. The theoretical power required by a circulation pump to overcome a given pressure drop when flowing antifreeze in a closed-loop system is shown in Eq.1:[17]

$$E_{pump} = \frac{\Delta P \; Q}{\eta_{pump}} \qquad (1)$$

Where:

E_{pump} = Pump power in W

ΔP = Pressure drop in Pa

Q = Volumetric flow rate in m^3/s

η_{pump} = Pump efficiency (dimensionless)

Considering Eq.4 in the following chapter shows that the pressure drop is related to power two of the flow rate, and Eq.1; it is possible to infer that, the electrical consumption of the circulation pump is roughly proportional linearly to the pressure drop and third power of the flow rate.

However, single U-pipes and double U-pipes collectors cannot be used in deep geothermal boreholes due to the hydronic limitation (as discussed above due to the high pressure drop); therefore, it is of great relevance to design effective coaxial GHEs characterized by moderate temperature differences between the fluid and the surrounding ground with a lower pressure drop in the collector for the deep boreholes.

3.3 Coaxial collector

A pipe-in-pipe or coaxial borehole heat exchanger is a configuration in which one tube is positioned coaxially inside the other tube of larger diameter, as shown in Figure 11. The heat exchange fluid flows downwards in the inner tube and upwards in the space between the two tubes. In this case, to separate the flow, a head cap in the top part of the collector is needed.

Figure 11 Schematic of a coaxial heat exchanger designed by MuoviTech

Among the advantages of using coaxial heat exchangers, reduced pressure loss compared to U-pipes is one of the most significant. The thermal performance is also improved in respect to the earlier mentioned U-pipe collectors, having a more balanced heat exchange of the fluid coming downwards and the bed rock. In addition, a closer contact with the borehole wall may lead to lower borehole thermal resistances. However, it must be emphasized that the coaxial configuration still faces considerable challenges mainly in the installation phases compared to the U-pipe heat exchanger. The requirement of placing the outer pipe as close as possible to the borehole wall sometimes leads to difficulties when the borehole has some vertical deviation, getting stuck in these areas. Costs of the production, transportation and logistics, joints and mechanical properties are other challenges that need to be addressed.

Two design parameters i.e. ground thermal conductivity and borehole thermal resistance are required for the sizing of the system. Ground thermal conductivity is a physical property of the ground surrounding the boreholes and cannot be changed. Borehole thermal resistance is defined as the thermal resistance between the heat carrier fluid in the GHE and the borehole wall and should be as small as possible. In a coaxial configuration the thermal resistance R1 between the center pipe and the annular pipe (Eq. 2) and the thermal resistance R2 between the annular pipe and the borehole wall (Eq. 3) are very important parameters in the designing and construction of the coaxial collector. [15]

$$R_1 = \frac{1}{2\pi r_1 h_c} + \frac{\ln(r_2/r_1)}{2\pi k_c} + \frac{1}{2\pi r_2 h_a} \quad (2)$$

$$R_2 = \frac{1}{2\pi r_3 h_b} + \frac{\ln(r_4/r_3)}{2\pi k_o} + \frac{\ln(r_b/r_4)}{2\pi k_{water}} \quad (3)$$

Where:

k_c , k_o , and k_{water} are the thermal conductivity of the inner pipe material, outer pipe material and ground water respectively.

h_c , and h_a are the convective heat transfer coefficients on the inner and outer surface of the centre pipe and h_b is the convective heat transfer coefficient on the inside surface of the outer pipe.

The first term on the right-hand side of Eq.2 corresponds to the resistance associated with convection on the inside of the internal pipe. The second term represents the resistance of the internal pipe wall. The third term corresponds to convection on the outer surface of the internal pipe.

