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"Novel tool and guidelines for ground source heat pumps in densely populated areas": a Swedish project.

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ABSTRACT

With one system installed for every twenty inhabitants, Sweden is by far the country with the highest penetration of Ground Source Heat Pumps (GSHPs). Unsurprisingly, it has initiated a project to support designers and decision makers working with GSHPs in densely populated areas. The project includes the development of a software implementing state-of-the-art ground heat transfer models, the study of possible scientific-based guidelines for the release of drilling permits, and the analysis of ground temperature data from densely populated areas.

We believe that Sweden being a forerunner in this field, the lessons learned during this project will be useful for other countries. Therefore, in this article, we discuss the progress of our project: we present the developed software and examples of its applications; summarize the discussion on the possible guidelines; and describe the process to retrieve data about densely populated areas.

INTRODUCTION

With 20-25% of its two million single-family houses heated through Ground Source Heat Pumps (GSHPs), Sweden has the highest penetration of GSHPs in the world (Rees, 2016). In certain areas, the penetration of GSHPs is even significantly higher than the national average (SGU, 2022). When installed in small residential buildings, GSHPs are typically used for heating purposes only; therefore, the continuous heat extraction of several neighbouring systems can lead to their thermal interference and performance degradation. Therefore, in Sweden, it is recommended – and in Stockholm it is mandated - to maintain a distance of at least 20 m between boreholes belonging to different properties (SGU, 2016). However, a software to allow shorter distances by increasing the depth of the energy wells has been proposed already in 2005 (Stockholms stad, 2005).

Since 2005, new mathematical methods for GSHPs in densely populated areas (Rivera et al., 2017; Fascì et al., 2021; Fascì et al., 2022a) and the increased computational speed allows more accurate simulations. Moreover, recommending a minimum distance between the boreholes is relatively arbitrary as it may be unnecessary in areas with a few systems and too permitting in areas with many systems. Therefore, a new Swedish project was started in 2021 to:

1. Create a new software implementing the state-of-the-art models to calculate the temperature influence between neighbouring boreholes
2. Propose and analyse new possible guidelines
3. Collect data from densely populated areas to study the real influence between neighbouring systems

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In this article, we describe the progress on our three working packages, with a focus on the first one.

WORK PACKAGE 1: GSHP$_S$DESIGNER (THE SOFTWARE)

Models implemented

GSHPsDesigner can simulate the annual-average wall temperature of all the boreholes of an area by using two different models: the Finite Line Source (FLS) (Li et al., 2016) and the Stacked Finite Line Source (SFLS) (Fascì et al., 2021) models. The software refers to these models respectively as FLS_I and FLS_{IV}). These models are suited for grounds characterized by heat conduction as the dominating heat transfer phenomenon - as it is for most of Sweden - and provide the upper and lower boundaries of the range within which the ground temperature is expected to fall (Cimmino, 2015). Both FLS_I and FLS_{IV} could also take into account the thermal influence of the built environment (Rivera et al., 2017; Fascì et al., 2022a); however, this possibility is currently not implemented. The models allow to account for the heat extraction from all the boreholes in an area. They can consider the exact year when the different boreholes started operating and account for the exact positions of each borehole, i.e., they can model irregular borehole configurations. However, they assume vertical borehole heat exchangers, while in reality borehole heat exchangers may also be inclined.

So far, we have not focused on the computational speed of the models. While FLS_I typically provides results in seconds, FLS_{IV} requires tens of minutes for areas with hundreds of boreholes. Possible acceleration techniques exist for FLS_{IV}, e.g., assuming a piece-wise linear borehole load (Lamarche, 2017), but have not been implemented yet.

GSHPsDesigner can also simulate the hourly temperature of the carrier fluid of one specific borehole in the area. A constant borehole resistance that connects the borehole wall temperature to the fluid return temperature is used for this purpose (Javed and Spitler, 2016). Calculating the fluid temperature with hourly resolution for several years would be computationally expensive using a standard convolution product for the temporal superposition. Therefore, a load aggregation scheme is used for this calculation (Claesson and Javed, 2012).

