Project details

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Bygningsintegreret varme- og køleforsyning til fremtidens resiliente byer

Final report, EUDP-project 64017-05182

Project partners:

VIA UNIVERSITY COLLEGE

CENTRUM

VØLUND VARMETEKNIK

Vejle Kommune

Vejle Fjernvarme

Contents

1. Short description of project objective and results

1.1 English

This project investigates the possibilities of supplying a new residential area, Rosborg Ø in Ny Rosborg in Vejle, Denmark with ground source based heating and passive cooling utilizing foundation pile heat exchangers (heat exchanger abbreviated HE in the following) commonly referred to as energy piles. The energy pile foundations are connected to a distribution system of uninsulated pipes buried at shallow depth (referred to as Cold District Heating and abbreviated CDH in the following) from which connected energy consumers can supply heating with heat pumps as well as passive cooling.

To achieve this goal, the project has developed a geothermal screening procedure based on geophysical mapping, borehole information, pile testing and laboratory measurements of soil thermal properties. A prototype computational model for CDH has been developed and used for assessing the potential for heating and cooling supply of Rosborg Ø, a small, residential subarea of Ny Rosborg. Finally, the project has developed a complete business model for energy pile based, collective heating and cooling (CDH) with a well-defined cost structure in which total fixed and variable costs can be quantified in specific projects such as e.g. Rosborg Ø.

The comparative case study of the geothermal potential and the estimated energy demand of the planned buildings on Rosborg Ø in Ny Rosborg shows that CDH can fully supply the energy demand so long the ratio between the building footprint and liveable area exceeds 11%. Thus, Ny Rosborg is well-suited for CDH based on energy piles, however, recalculation of the scenario is necessary once additional information on the planned buildings become available. This conclusion is further supported by operational data from the energy pile foundation at Rosborg Gymnasium, demonstrating excess heating and cooling possibilities. A further analysis of operational data from the energy pile foundation at Rosborg Gymnasium shows an energy efficiency ratio of 24.8 for the passive cooling during the summer of 2018 which is roughly ten times more efficient than traditional Air Conditioning (AC). Moreover, the analysis shows that Rosborg Gymnasium can supply their cooling needs passively with energy piles 97% of the time where cooling is required. As such, the variable costs of building cooling with energy piles is exceptionally low.

The initial investment is higher for energy piles, however, the variable costs of heating and cooling are greatly reduced relative to traditional District Heating (DH) and AC. In WP 5 the estimated payback period for collective heating and cooling supply of Rosborg Ø based on energy piles is 4.24 years. The relatively short payback period is due to a drastic reduction in the variable costs of heating and cooling with energy piles of ca. 80% relative to traditional DH and AC. The contributing factors to the short payback period are the relatively low costs of electricity, the high COP of the Ground Source Heat Pump (GSHP) system, the relatively high power tariff (effektbidrag) from traditional DH and finally the exceptionally low costs of passive cooling/seasonal heat storage.

In the current project, the partners have developed a truly renewable, economically competitive heat pump technology to supply collective building heating and passive cooling/seasonal heat storage for the future energy supply in Denmark.

1.2 Dansk

Dette projekt undersøger mulighederne for at anvende jorden som kilde til kollektiv, varme- og køleforsyning af et nyt boligområde, Rosborg Ø i Ny Rosborg i Vejle, ved anvendelse af funderingspæle med indstøbte jordvarmeslanger (energipæle). Energipælefunderede bygninger forbindes til et uisoleret Koldt Fjernvarmenet (CDH fremover) beliggende i ca. 1 m. dybde under terræn, som forbrugere kan koble sig på med en varmepumpe. Der er i projektet udviklet en geotermisk screeningsprocedure til bestemmelse af energipotentialet i de øverste 20 meter af undergrunden, hvorfra varme og køl indvindes. Proceduren er baseret på geofysisk kortlægning, borehulsinformation, pæleundersøgelser og laboratoriemålinger af jordens termiske egenskaber. Projektet har i tillæg udviklet en prototype af et simuleringsværktøj for CDH med tilsluttede energipælefundamenter og yderligere forbrugere. Modellen anvendes til at vurdere potentialet for energiforsyning af et mindre delområde Rosborg Ø i Ny Rosborg. På forretningssiden er der i projektet udviklet en komplet forretningsmodel for kollektiv, energipælebaseret varme- og køleforsyning med en veldefineret omkostningsstruktur, hvor de faste og variable totalomkostninger samt tilbagebetalingstid kan estimeres i specifikke projekter, såsom eg. Rosborg Ø.