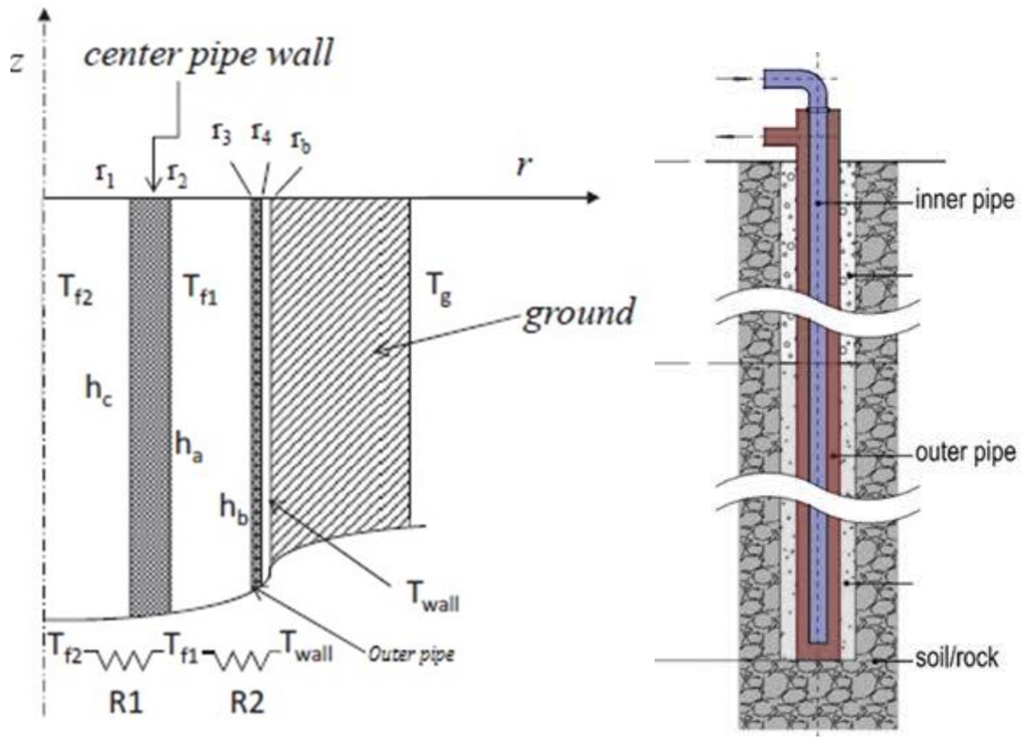

Figure 12 Borehole thermal resistance in a coaxial collector (reference)

The value of R2 might be determined by the convective thermal resistance and the conductive thermal resistance of the annular pipe and the conductive thermal resistance of the backfilling material (light gray in Figure 12), which can be given by Eq.3. In the demo case in Finland, since there is a water filled borehole, the last part of the Eq.3 is given by the thermal conductivity of the ground water where the space between the coaxial collector and the borehole surface is treated as a thermal resistance and heat conducts through the ground water by the thermal conduction.

3.3.1 Building and energy system setting requirements for the collector design

The project co-innovates and integrates technological solutions in positive energy building (PEB) house concepts and demonstrates the performance of these solutions in a real case study in Helsinki. The house concepts and technologies for them will be conceptualized and productized at easy-to-select and easy-to-install level. The objective is to develop and demonstrate the ability of the PEB solutions (e.g. semi-deep geothermal resource, system and borehole technologies, collectors/heat exchangers, multisource heat pump, solar PV(T), ground seasonal storage, energy storages and building service systems e.g. HVAC, lighting) to fulfil the end user's heating and cooling needs with a minimum ecological footprint. The concepts will be developed for different sizes and types of buildings and finally the task will suggest conceptual solution(s) for the demonstration house at Kalasatama Helsinki. The system concepts include a combination of technologies, e.g. geothermal borehole, heat pump, ventilation, heat recovery of ventilation, solar heat, solar PV and different associated control strategies. Figure 13 shows an energy system model which was developed by VTT and illustrates how different components are connected to each other. This is a preliminary design and energy simulations have been done based on this model.

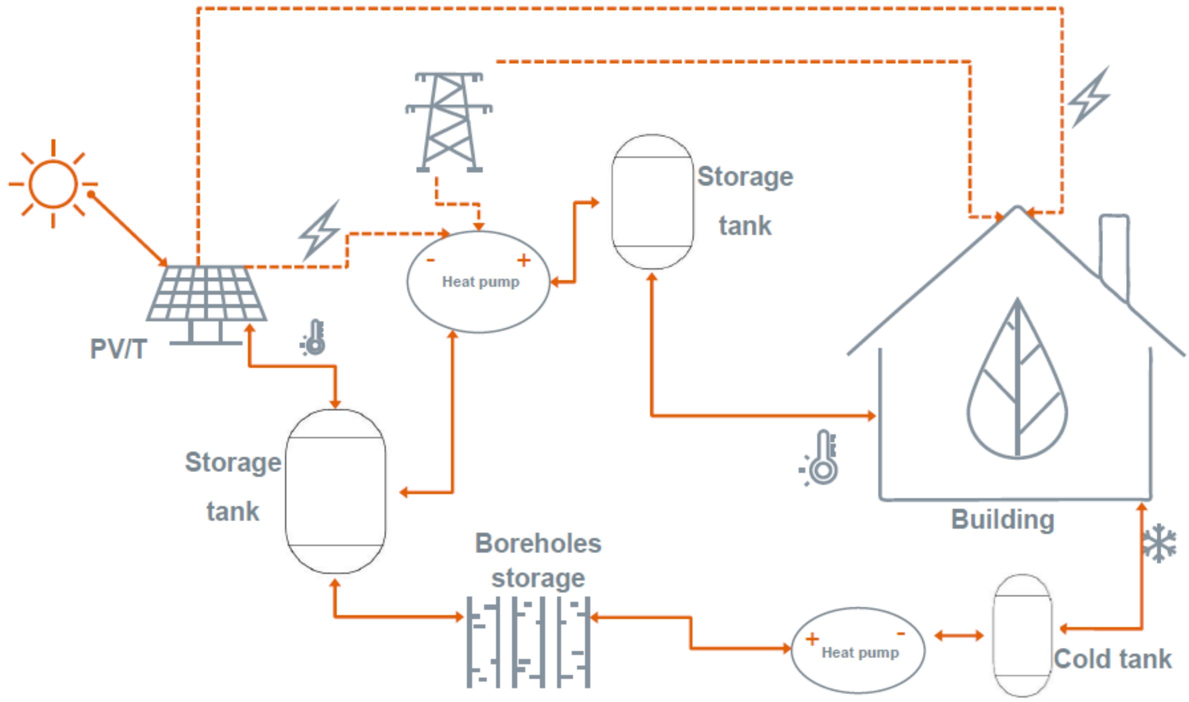

Figure 13 Conceptual energy system model by VTT

The demo implementation also requires adequate planning before and during the PEB construction phase. The results will help the business as usual planning process to go beyond the current status, thus enabling the new norms for PEBs. The demo plans will be elaborated by designers and participating companies. The energy envelope characterization and simulation for the demo case in Finland done by VTT[1] are shown in Figure 14 and summarized as follows:

- Heated floor area 4000 m^2
- Thermal insulation in walls 0.14 W/m^2 K
- Thermal insulation in roof 0.09 W/m^2 K
- Thermal insulation for floor 0.16 W/m^2 K
- Windows characterization 0.88 W/m^2 K
- Heat recovery 80% efficiency
- PV/T area 1635 m^2
- Space heating and ventilation demand 15.4 kWh/m^2 year
- Domestic hot water 42.1 kWh/m^2 year
- Cooling demand 2.36 kWh/m^2 year

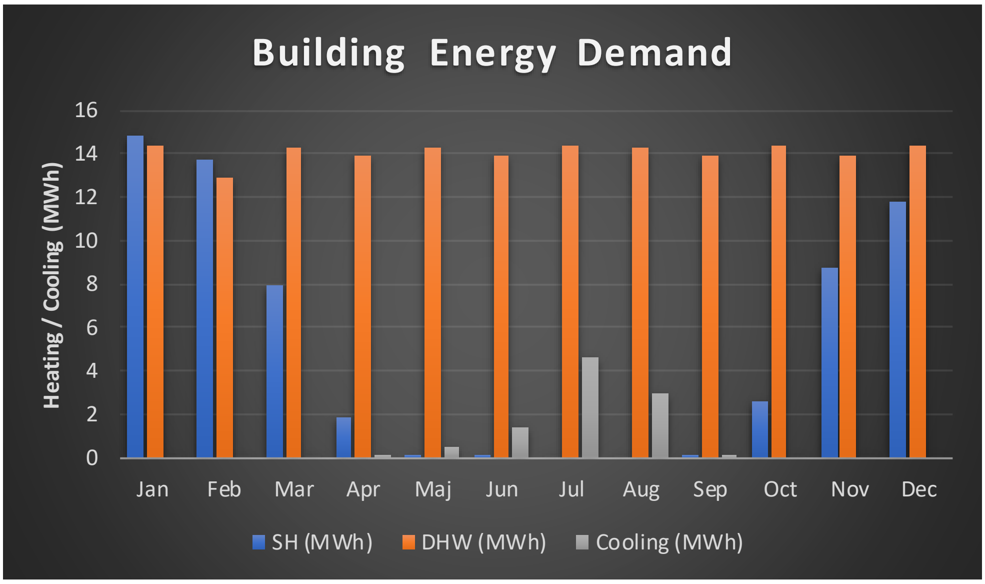

Figure 14 Building thermal loads for the demonstration house at Kalasatama Helsinki (SH=space heating, DHW=domestic hot water

3.3.2 Ground thermal loads, EED simulation and test results

The analytical approach was used by the Earth Energy Design (EED v 4.2) software to evaluate of the mean hourly values for the fluid return temperature from the ground for 30 years of operation. Borehole thermal resistance calculations were also performed to evaluate the impact of different design parameters such as the fluid flow rate, fluid type, the backfilling material as well as the pipes thermal conductivity and their geometries. Some parameters such as ground thermal properties were kept constant to verify how design parameters, especially those related to piping, can improve GHE performances. In order to do so, the design characteristics of the ground heat exchanger, ground thermal properties and the hourly energy load injected/extracted to the ground were introduced into the simulation model.

[1] Raw data provided by Mr. Ari Laitinen dated 21 08 2020

Values for ground thermal properties (thermal conductivity, volumetric heat capacity and undisturbed ground temperature were taken from literature, however these values will be validated during the Thermal Response Test in WP4 after drilling the boreholes in the site by the project partner Basso. Other assumptions that were used during the simulation:

- Thermal loads for the first year were used for all simulated years
- COP for different conditions considered: For space heating system 4.5, for DHW and circulation heat loss 4.0 and cooling considered as free cooling
- The borehole diameter was 146 mm and constant from top to bottom (no vertical deviation or shift)
- September is the starting month of the operation in the simulations
- There is no cooling from PV/T panel connected into the boreholes and all cooling loads are considered as free cooling
-

Figure 15 gives the ground thermal loads based on the building loads and considering the COP for one year. Earth Energy Designer (EED V4.2), a simulation software which is very well documented in the literature and widely used for borehole design is used in this project.[13,14]