Comparison with other software

Other software for the design of GSHPs exist, e.g., BHEDesigner8 (Università di Genova, 2022), EED (Hellström and Sanner, 1994), GLHEPRO (Spitler, 2000). The fundamental difference between GSHPsDesigner and most existing software is its scope. GSHPsDesigner is dedicated to small residential systems, it was born out of the need to account for the thermal influence between neighbouring independent systems, as this influence may be relevant (Fascì, 2022b). On the contrary, most other software focus on the design of commercial installations, and do not include the possibility to account for the influence of neighbouring systems. This difference in their scope is reflected in the models implemented to compute the borehole wall temperature: the existing software use the g-functions (Eskilson, 1987), a method for hydraulically connected boreholes; GSHPsDesigner uses the FLS (Li et al., 2016) and SFLS (Fascì et al., 2021) models, in their versions suitable for hydraulically independent boreholes.

Another difference is the user for which the software are designed: existing software are mostly meant for designers, GSHPsDesigner is also suited for decision makers, thus it also provides functions to check the satisfaction of given requirements, e.g., temperature in the underground. In this, it is a follow up on Temperatursänkning3000 (Stockholms stad, 2005), another software dedicated to Swedish residential areas. However, Temperatursänkning3000 is limited to the possibility of accounting for maximum 16 neighbouring boreholes while GSHPsDesigner is not limited in the number of boreholes it can account for. Moreover, Temperatursänkning3000 limits its scope to the suggestion of an increased borehole length to compensate for the neighbouring boreholes while GSHPsDesigner includes more functions, e.g., providing information about the ground temperature evolution and the carrier fluid temperature. Finally, GSHPsDesigner is also thought for researchers with access to the source code and the possibility to modify it. In this respect, it is inspired by pygfunction, the python library dedicated to the calculations of g-functions (Cimmino, 2018).

The input data

The main functionality of GSHPsDesigner is to simulate the ground temperature evolution in presence of GSHP installations. Several inputs are necessary for this scope. These can be divided into two main categories:

- Ground properties
- Boreholes characteristics

The ground properties include the thermal conductivity and diffusivity, and the undisturbed ground temperature. The ground properties vary locally; therefore, for the design of relatively large systems, they are typically measured by means of thermal response tests (TRTs) (Gehlin, 2002). However, such measurements are relatively expensive, and their cost is unjustified for single-family houses. Typical properties for the geographical location of the installations are usually assumed instead. These properties can typically be extrapolated from the geology of the place and the literature on soil and rock types. However, to accelerate the calculation of the ground properties, we recommend the creation of a database containing the necessary ground information as a function of the geographical location considered. Moreover, we suggest including the information from the TRTs performed for the bigger installations in the database.

Concerning the borehole characteristics, the boreholes positions, lengths and years of installation must be known. For Sweden, this data is available on the SGU website (SGU, 2022). However, this information cannot be retrieved automatically but needs to be retrieved manually for each system, making the process time-consuming and sensitive to errors. The net annual heat loads are another necessary input. At the moment, the boreholes heat loads cannot be retrieved from Swedish public sources. Moreover, this information might not be retrievable at all, since typically, in small installations, boreholes heat loads are not measured. However, recent installations are equipped with sensors that make an estimation possible. Therefore, we believe that, for new installations, the information on the boreholes heat load should be available. Finally, the borehole load is estimated during the design phase of a GSHP system. These estimations may be used as a reference when no measurements are available. Other types of estimations may be possible considering the electricity bills or the building types. However, we expect that accessing and using this information may be more complicated than accessing the information on the systems design.

Given the uncertainty on the input data, the possibility to run Monte Carlo simulations or sensitivity analysis has been considered. However, nothing has been implemented in this respect yet.

Needs of decision makers and designers

Decision makers. Once the guideline to determine the sustainability of a GSHP is decided, our software will help the decision makers in determining whether the guideline is respected or suggest how to make that possible. For being useful for the Swedish decision makers, the software needs to:

1. Be easy to install and use by administrators without a scientific or engineering background
2. Provide the results in a few minutes
3. Determine whether a request should be accepted or rejected, but also suggest modifications to make a rejected proposal acceptable, e.g., proposing a longer borehole
4. Offer default input for information that might not otherwise be retrievable, e.g., borehole heat loads

In order to satisfy the needs of the decision makers, the software has the following characteristics:

1. The software consists of a Julia package (Bezanson et al., 2017). People with no programming experience likely need guidance for its installation. Detailed instructions are available for this reason. Microsoft Excel (Microsoft Corporation, 2018) can be used as an interface to input the data and obtain the results, simplifying the use of the software. The possibility to create a "standard software", typically easier to use, is also under discussion
2. Two different models to evaluate the ground temperature evolution have been implemented, a conservative and an optimistic – more accurate - model. When analysing areas of hundreds of boreholes, the more accurate model may give results in tens of minutes. However, the conservative model always gives results in less than a few minutes. This allows the decision makers to take preliminary decisions in the desirable time.