Sammenligningen af det geotermiske potentiale og det anslåede energibehov for de planlagte bygninger på Rosborg Ø i Ny Rosborg viser, at CDH kan dække energibehovet fuldstændigt, så længe at forholdet mellem det bebyggede og beboede areal er større end 11%. Ny Rosborg er således velegnet til CDH baseret på energipæle, hvilket understøttes yderligere af analyse af driftsdata fra energipælefundamentet på Rosborg Gymnasium, der påviser en overkapacitet af varme- og køl. Ydermere dokumenterer projektet en gennemsnitlig virkningsgrad på 24,8 for køl i den passive køletest i sommeren 2018 på Rosborg Gymnasium, hvilket er ca. ti gange mere energieffektivt end traditionel air conditioning (AC). Analysen viser desuden, at Rosborg Gymnasium kan dække deres kølebehov med frikøling 97% af tiden, hvor der er et kølebehov, hvorfor de variable omkostninger ved køling med energipæle er exceptionelt lave.

Energipæle kræver en større startinvestering men sikrer til gengæld en betydelig reduktion i de årlige omkostninger til varme og køl. På baggrund af arbejdet i WP 5 estimeres tilbagebetalingstiden for kollektiv varme- og køleforsyning af Rosborg Ø i Ny Rosborg til 4,24 år i forhold til traditionel fjernvarme og AC. Den relativt korte tilbagebetalingstid skyldes i al væsentlighed at de årlige omkostninger til opvarmning og komfortkøling reduceres med ca. 80% med energipæle i forhold til traditionel fjernvarme og komfortkøling med AC. De medvirkende faktorer til denne betydelige reduktion i de variable omkostninger er de lave elpriser, den høje virkningsgrad af varmepumpen, det relativt høje effektbidrag, der pålægges ved traditionel fjernvarme samt de ekstraordinært lave omkostninger ved passiv køling/sæsonvarmelagring.

Der er i nærværende projekt udviklet en ægte vedvarende, økonomisk konkurrencedygtig varmepumpeteknologi til kollektiv forsyning af bygningsopvarmning og passiv køling/sæsonvarmelagring til den fremtidige energiforsyning i Danmark.

2. Executive summary

This project investigates the possibilities of supplying a new residential area, Rosborg Ø in Ny Rosborg in Vejle, Denmark with ground source based heating and passive cooling utilizing foundation pile heat exchangers (heat exchanger abbreviated HE in the following) commonly referred to as energy piles. Energy piles are simply traditional foundation piles with embedded geothermal piping. The supply system includes a network of "cold" uninsulated pipes, buried at ca. 1 m depth below terrain, that distribute heating and cooling between connected consumers and energy producers. The latter include Borehole HEs (BHE), energy piles, solar panels, waste heat, etc. and consumers extract heat from the pipe network by means of individual ground source heat pumps. The concept is similar to that of traditional district heating, except that the average fluid temperatures roughly equate to those of the undisturbed ground (8-10°C). Moreover, the network of horizontal distribution pipes exchange energy with the ground adding further capacity to the heating and cooling supply. In the following, we refer to this energy supply concept as "Cold District Heating and Cooling" or simply CDH.

In order to evaluate the potential for CDH in Ny Rosborg, the project is divided into separate work packages (WP). The first step taken in WP 2 includes a geothermal screening of Ny Rosborg that encompasses geological modelling based on geophysical mapping and borehole information that subsequently is combined with laboratory measurements of soil thermal properties, to provide a series of planning maps delineating areas suitable for construction in addition to the geothermal potential of the shallow subsurface.

The screening procedure is relevant for and easily adopted by engineering companies that work with climate adaption and energy, as it draws upon well-known field methods such as geological mapping based on geophysical surveys and borehole information. Mapping the geothermal potential is simply an add-on to standard investigations that engineering companies are able offer future customers. Laboratory measurements of soil thermal properties is easily out-sourced to third party companies. Rambøll, who is member of the steering group, has shown interest in offering "energy mapping" as an addon to their standard geological, geophysical and geotechnical field investigations.