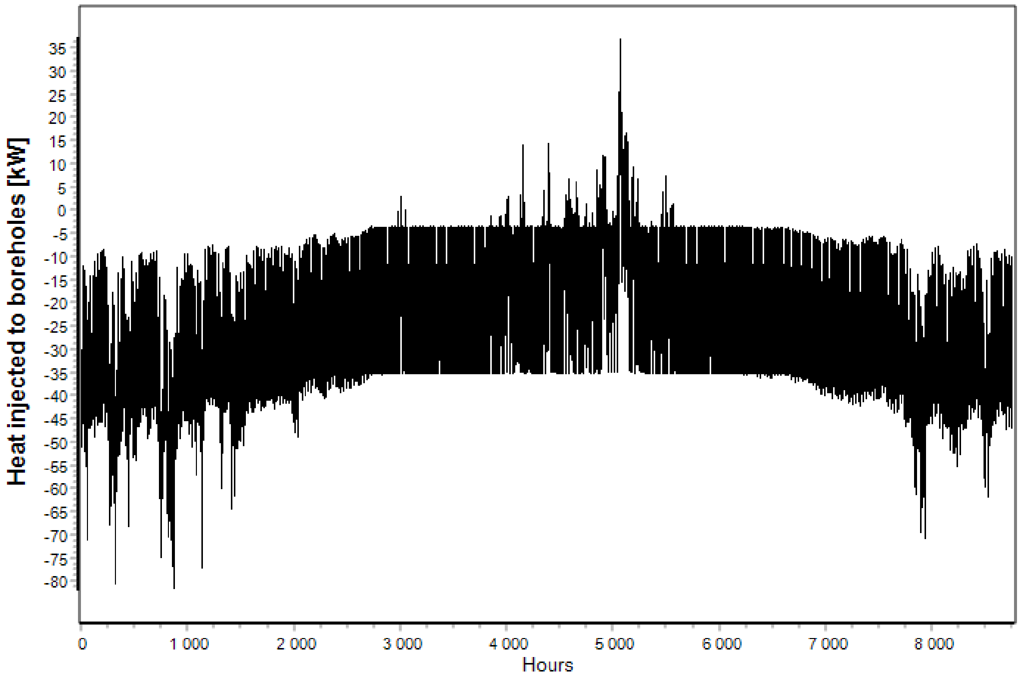

Figure 15 Ground loads during the first year of operation (Positive values show rejection heat into the ground and negative values show heat extraction from the boreholes

Simulation results from the EED software show that during the first 5 years of operation, the fluid temperature coming from the ground is expected to decrease around 0.5 K (from 3.06 °C to 2.59 °C during the peak load in February), and finally reaching a 1.33 K reduction (the minimum fluid temperature would be 1.75 °C in February) after 30 years of operation.This redction of the fluid temperature is dut to unbalanced heat extraction and rejection from the ground. Figure 16 shows the variation of the mean hourly values for the fluid return temperature from the ground for the last year of the operation. Reynold's Number for the inner pipe and annulus pipe are 7437 and 2586 respectively.

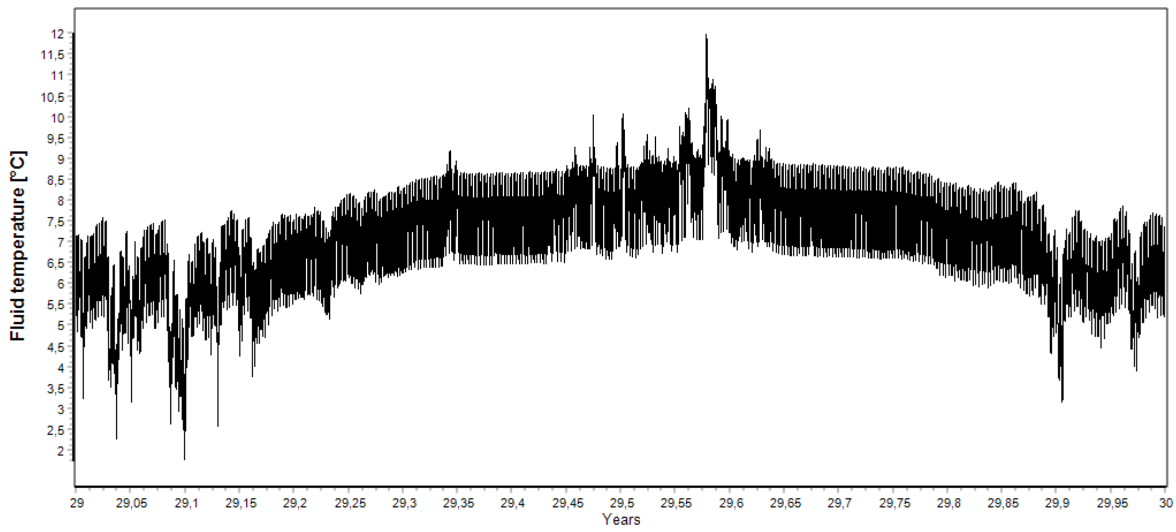

Figure 16 Fluid temperature into the heat pump for the last year of the operation: Minimum temperature 1.75 °C in February (into the borehole) and maximum fluid temperature would be 12 °C during July.

3.3.3 Hydronic, mechanical, flow rate, and antifreeze analysis

After sizing and simulating the ground source heat pump system the min/max fluid temperature for the whole period of operation was estimated.

Different antifreeze water-based solutions used in Europe and other markets for GSHP applications were studied in this simulation. The thermophysical properties (freezing point, density, dynamic viscosity, thermal conductivity and specific heat capacity) for different antifreezes were considered in the simulation and calculation (see Table 1).