3. The software is able to suggest an increased borehole length to prevent an unwanted ground temperature change; proposing to recharge the borehole during summer will also be considered
4. Default values for the ground characteristics and borehole heat extractions are used unless otherwise specified. The default values for the ground are typical for granite, most common rock in Sweden. The default values for the borehole heat extraction refer to a linear heat extraction of 15 W/m as a yearly average

Designers. Designers need to establish the techno-economic performance of a GSHP system. This requires the simulation of the system operation. This is a function of the ground-loop fluid temperatures that our software can simulate. However, our software is not currently able to simulate the whole GSHP operation. Moreover, the heat pump (HP) manufacturers have shown a higher interest in implementing our algorithms in their own rather than adopting a new software. Therefore, we are thoroughly commenting the source code of the software so that programmers can translate it to a different programming language if needed. In addition, the Excel interface may be used to connect GSHPsDesigner to another software. Finally, the possibility of implementing the necessary functions for the techno-economic analysis is planned for the future, but no effort has been initiated in this direction yet.

Examples of application

Borehole wall temperature evolution. GSHPsDesigner can simulate the borehole wall temperatures in an area with a high density of independent boreholes. To show this function, we have selected a recent installation in an area characterized by diversified systems in terms of size and installation period, with the oldest installation dating back to 1998. The area considered is shown in Figure 1. The installation of interest is represented by the blue square, the neighbouring installations taken into account in the simulation are the squares within the orange area, corresponding to the 50 closest boreholes. This number was chosen because it had already been calculated that accounting for the 50 closest boreholes or the 450 closest boreholes resulted in less than 0.2 K difference for this scenario (Eriksson, 2022). The file containing the input for the simulations is available online (Fascì, 2022a).

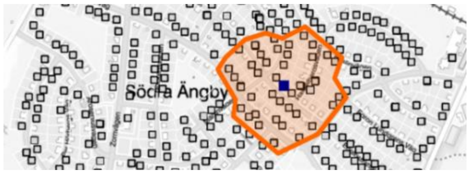

Figure 1 Map of the energy boreholes in Södra Ängby (Stockholm, Sweden). In orange the area containing the boreholes accounted for in the simulation; in blue the borehole under study.

The software calculates the temperature evolution both assuming that there are no neighbouring installations and accounting for the neighbouring installations given as an input by the user. As for now, it is up to the user to decide how many boreholes to consider in the simulation. However, it was shown that considering boreholes beyond a certain distance becomes insignificant (Fascì et al., 2019). A future version of the software will suggest the size of the area the user should consider in their simulation. As already mentioned, the software uses two different models for the computation of the temperature evolution: a more conservative, less accurate and faster to run model, referred to as $\mathrm{FLS_{I}}$; and a more optimistic, more accurate and slower to run model, referred to as $\mathrm{FLS_{IV}}$ (Fascì et al., 2021). For our case study, the computational time of $\mathrm{FLS_{I}}$ was 0.7 s; the computational time of $\mathrm{FLS_{IV}}$ was 246 s. The results obtained with the two models are shown in Figure 2. For thorough details of how to use GSHPsDesigner through the excel interface and information on other functionalities of GSHPsDesigner we refer to Fascì et al. (2022b).

Figure 2 shows that the temperature on the borehole wall of the new system was, according to the simulations, 2 K lower than it would have been if undisturbed already after 1 year of operation. This is attributable to the several neighbouring systems that have been operating for already a decade or more. After 25 years, the temperature is forecasted to be 5 K lower. These results, related to a real case study, show the importance of accounting for the neighbouring systems to correctly size a new installation, and the importance of the availability of tools like GSHPsDesigner for this scope. The difference between the two models implemented in the software - FLS_I and FLS_IV – is always lower than 0.5 K, confirming that FLS_I can be a valid solution for a fast evaluation of a neighbourhood.