Work package 3 includes testing of a novel HE design for the arrangement of geothermal pipes in the energy pile. The WP further explores the possibilities of connecting piles in series in order to reduce the complexity and costs of connecting the energy piles to the heat pump. The new design utilizes a single-U (1U) pipe with a larger diameter (32 mm) relative to the former design that employs a W-shaped HE with 20 mm pipes. The tests and temperature modelling in WP 3 show that the thermal resistance of the energy pile increases by 58% (to 0.071 m·K/W) which is still significantly lower than the corresponding resistance of traditional BHEs. Pressure drops are greatly reduced with bigger 1U pipes. Therefore, two energy piles can be put in series, potentially reducing the complexity of the plumbing work connecting the energy piles to the heat pump. Moreover, construction and pumping costs are significantly reduced with the new 1U HE.

In work package 4, a prototype computational model for energy pile-based collective district cooling and heating was developed and used for assessing the potential for supplying for Rosborg Ø in Ny Rosborg with district heating and cooling. The model provides a complete simulation of fluid temperatures in the CDH network with connected energy consumers and producers. The modelling based assessment shows that it is possible to cover entirely the heating and cooling demand of Rosborg Ø so long the ratio between the building footprint and liveable area is greater than 11%.

Finally, in WP 5, the project has developed a complete business model for collective heating and cooling (CDH) with a well-defined cost structure in which the total fixed and variable costs can be quantified in specific projects such as e.g. Rosborg Ø. Moreover, the payback period can be estimated using traditional DH and AC as reference. The estimated payback period for collective heating and cooling supply of Rosborg Ø based on energy piles is 4.24 years. The relatively short payback period is due to a drastic reduction in the variable costs of heating and cooling with energy piles of ca. 80% relative to traditional DH and AC. The contributing factors to the short payback period are the low costs of electricity, the high COP of the Ground Source Heat Pump (GSHP) system, the relatively high power tariff (effektbidrag) from traditional DH and finally the exceptionally low costs of passive cooling/seasonal heat storage with energy piles.

3. Project objectives

The main objective of the project is to evaluate the possibilities of collective ground source heat pump based heating and cooling supply with foundation pile HEs in the new residential area Rosborg Ø in Ny Rosborg in Vejle. A network of uninsulated distribution pipes serves to supply heating and cooling to connected consumers utilizing the concept of Cold District Heating and cooling (CDH). The evaluation of this overall objective is divided into a number of tasks:

1. Develop a field method for mapping the geothermal potential in Ny Rosborg (WP 2 and WP 3) by utilizing borehole information, laboratory measurements of thermal conductivity and heat capacity on soil samples and geophysical surveys.

2. Assess the heating and cooling demand of the planned buildings on Rosborg Ø in Ny Rosborg by using state-of-the-art building energy simulations (WP 4).

3. Develop a computational model that computes fluid temperatures in the CDH with connected energy pile foundations (WP 4). The model takes the heating and cooling

demand of connected consumers and the estimated thermal properties of the subsurface from the geothermal screening from WP 2 and 3 as input.

4. Assess by 2) and 3), to which extent that energy piles are able to cover the heating and cooling demand of Rosborg Ø (WP 4).

5. Develop a business model for the establishing energy pile based CDH to supply heating and cooling to residential areas (WP 5). Traditional DH and AC serve as the reference scenario in the business model. Apply the business model

Overall, the project has succeeded in realising these objectives and the associated milestones. The technical and economic feasibility of energy pile based collective heating and cooling have both been demonstrated with a good deal of certainty for the Rosborg Ø case study. However, the project would have been able to further develop and mature the CDH computational model if Maria Alberdi-Pagola and Theis Raaschou Andersen had not left the project prematurely.

3.1 Implementation of the project

The implementation of WP 2 and 3 is done by establishing boreholes in Ny Rosborg from which soil samples are acquired for measurement of soil thermal conductivity and heat capacity in the laboratory at VIA University College in Horsens, Denmark. To better understand, the spatial variation in the different soil layers in the Ny Rosborg area, the boreholes are supplemented by geophysical surveys, serving as a basis for extrapolating soil thermal properties between boreholes. The screening method developed in WP 2 aligns well with existing site investigations e.g. ground water mapping and is therefore easily implemented by engineering companies who carry out such mapping tasks. The screening in future projects should take advantage of the possibility of acquiring soil samples from mandatory geotechnical drillings prior to the construction phase for thermal property assessment.

WP 4 is implemented by employing building energy simulations to estimate the heating and cooling demand for Rosborg Ø and by developing computer algorithms for solving the CDH heat transport equations.