Table 1. Thermophysical properties of different heat carrier fluids

Heat carrier fluid	Characteristics					Outputs		
	Density (g/cm³)	**Viscosity (kg/ (m s))**	Thermal conductivity **(W/ (m K))**	Specific heat capacity **(J/ (g K))**	**Freezing point (°C)**	**Minimum flow rate (l/s)**	**Pressure drop (kPa)**	Specific heat load **(W/m)**
Bioethanol (25% wt.)*	0.971	0.0061	0.414	4.27	-15	2.24	204	34.8
Polypropelen glycole (33% wt.)*	1.042	0.0112	0.45	3.725	-17	3.83	643	55.9
Kilfrost GEO (30% v/v)**	1.116	0.00387	0.482	3.72	-15	2.0	161	31.2

* Data from EED, ** values extracted from supplier's technical data sheet

All mechanical loads, pressure loss and pumping power are calculated based on thermo-physical properties of this antifreeze solution. The hoop stress, longitudinal stress and buckling stress were calculated based on the pressure gradient due to differences of the densities between the fluid inside of the collector and the ground water, hydrostatic pressure after installation (see Figure 17). Based on these results for the maximum and minimum fluid temperature, pressure drop, borehole thermal resistance and mechanical loads, the bioethanol with a minimum of 25 wt.% of the concentration was chosen as the heat carrier fluid. However, Kilfrost GEO might be considered as an alternative heat carrier fluid.

A thin-walled pressure vessel theory was formulated since the thickness is less than a tenth of the vessel radius.[18] Different components of the collector must withstand the required internal and external pressure plus the additional hydrostatic pressure by circulation pump. Based on this analysis the minimum wall thickness of each pipe was calculated.

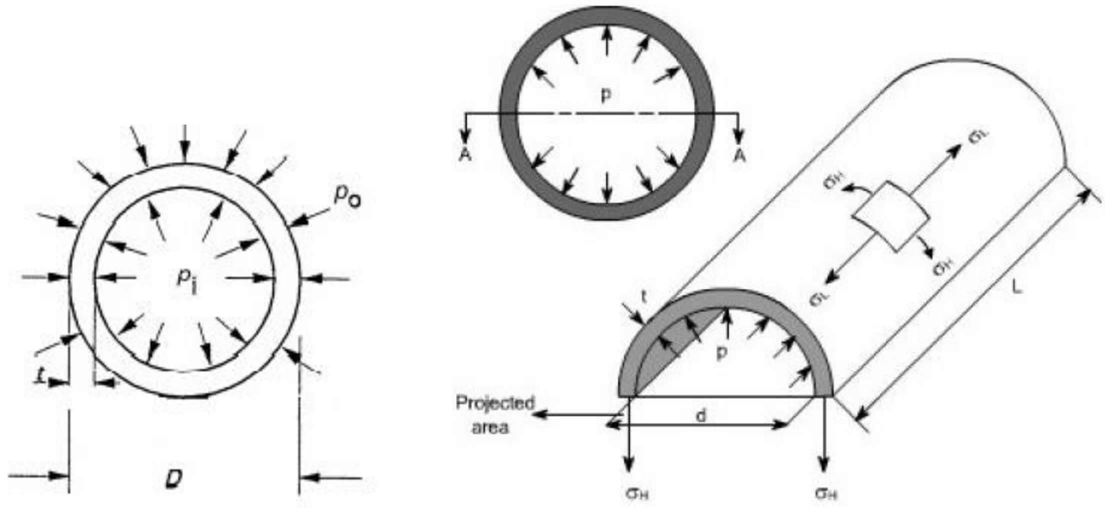

Figure 17 Cross section of a pipe applied forces and stresses from inside and outside (left). Hoop and longitudinal stress due to the dominated internal pressure (right)

Another objective of the simulation was to establish a sensitivity analysis of the GHE length based on the parameters mentioned above to prepare for different scenarios for on-site drilling. Depending on the geological conditions of the bedrock on the site, if successful, the boreholes will be drilled as designed: 3 x 800 m according to Figure 18. However, if 800 m boreholes are not reasonably attainable, based on the global sensitivity analysis of the project, the boreholes lengths can be modified from 800 m to 760 m and then the minimum temperature of the fluid after 30 years on operation is expected to be as low as 1 ˚C. The results of the sensitivity analysis on the borehole length is shown in Figure 19 in the following chapter.

Different scenarios like ground water level, density of the ground water, and density of the heat carrier were evaluated and outcomes were used to define minimum requirements for the material properties and the geometry. As a result, some new boundary conditions were formed, and new simulations were run. These activities will be sustained until the end of the prototyping and even during the activities of WP4, then final tuning and modification will be made accordingly.

According to the simulation, in order to obtain an optimal borehole thermal resistance, the flow regime in the annulus pipe should be turbulent. To reach this condition the minimum flow rate for each borehole should be 2,41 l/s. This is valid during the peak heating load, while during the off-peak period the flow rate can be reduced to some extent.

However, for thermal efficiency reasons, it is important to keep the borehole thermal resistance as low as possible. These results are in good agreement with other studies which have shown the importance of these parameters. [15,16]

The Darcy-Weisbach equation was used to calculate head loss through piping under a worst-case scenario, i.e., when the viscosity of the fluid is higher at lower temperatures (heating peak loads).

This equation is well known in thermodynamic literature assuming the steady state flow and an incompressible fluid. Many research studies in the geothermal science have been conducted and have shown that the estimation by the Darcy-Weisbach equation was in a reasonably good agreement with the experimental values. [17] The relation is given by Eq. 4:

$$\Delta \boldsymbol{P} = f * (\boldsymbol{\rho} * \nu^2 * \boldsymbol{l})/(2 * D_h) \qquad (4)$$

Where pressure drop ($\Delta \boldsymbol{P}$) is in Pa, flow velocity ($\boldsymbol{\nu}$) is in m/s, $\boldsymbol{f}$ is dimensionless Darcy-Weisbach constant or friction factor, $\boldsymbol{\rho}$ is the fluid density in kg/m^3 , $\boldsymbol{l}$ is the length of the pipe in m, and D_h is hydraulic diameter in m.