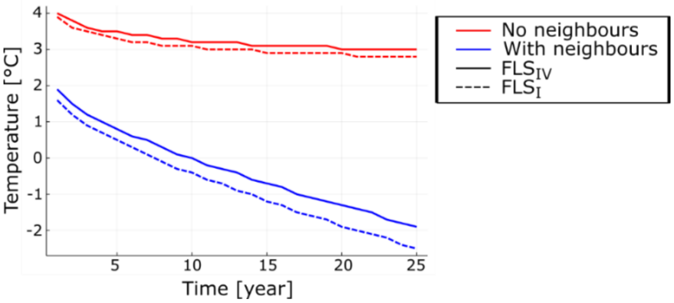

Figure 2 Annual average temperature evolution of the borehole under study (blue borehole in Figure 1).

Minimum required length to respect a temperature threshold. Another feature of GSHPsDesigner is checking whether new installations may cause the underground temperature to vary more than a desired magnitude, and if it is the case proposing the adoption of longer boreholes. We showcase this feature on the same area as in Figure 1. We have assumed that all the buildings currently without a GSHP install an identical borehole; the new fictitious boreholes are installed together with the real newest installation (blue square in Figure 1) and are identical to it, i.e., 170 m deep. This corresponds to eleven new fictitious installations along with the one real new installation. The data about the new installations are available in Fascì (2022a). We have then calculated if the suggested borehole length allows the satisfaction of the temperature requirement or how much longer the borehole length should be. We have conducted a sensitivity study on the temperature change allowed: this varies between 13 – 15 K; 13 K is a threshold already overcome with the current installations, 15 K is a threshold that would not be overcome with the initial borehole length proposed.

We have considered different scenarios:

- Base scenario: the fifty existing installations are equal to the real existing installations
- Scenario(s) 5%, 8% and 10%: the existing boreholes are 5%, 8% and 10% longer than the real existing installations; the total extraction from the boreholes is unchanged compared to the real scenarios. This results in a lower heat extraction per borehole length

The results are shown in Figure 3.

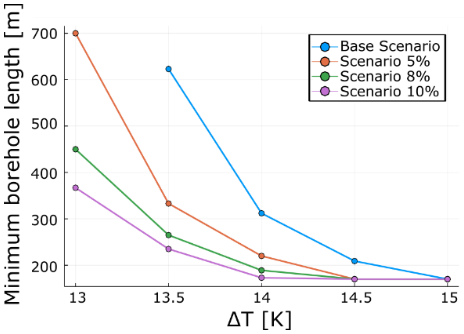

Figure 3 Minimum borehole length as a function of the maximum temperature change allowed. Results assuming the actual borehole length for the existing boreholes (Base Scenarios) or deeper boreholes (Scenarios 5%, 8%, 10%).

Figure 3 shows that the minimum borehole length allowed may be very sensitive to the temperature change allowed. For example, in the Base Scenario, the proposed borehole length of 170 m would be acceptable if a temperature change of 15 K were allowed ; however, the borehole length should be increased to 209 m, 312 m and 623 m if the temperature change allowed were respectively 14.5, 14.0 and 13.5 K. The new boreholes could not be installed at all if the maximum temperature change allowed were 13 K since this threshold would be already exceeded with the existing installations. This shows the importance – for a country that decides to limit the underground temperature change – of carefully selecting the temperature threshold, since being excessively conservative may result in the need of unnecessarily expensive installations thus limiting the access to this technology. Moreover, such a high sensitivity of the borehole length on the underground temperature change allowed, on top of the uncertainty on the input data and the model itself, suggests that sensitivity and Monte Carlo analysis should be preferred to deterministic approaches.

Figure 3 also shows that if the new installations alone were responsible for respecting a given temperature threshold while the old boreholes were designed without taking into account future installations, this could result in the need of extremely long boreholes for the new owners, possibly completely precluding the new installations. However, if a neighbourhood is designed since the beginning so that all the boreholes share the responsibility of limiting the underground temperature change, this may be possible with an increase of a few meters by every borehole. For example, if the existing fifty boreholes had been 5% longer, i.e., 3-10 m longer, the new boreholes would need to be 50 m - rather than 142 m- longer than the initial design to respect a temperature change limit of 14 K; if the existing boreholes had been 8% longer the new boreholes would need to be 19 m longer than the initial design; if the existing boreholes had been 10% longer the new boreholes would need to be only 3 m longer.

WORK PACKAGE 2: GUIDELINES

Another goal of this project is to suggest new possible guidelines to guarantee a sustainable penetration of GSHPs. At the moment, different countries have different rules/recommendations (Hähnlein et al., 2013). The recommendations are heterogeneous even within Sweden, where, for example, in Stockholm one must obtain a drilling permit to install a GSHP, but in other areas the permit is not required (Rydel, 2013). As we write this article, the investigation of the guidelines has not started yet; however, a few possibilities have been suggested.