WP 4 has two objectives:

1) Develop a method for energy demand profile calculations for the buildings in the area of interest

2) Implement a mathematical model that describes heat transport in CDH based on energy piles.

In 1) the energy demand screening is based on the open-source building energy simulation model EnergyPlus that simulates the energy needs of individual buildings and entire residential areas. This serves as a means to evaluate fluid temperatures during operation, given the energy demand profile for the area of interest.

With respect to 2) a new mathematical solution to the temperature equation for non-isothermal fluid flow in horizontal pipes, has been developed in the project and implemented in temperature model for CDH. The model implementation is done provisionally in the computational software MATLAB.

Work package 4 utilizes the implementation of objectives 1) and 2) to evaluate to what extent energy piles can supply the heating and cooling demand of the planned, small residential area Rosborg Ø in Ny Rosborg.

Work Package 5 has been implemented by first establishing the Value Proposition Canvas for energy piles during a series of additional project meetings that focused exclusively on developing the business model. Once the Value Proposition Canvas was defined, the attention in WP 5 was shifted to quantifying the cost structure for energy pile foundations and to establishing a framework for calculating payback periods for specific cases. In addition to the project participants, the external partners PlanEnergi, Geodrilling A/S and Tørring VVS have made significant contributions to quantifying the cost structure for energy pile foundations, facilitating the estimation of the payback period in specific cases using traditional DH and AC as reference.

3.2 Evolution of the project

The project has generally evolved in line with the original objectives in the work packages and in accordance with the predefined milestones. However, early in the project, the project partners realized that it was necessary to develop a business model for single energy pile foundations for individual buildings rather than for the full CDH network based on energy piles. This is mainly because the full cost structure for individual energy pile foundations was unknown prior to the project. If energy piles are economically infeasible for individual buildings it seems very unlikely that CDH based on energy piles will prove to be any different. The payback periods for individual buildings are surprisingly short which demonstrates that energy piles pose a viable alternative to traditional DH and AC. On that basis, it was possible to further develop the business model for collective heating and cooling supply with energy pile based CDH. To that end, Vølund Varmeteknik estimated the dimensions of the required piping and Søren Andersen from Geodrilling kindly estimated the costs of constructing the distribution network consisting of horizontal piping. The project partners reached out to Geodrilling the company owns and operates several CDH networks in Denmark.

3.2.1 Project risks

Several of the large, initial risks in the project have been minimized:

1. Risk associated with the security of supply
2. Risk of economical infeasibility

The project has demonstrated beyond any reasonable doubt, that CDH based on energy piles is a technically and economically viable option for collective heating and cooling of Rosborg Ø. The risk that by far causes the most concern, is the general reservation and conservatism towards new green technologies that pervades the energy sector and the construction and building industry. Even short payback periods such as those demonstrated in this project can pose a barrier towards market success.

The project did not encounter any serious issues or problems. However, two key participants, project manager Theis Raaschou Andersen (VIA) and Maria Alberdi-Pagola (CP) left the project early and somewhat unexpected. These events required some reorganization of the project and additional employment, taking time primarily from WP 1 and WP 4. The work in WP 4 was not critically hampered by the loss of Maria Alberdi-Pagola from the project. However, more progress in WP 4 would definitely have been possible with her continuance in the project.

In January 2019, the commercial partners in the project suggested that a consulting company specializing in renewable energy was invited for a meeting to discuss the possibilities of establishing a consortium of partners capable of offering energy pile foundations as a single and complete product to customers. The renowned consultant company on renewable energy, PlanEnergi, was invited and soon after teamed up with the project group, supplementing and structuring the work with the business model in WP 5. Moreover, PlanEnergi assists municipalities in their strategic energy planning and compilation of technology catalogues for renewable energy thereby creating an opportunity for disseminating the concept of energy pile based heating and cooling to decision-makers.

4. Project results and dissemination of results

This chapter initially and briefly summarizes the work packages in the project. The summary is followed by a more detailed description of the work and outcomes of the work packages.

4.1 Short summary of work packages

4.1.1 WP 2 and WP 3

The project initially maps the geological and geotechnical setting and subsequently the thermal properties of the subsurface at Ny Rosborg, thus proposing a new addon – "geothermal mapping/screening" - to existing field investigations based on borehole information and geophysical surveys.