For the turbulent flow regime, the Darcy-Weisbach constant is estimated by Eq. 5

$$f = 1/\,(0.79 * LnR_e - 1.64)^2 \qquad (5)$$

Where Re is Reynolds number (dimensionless) and ln is the natural logarithm.

Calculations show that the pressure drop in the collector is approx. 204 kPa. It should be noted that this pressure drop calculation is just for the collector (the length). Other parts within the system (like valves, horizontal pipes, main pipe, heat pump and other bending) will also add pressure drop in the system and therefore must be taken in account.

3.3.4 Borehole drilling, and circulation pump consideration

The amount of heat that can be transferred between the ground and heat exchanger depends on many factors mainly thermal conductivity of ground and borehole thermal resistance. To the best knowledge of the author, the properties of the ground mainly depend on the geographical location. The overall borehole thermal resistance itself depends on many factors such as borehole diameter, convective heat transfer between fluid and heat exchangers, fluid characteristics, position and type of heat exchanger in the borehole, and so forth. The successful application of commercial GSHP systems relies upon the careful consideration of these issues.

In the previous section the different technologies for the drilling of the GSHP systems were discussed and in this section the performance and development of the coaxial collector was demonstrated. Additionally, the combination of the drilling quality and drilling diameter is essential when installing ground heat exchangers. This is due to the relatively low heat conductivity in standing water; a large diameter borehole will increase borehole thermal resistance and reduce collector efficiency considerably. Therefore, a correctly dimensioned and properly drilled borehole should facilitate an easy and efficient collector installation.

Figure 18 shows the borehole's configuration and minimum distance between each other in the demo site. The borehole diameter in the simulation was considered 146 mm so from a practical point of view it is important:

- To keep the vertical borehole deviations as low as possible (e.g. less than 2%)
- Drill Bit Shift: a situation where the drilling bit moves sideways until the hammer meets the wall of the borehole should be avoided. One solution might be to use some borehole Near Bit Stabilizers (NBS) to reduce the risk of the Bit Shift
- The borehole should be drilled by a 5 inch hammer with a 152 mm crown from top and a minimum of 142 mm in the bottom

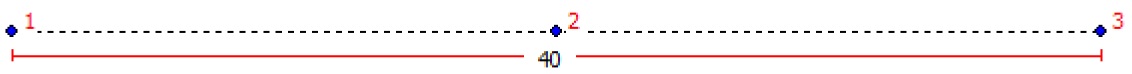

Figure 18 Schematic of the 3 boreholes configuration. The minimum distance between the boreholes should be 20 m

As mentioned previously, the flow rate of the fluid in the ground heat exchanger can significantly influence system performance. The data obtained from tests shows that the circulation pump should be able to deliver 2.24 l/s per borehole and the minimum available head for this flow rate should be 204 kPa. The circulation pump must overcome the system's pressure drop, and it is estimated that an electricity rated pump would need approx. 758 W with 60% efficiency for one borehole.

If the geological conditions of the bedrock on the site are favourable, the boreholes will be drilled as designed (3 x 800 m) according to Figure 18, therfore a sensitive analysis was done in order to solve a case for a required borehole length based on the temperature limitation. The results of this analysis are illustrated in Figure 19. As shown, if 800 m boreholes are not reasonably attainable, according to this sensitivity analysis boreholes with the minimum of 760 m would give a minimum fluid temperature of 1 °C into the heat pump in the last year of the simulation period.