A possible guideline may concern a threshold on the maximum ground temperature change for environmental reasons; in fact, changes in the ground temperature affect the microbiological activity in the ground and may affect the bacterial and faunal community as well (Hähnlein et al., 2013). Another possible guideline would involve the prescription of a minimum heat carrier fluid temperature; in fact, in Sweden, residential GSHPs typically shut down if the return temperature from the ground is lower than -12/-7 °C to prevent damages to the compressor (Wurtz, 2022). Frequent such shut downs would undermine the energy savings and techno-economic profitability of these systems, and should therefore be avoided. Other guidelines such as imposing a maximum temperature change on property borders for a fair access to geothermal energy, and making the new owners pay for the unexpected economic loss of the previous owners have been proposed. These four possible guidelines will soon be investigated.

WORK PACKAGE 3: DATA

In order to evaluate the accuracy of the software against real measurements and monitor the state of the underground temperature we want to gather data about the heat extractions and return temperatures from boreholes in densely populated areas. Retrieving this data is the biggest challenge of this project. Data collection from older installations is practically impossible due to the absence of sensors, while data collection from recent installations is hindered by privacy regulations and sometimes lack of communication between the sensors in the system and the heat pump manufacturers (Wurtz, 2022). To obtain data from an installation, the most straight forward procedure for us is to:

1. Check, for each property, who the HP manufacturer is (this information in openly available from the drilling permits for Stockholm (Stockholms stad, 2022)
2. Ask the HP manufacturer if they have data from that installation
3. If the data exists, ask the HP owner if their data can be shared

This procedure cannot be automatised and is very time consuming. As a matter of fact, as for now, we have only obtained data from two installations belonging to employees of our project partners.

We believe that relying on GSHPs without monitoring the evolution of the underground temperature around the installations can lead to under- or overexploiting the shallow geothermal heat, comparable to using wood oblivious of the size of the forest. Therefore, we believe that basic information like the borehole heat loads and the supply and return temperatures from the boreholes should be measured and easily available as it currently is for the boreholes positions and years of installations. For this scope, we suggest that this data is made available in a database.

CONCLUSION

We have presented an ongoing Swedish project to promote the sustainable penetration of GSHPs. We have focused on describing GSHPsDesigner, the open-source software under development implementing state-of-the art research and designed so that designers and decision makers can use it. We have shown that the software can analyse a relatively big area in a few seconds or minutes, depending on the accuracy wanted. We have studied a real area in Stockholm and discovered mathematically that existing installations should already be significantly affected by their neighbours, making the use of such software paramount for optimal design. We have also summarized possible guidelines that we will investigate to ease the sustainable penetration of GSHPs. One of our simulations has pointed out the importance of carefully analysing the possible guidelines to avoid unnecessarily hindering the installation of new systems. Finally, we have described the inefficient process that we currently have to undergo to obtain data from real installations hoping that countries that have recently started installing these systems plan since the beginning methods to collect data and make them easily accessible.

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REFERENCES

Bezanson, J., A. Edelman, S. Karpinski and V.B. Shah. 2017. *Julia: A fresh approach to numerical computing.* SIAM Review, 59(1): 65-98.

Cimmino, M. 2015. *The effects of borehole thermal resistances and fluid flow rate on the g-functions of geothermal bore fields.* International Journal of Heat and Mass Transfer 91: 1119–1127.

Cimmino, M. 2018. *pygfunction: an open-source toolbox for the evaluation of thermal response factors for geothermal borehole fields.*In Proceedings of eSim 2018, the 10th conference of IBPSA-Canada (pp. 492-501). IBPSA. ISBN 978-2-921145-88-6.

Claesson, J. and S. Javed. 2012. *A load-aggregation method to calculate extraction temperatures of borehole heat exchangers.* ASHRAE Transactions 118: 530–539.

Eriksson, L. 2022. *Performance of ground source heat pumps in densely populated areas.* Bachelor Thesis. Department of Energy Technology, KTH - Royal Institute of Technology, Stockholm, Sweden.

Eskilson, P. 1987. *Thermal Analysis of Heat Extraction Boreholes.* Ph.D. Thesis. Department of Mathematical Physics, Lund Institute of Technology, Lund, Sweden.