In addition, the project also tests a new HE design with larger diameter pipes to be used in future energy piles that is both cheaper to produce and reduces the pumping costs significantly during operation. Moreover, the new HE design facilitates coupling of energy piles in series, which potentially reduces the costs of connecting the piles to the heat pump. The drawback of the 1U HE is an increased thermal resistance between the pipe fluid and the ground. Heat transport simulations, however, reveal that this is not a serious issue when considering the benefits of the simpler 1U HE.

4.1.2 WP 4

The geothermal maps of thermal conductivity and heat capacity serve directly as input to the computational model developed in the project that allows for dimensioning CDH networks (WP 4). The computational model developed in this work package simulates fluid temperatures in the CDH network with connected consumers and energy providers. It takes into account the thermal interaction between the ground and the uninsulated pipes that distribute heating and cooling between energy producers and consumers.

The computational model inputs the energy demand profile for the buildings in the area of interest which is Rosborg Ø in this project. To that end, building energy simulations for Rosborg Ø done with the open-source model EnergyPlus show that it is likely that the energy consumption will exceed that allowed by the BR20 regulations. Utilizing the developed CDH model shows that energy pile based CDH can fully supply the energy demand on Rosborg Ø so long the ratio between building footprint and liveable area exceeds 11%. Thus, Rosborg Ø is well-suited for CDH based on energy piles, however, recalculation of the scenario is necessary once additional information on the planned buildings become available.

4.1.3 WP 5

The geothermal screening, heat transport simulations and technical investigations serve as the basis for a complete business model for collective, energy pile based heating and cooling supply for residential areas. The project has quantified the cost structure for deploying energy pile foundations including the installation of energy piles, plumbing of pipes and connections to the heat pump, the cost of the heat pump and additional installations required for heating and cooling of individual buildings connected to the CDH. The variable costs of operation that are mainly attributed to electricity consumption, have been quantified for both heating and cooling with energy piles. A fully quantified cost structure is a prerequisite for estimating the payback period when comparing to traditional DH and AC.

By utilizing the business model, the estimated payback period for collective heating and cooling supply of Rosborg Ø based on energy piles is estimated to be 4.24 years. The relatively short payback period is due to a drastic reduction in the variable costs of heating and cooling with energy piles of ca. 80% relative to traditional DH and AC. The contributing factors to the short payback period are the low costs of electricity, the high COP of the Ground Source Heat Pump (GSHP) system, the relatively high power tariff (effektbidrag) from traditional DH and finally the exceptionally low costs of passive cooling/seasonal heat storage.

4.1.4 WP 6

The dissemination of the project is shown in the context of the dissemination plan in the application as shown in Table 1.

Table 1: Dissemination of the project results

Activity	No.	Product	Format	Target	Time	Responsible	Completed
WP 1: Project management	1.1	Minutes etc.	Document	Partners + steering group	Ongoing	VIA	Yes
WP 2: Mapping of the shallow geothermal potential in Ny Rosborg	2.1	Internal document + final report	Report	Partners + steering group	Before 1st of April 2018	VIA	Yes
WP 3: Installation and testing of energy piles	3.1	Presentation of preliminary results from the project	Presentation at national conference	Entrepreneurs Construction industry	Autumn 2018	VIA/Centrum Pæle	Meeting in the Danish Geotechnical Association (DGF), 19/92019
WP 4: Energy calculations for energy pile based heating and cooling supply	4.1	Internal document	Document	Partners + steering group	Primo 2019	VIA	Final report
AP 5: Business model for energy pile based collective heating and cooling supply	5.1	Documentation of the business model for energy piles	Document	Developers Entrepreneurs	Autumn 2019	Centrum Pæl Vølund Vejle Fjernvarme	Final report
	5.2	Guideline to municipalities on implementing energy piles in future construction projects	Guideline report	Authorities	Autumn 2019	Vejle Municipality	**No (not possible)**
	5.3	Presentation of preliminary results from the project	Presentation at national conference	Municipalities Construction industry District heating companies	Autumn 2019	Vejle Kommune VIA	Innovationsfestival i Dandy Business Park, 29/8-2019
AP 6: Dissemination	6.1	Final dissemination	Report	The national energy sector Authorities Consultants	Ultimo 2019	All	Final report
	6.2	Presentation of project results	Presentation at national conference	The national energy sector Authorities Consultants	Ultimo 2019	All	Meeting at VIA scheduled in February 2020
	6.3	Presentation of project results	Presentation at international conference	The international energy sector Authorities Consultants	Ultimo 2019	All	ECSMGE 2019, Iceland, 1.-6. September, 2019
	6.4	Article in national journal	Article	Municipalities District heating companies	Ultimo 2019	All	Building Supply Energy Supply Licitationen
	6.5	2 journal articles with international peer review	Article	International stakeholders	2020-2021	VIA	One paper published Two papers in preparation

The target group for the dissemination of project results include a wide range of stakeholders:

1) **Municipalities** should be allowed to impose restrictions on the sources of heating and cooling in new residential areas in the future to accelerate the green transition. Energy piles consume much less energy in supplying heating and cooling compared to traditional sources, and therefore serve as unique systems to maximize the share of renewable energy and resource efficiency.