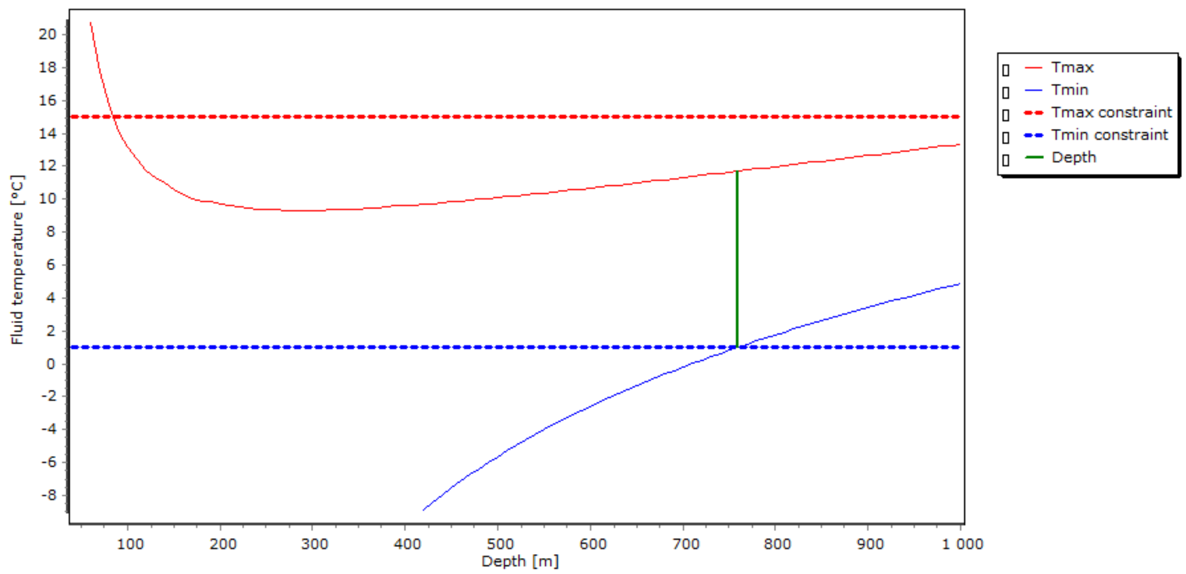

Figure 19 The variation of temperature of the fluid with depth

4 CONCLUSIONS AND FUTURE WORKS

Geothermal energy has a unique position among the renewable energy resources. It is available on demand and scalable. It can be used as a heat source during winter and as a heat sink during summer. However, larger systems require a certain amount of space for the drilling area, which might be difficult to find in densely populated urban areas, such as city centres. Therefore, in order to upscale the installations, increasing the depths of the boreholes is essential. The traditional types of borehole heat exchangers are single and double U-pipes fitted within a vertical borehole with lengths that may vary between 100 and 500 meters. In contrast to the conventional U-tube collector, the coaxial collectors utilize a larger fraction of the borehole cross sectional area as flow area. It is, therefore, more appropriate for deeper boreholes since a larger mass flow rate can be applied. Furthermore, in this report, challenges related to borehole heat exchangers design and installation in semi-deep boreholes are addressed. Simulation results using the EED heat exchanger model showed the minimum and maximum fluid temperature that can be expected in the proposed heat exchanger configuration. Different antifreeze solutions were examined as heat carrier fluids, the bioethanol with a minimum of 25 wt.% of the concentration (as discussed in section 3.3.3) will be used in WP4.

The work in WP2 (Technologies and their integration into PEBs) continues in WP4 (PEB implementation and monitoring). The technologies developed in WP2 will be implemented in demo houses, and lessons learned in WP2 will be taken into account in the selection and implementation phase. With reference to Figure 20, an energy system model was developed in WP2 and it will be implemented in the Finnish demo site. WP4 will evaluate the performance of these technologies applied to the demo building and the selected technologies will be validated.

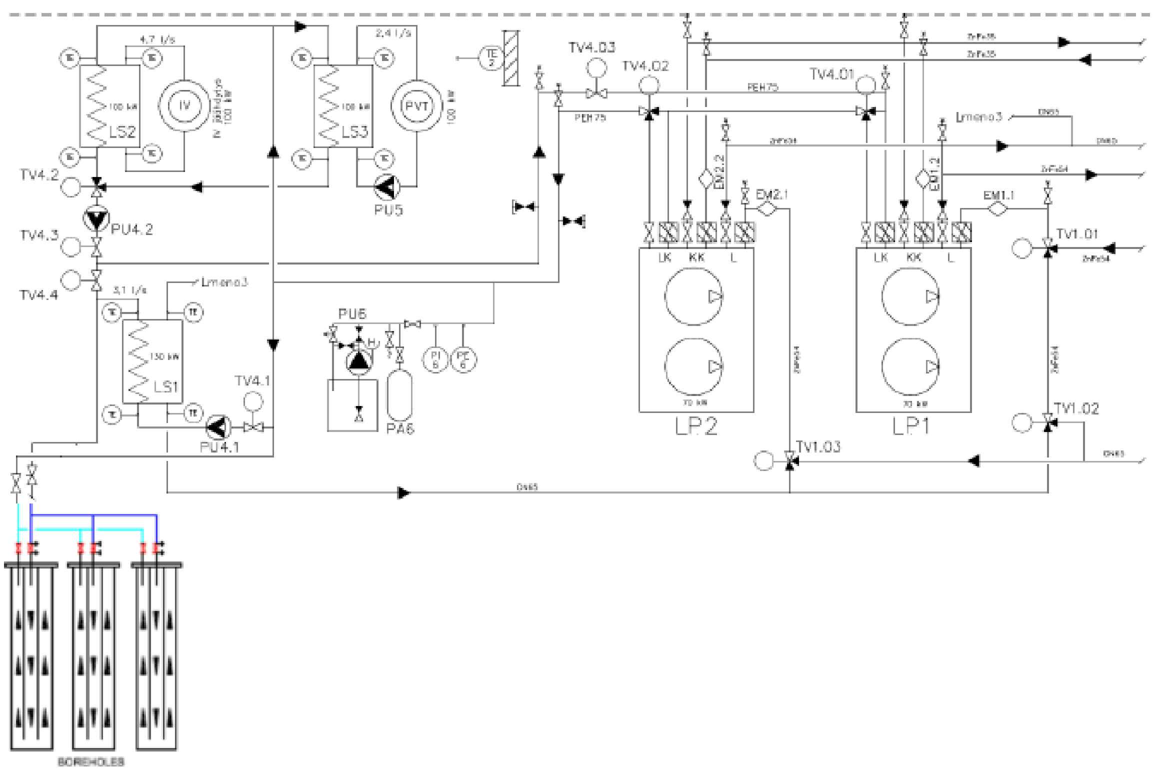

Figure 20 Energy system model which was developed in WP2 and will be implemented in the Finnish demo site as WP4