Fascì, M. L., A. Lazzarotto, J. Acuña and J. Claesson. 2019. *Analysis of the thermal interference between ground source heat pump systems in dense neighborhoods.* Science and Technology for the Built Environment, 25: 1069-1080.

Fascì, M. L., A. Lazzarotto, J. Acuña, and J. Claesson. 2021. *Simulation of thermal influence beween independent geothermal boreholes in densely populated areas.* Applied Thermal Engineering, 196: 117241.

Fascì, M. L., W. Mazzotti, A. Lazzarotto, and J. Claesson. 2022a. *Temperature of Energy Boreholes Accounting for Climate Change and the Built Environment - a New Model for its Estimation.* SSRN preprint 4113861.

Fascì, M. L. 2022a. *GSHPsDesigner*. Retrieved from: https://gitlab.com/mlfasci/GSHPsDesigner/-/tree/master/Projects

Fascì, M. L., A. Lazzarotto, and J. Claesson. 2022b. *GSHPsDesigner: an open access tool for ground-source heat pumps designer and decision makers.* European Geothermal Congress 2022, Berlin, Germany.

Fascì, M. L. 2022b. *Air-, ground- and dual-source heat pumps a comparison between energy-efficient systems for a Swedish dwelling.* BuildSim Nordic 2022, Copenhagen, Denmark.

Gehlin, S. 2002. *Thermal response test: method development and evaluation*. PhD thesis. Luleå University of Technology, Luleå, Sweden.

Hähnlein, S., P. Bayer, G. Ferguson and P.Blum. 2013. *Sustainability and policy for the thermal use of shallow geothermal energy.* Energy Policy, 59: 914-925.

Hellström, G., and B. Sanner. 1994. *Software for dimensioning of deep boreholes for heat extraction.* Proc. Calorstock, 94, 195-202.

Javed, S. and J. D. Spitler. 2016. *Calculation of borehole thermal resistance.* In S. J. Rees, Advances in Ground-Source Heat Pump Systems. Woodhead Publishing.

Lamarche, L. 2017. *g-function generation using a piecewise-linear profile applied to ground heat exchangers.* International Journal of Heat and Mass Transfer, 115: 354-360.

Li, M., K. Zhu and Z. Fang. 2016. *Analytical methods for thermal analysis of vertical ground heat exchangers.* In S. J. Rees, Advances in Ground-Source Heat Pump Systems. Woodhead Publishing.

Microsoft Corporation. 2018. *Microsoft Excel.* Retrieved from https://office.microsoft.com/excel.

Rees, S. J. 2016. *An introduction to ground-source heat pump technology.* In S. J. Rees, Advances in Ground-Source Heat Pump Systems. Woodhead Publishing.

Rivera, J. A., P. Blum and P. Bayer. 2017. *Increased ground temperatures in urban areas: estimation of the technical geothermal potential.* Renewable Energy, 103: 388-400.

Rydel, D. A. 2013. *Geoenergiborrhål som avviker och hamnar under en grannes fastighet - Gör de intrång i grannens äganderätt?* Master Thesis. Stockholm University, Stockholm, Sweden.

SGU, Sverige Geologiska Undersökning. 2016. *Vägledning för att borra brunn.* Retrieved from: https://resource.sgu.se/produkter/broschyrer/vagledning-normbrunn-16.pdf .

Spitler, J.D. 2000. *GLHEPRO -- A Design Tool For Commercial Building Ground Loop Heat Exchangers.* Proceedings of the Fourth International Heat Pumps in Cold Climates Conference, Aylmer, Québec. August 17-18, 2000.

SGU, Sverige Geologiska Undersökning. 2022. *Wells*. Retrieved from https://apps.sgu.se/kartvisare/kartvisare-brunnar.html.

Stockholms stad. 2005. *Beräkningsprogram för dimensionering av energibrunnar.* Retrieved from https://boende.stockholm/siteassets/mitt-boende/blanketter/miljoforvaltningen/varmepumpar/om-berakningsprogram-for-dimensionering-av-energibrunnar.pdf .

Stockholms stad. 2022. *e-arkiv Stockholm*. Retrieved from https://etjanst.stockholm.se/earkivet/.

Università di Genova. 2022. *GeoSensingDesign.org*. Retrieved from https://en.geosensingdesign.org/ .

Wurtz, A. 2022. *Personal communication*. Designer and software developer at Thermia.