2) Two major **engineering companies**, Rambøll and COWI, have participated in the steering group and the project results have enabled them to put energy piles and the geothermal screening into their product portfolio.

3) Once consultants and municipalities suggest/demand energy piles as clean energy technologies, **entrepreneurs and construction companies** are strongly motivated to incorporate them into their product portfolio. Nevertheless, the overall nudging process of breaking down conservatism, retrogressivity and scepticism among stakeholders must include practical guidelines directed at **practitioners**.

4) The **district heating association and companies** in Denmark must view this project as an opportunity to extend their vision beyond the use of biomass and to learn more about competitive renewable energy sources, allowing them to better adjust to a future energy supply dominated by heat pumps. Moreover, dissemination to **the international energy sector** is vital, as Europe alone comprises a huge market for renewable, collective heating and cooling systems, as the current coverage of district heating in the EU (12%) is set to increase to 50% in 2050. If ground source heat pump based collective heating and cooling can be "exported" to areas without the possibility of traditional district heating in Denmark (Dansk: område 4) then it is likely that it can be converted into export to the European countries.

It was not possible for Vejle municipality to deliver the guideline to municipalities on implementing energy piles in future construction projects (dissemination product 5.2 in Table 1). Vejle Municipality explains this in the following way (quote):

(In English) *"Vejle Municipality has participated with great interest in the EUDP project on the potential of using energy piles for district heating and cooling of buildings.*

With the urban development project Ny Rosborg, energy piles comprise an experiment i.e. an opportunity that is tested on a theoretical level in relation to uncovering the potential for supplying an entire residential district. The results of the EUDP project are included continuously in the work on the development plan for the resilient district of the future. This is both physical in the form of the test set-up at the pavilion, which is used as a meeting place and information center, but also as a potential strategic element in relation to urban development. In addition, the theoretical business case/total economy is also included as a possible strategic element in the economic planning.

In this way, the municipality of Vejle has already gained significant knowledge about the technology and the potential. So has other stakeholders such as politicians, citizens and the employees in the municipality who have been involved along the way.

Public authorities are restricted by competition clauses to prevent predisposition of particular companies. This also means that Vejle Municipality cannot specifically recommend or establish guidelines on energy piles, however, they can be included in our science catalog on heating/cooling technologies, in particular when constructing on soft sediments that require foundation piles such as in river valleys.

Nor is it possible to make strategic energy planning in which different types of preferred energy supply are differentiated in distinct areas including where, for instance, there is potential for district heating, natural gas or individual heat sources.

However, special requirements can be imposed in tenders by the landowner. Such requirements can be defined in terms of price, features, aesthetics and also sustainability and energy frameworks."

(På dansk) *"Vejle Kommune har med stor interesse deltaget i EUDP projektet omkring, hvilke potentialer der ligger i energipæle til fjernvarme og køling af bygninger.*

Med byudviklingsprojektet Ny Rosborg er energipæle brugt som et eksperiment – en mulighed som afprøves på et teoretisk niveau ift. at afdække potentialerne for en hel bydel. Resultaterne fra EUDP projektet er løbende inddraget i arbejdet med udviklingsplanen for fremtidens resiliente bydel. Dette både fysisk i form af test-opstillingen ved pavillonen, der bruges som mødested og informationscenter, men også som et potentielt strategisk element i forhold til byudviklingen. Desuden inkluderes den teoretiske totaløkonomi også som et muligt element i den økonomiske plan.

På den måde har Vejle Kommune allerede fået en masse viden om produktet og potentialerne – både direkte og som arbejdsgruppe, men også andre politikere, borgere og andre medarbejdere, som har været involveret undervejs.

Som offentlig myndighed er man bundet af konkurrenceklausuler ift. at man ikke må forfordele andre virksomheder. Det betyder også, at vi ikke specifikt kan anbefale eller lave vejledninger omkring energipæle, men at de kan indgå i vores videnskatalog omkring muligheder for opvarmning/køling – særligt når vi bygger i Ådale, altså blød bund.