4.1 Finnish WP4 demo house implementation plan (in sense of drilling & planning of drilling)

The Finnish demo case implementation plan for the boreholes and associated energy system also takes into account cost and risk management and mitigation. The pilot site borehole plan will probably include 6 borehole positions in the construction permit drawings, although the initial design is to drill 3 x 800 m boreholes. Depending on eventual technical/geological barriers, the number of boreholes may deviate from 3 x 800 m to 4 x 600 m as the techno-economical structure of air DTH is predictable to the depth of 600 m. If the geological conditions of the bedrock on the site are favourable, the boreholes will be drilled as designed (3 x 800 m according to Figure 18), leaving the three other borehole positions unused. If 800 m boreholes are not reasonably attainable (or 760 m according to the sensitivity analysis with reference to Figure 19), then one or more of the spare positions will be used. The surface area of the construction site / plot is limited and drilling more boreholes than designed can cause thermal depletion of the bedrock in the long term. In order to compensate for this, excess heat from the PVT panels can be used to recharge the underground, this can be simulated with the energy system model as part of WP4 once other site-specific information and data are available.

5 ACKNOWLEDGMENT

The authors are thankful to Mr. Koen Allaerts from VITO and Mr. Krzysztof Klobut from VTT for their comments and suggestions. We believe that the reviewer's contributions were very useful and helpful in improving the quality of this report.

6 REFERENCES

1. https://en.wikipedia.org/wiki/Down-the-hole_drill (October 2020)

2. Picture source Epiroc (Previously Atlas Copco). : https://www.geodrillinginternational.com/surface-drilling/news/1375812/faster-lighter-dth-hammers-from-epiroc (October 2020)

3. Photo from Tom Allen Senera

4. Wittig, V., Bracke, R., & Hyun-Ick, Y. (2015). Hydraulic DTH Fluid / Mud Hammers with Recirculation Capabilities to Improve ROP and Hole Cleaning For Deep, Hard Rock Geothermal Drilling.

5. From Tom Allen Senera project data base.

6. https://www.wassara.com/about-us/ (October 2020)

7. Kalantar Mehrjerdi, A. (2020). *Thermally Conductive High-Density Polyethylene Composites for Ground Heat Exchangers.* Doctoral thesis, monograph, Högskolan i Borås, Borås..

8. Cole, R. J., & Fedoruk, L. (2015). *Shifting from net-zero to net-positive energy buildings*. *Building Research & Information, 43*(1), 111-120. doi:10.1080/09613218.2014.950452

9. Javed, S., & Spitler, J. D. (2016). 3 - *Calculation of borehole thermal resistance*. In S. J. Rees (Ed.), *Advances in Ground-Source Heat Pump Systems* (pp. 63-95): Woodhead Publishing.

10. Gehlin, S. (1998). *Thermal response test : in situ measurements of thermal properties in hard rock.* (1998:37 Licentiate thesis, comprehensive summary), Luleå tekniska universitet, Luleå. Retrieved from http://urn.kb.se/resolve?urn=urn:nbn:se:ltu:diva-18128 DiVA database.

11. Zhu, N., Hu, P., Xu, L., Jiang, Z., & Lei, F. (2014). *Recent research and applications of ground source heat pump integrated with thermal energy storage systems: A review*. *Applied Thermal Engineering, 71*(1), 142-151. doi:http://dx.doi.org/10.1016/j.applthermaleng.2014.06.040

12. Kurevija, T., Kalantar, A., Macenić, M., & Hranić, J. (2019). *Investigation of Steady-State Heat Extraction Rates for Different Borehole Heat Exchanger Configurations from the Aspect of Implementation of New TurboCollector™ Pipe System Design*. *Energies, 12*(8), 1504

13. Claesson, J., & Eskilson, P. (1988). *Conductive heat extraction to a deep borehole: Thermal analyses and dimensioning rules. Energy, 13*(6), 509-527. doi:https://doi.org/10.1016/0360-5442(88)90005-9

14. Do, S. L., & Haberl, J. S. (2010). *A review of ground coupled heat pump models used in whole-building computer simulation programs*. Energy Systems Laboratory (http://esl.tamu.edu).

Available electronically from http://hdl.handle.net/1969.1/93221

15. Beier, R. A., Acuña, J., Mogensen, P., & Palm, B. (2014). *Transient heat transfer in a coaxial borehole heat exchanger. Geothermics, 51*, 470-482. doi:10.1016/j.geothermics.2014.02.006

16. Deng, J., Wei, Q., He, S., Liang, M., & Zhang, H. (2020). *Simulation Analysis on the Heat Performance of Deep Borehole Heat Exchangers in Medium-Depth Geothermal Heat Pump* Systems. *Energies, 13*(3), 754.

17. Banks, D. (2012). Pipes, Pumps and the Hydraulics of Closed-Loop Systems. *An Introduction to Thermogeology: Ground Source Heating and Cooling* (pp. 248-278): Wiley-Blackwell.

18. Bai, Q. (2014). Subsea pipeline design, analysis, and installation. Waltham, [Massachusetts] ;: Gulf Professional Publishing.

19. Riechers (2010), Innovatives hydraulisches Bohrverfahren für die oberflächennahe Geothermie als Alternative zum pneumatischen Bohrstandard / *Innovative hydraulic drilling process for shallow geothermal applications as alternative to the pneumatic standard*; BA Thesis, Bochum University of Applied Sciences – International Geothermal Centre, Bochum, Germany (2010)