I forhold til planlægningen er det heller ikke muligt at man kan lave en strategisk energiplan, hvor man kan differentiere forskellige ønskede energiforsyningsformer i forskellige områder områder – herunder hvor der f.eks. er potentiale for fjernvarme, naturgas eller individuelle varmekilder.

Man kan dog stille særlige krav ift. et udbud, hvis man selv ejer grunden. Det kan være ift. pris, funktioner, æstetik – og også bæredygtighed og energirammer."

5. WP2: Thermal potential in Ny Rosborg

5.1 Purpose

The purpose of this work package is to map the thermal potential in the Ny Rosborg area (Figure 1), including the monitoring of the groundwater table to determine potential groundwater flow. Geology and hydrogeology are important parameters affecting the efficiency and capacity of the energy pile foundations. Fifteen short drillings are established in the Ny Rosborg area (Figure 2), from which soil samples are collected for geological and thermal property analyses. The latter are determined by means of the "Hot Disk" (transient plain source method). Piezometers are installed in selected wells for monitoring the groundwater table.

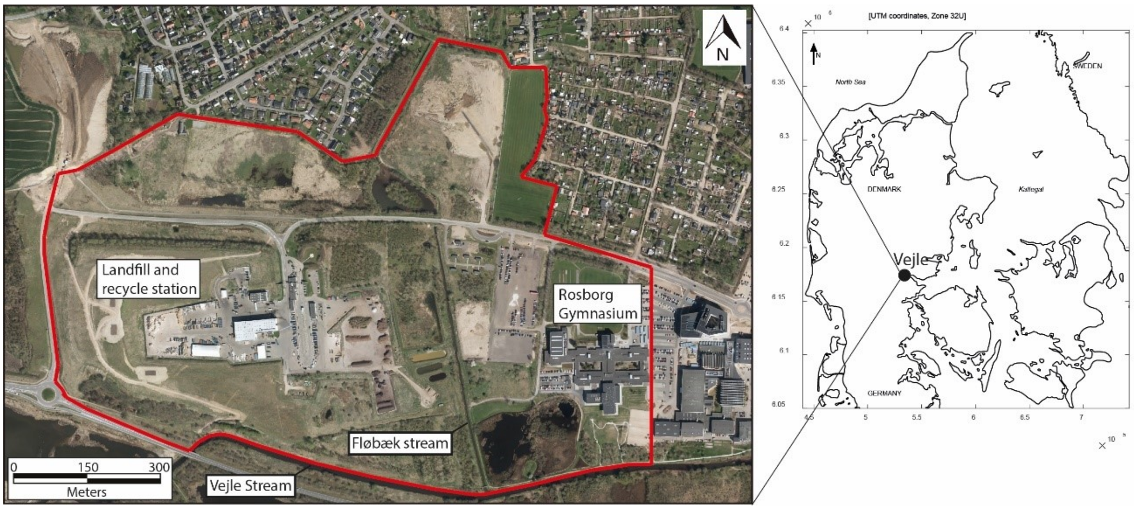


Figure 1: Overview map showing the study site Ny Rosborg.

5.2 Methodology

The fieldwork has been carried out in the Ny Rosborg area, situated in the west part of Vejle, Denmark (Figure 1). The work consists of drilling boreholes, soil sampling, soil description and measurements of water content and thermal properties. The laboratory work was carried out at VIA UC in Horsens, Denmark.

5.2.1 Drilling and soil sampling

Twelve 10 m deep drillings as well as three drillings deeper than 15 m were established in the Ny Rosborg area between the 12/12/2017 and the 01/04/2018. The position of the drillings is shown in Figure 2. The boreholes are drilled using the rotary auger technique, without casing. Soil samples are collected every 0.5 m when possible, and they were kept in sealed plastic bags.

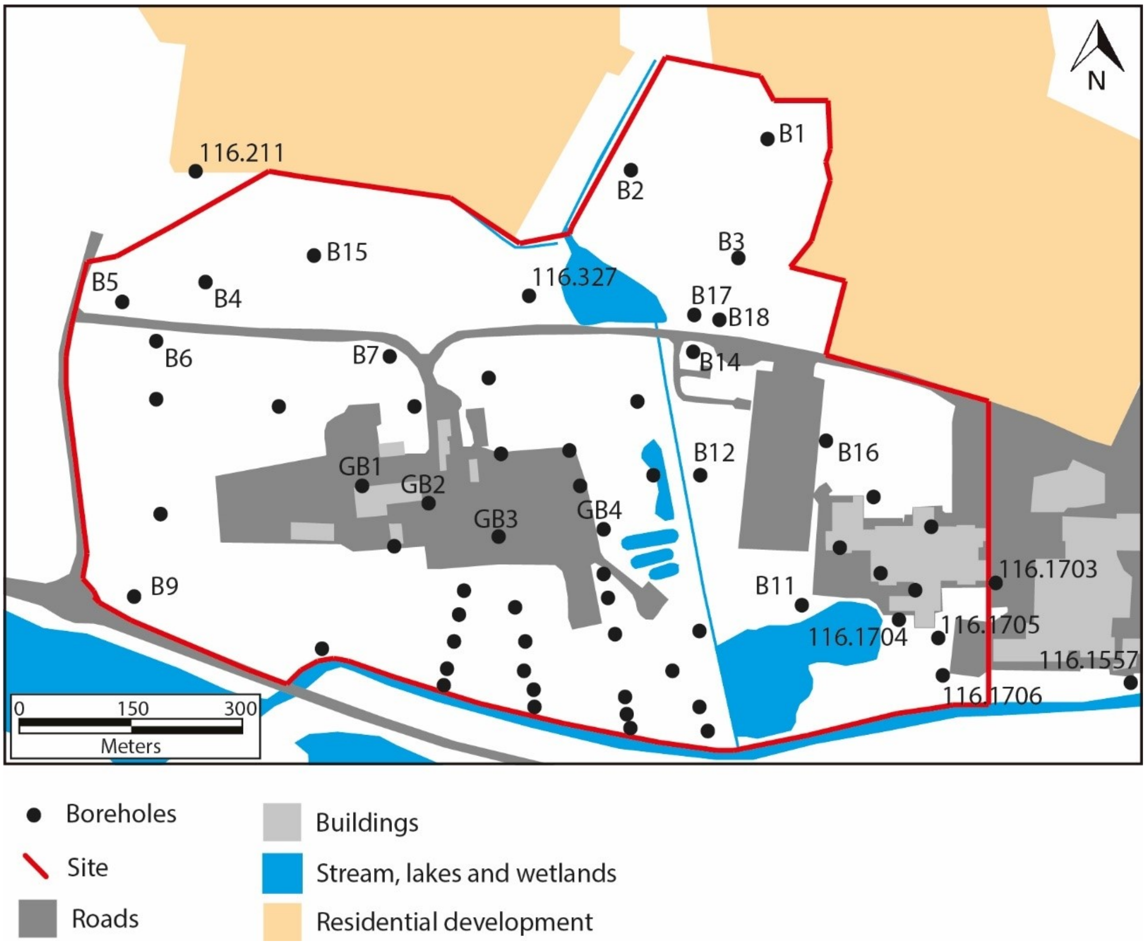


Figure 2: Overview map showing location of drillings

5.2.2 Soil description and properties

The soil description procedure has been carried out according to the DGF Bulletin 1 [1].

The laboratory work took place between the 19/12/2017 and the 22/12/2017. The thermal properties were measured first to document the undisturbed conditions. The water content and the density have been measured following the ISO standards [2,3]. The water content has been measured in drillings: B1, B2, B3, B4, B7, B9, B11 and B12. B16 was analysed in a previous research project [4]. The thermal properties have been measured by means of the Hot Disk apparatus [5]. The Hot Disk equipment relies on the transient plane source method [6]. The transient plane source method yields estimates of the thermal conductivity λ [W/m/K], volumetric heat capacity ρc [MJ/m^3/K]. Thermal diffusivity α [m^2/s] is defined as the ratio between the thermal conductivity and volumetric heat capacity.

The Hot Disk sensor is an electrically conducting metallic double spiral (nickel), covered by two thin layers of insulating material (kapton). During the measurement, the sensor is placed between two pieces of sample. As the electrical current flows, the temperature of the sensor increases and at the same time, the temperature resistance as a function of time is measured. Hence, the sensor acts as a heat source and a dynamic temperature sensor.

Five repeated measurements have been taken for each sample at a room temperature between 19 to 21 °C. The measurement procedure follows the steps defined in [7]. The thermal properties have been measured in drillings B1, B4 and B9, in selected samples.

5.2.3 Mapping of the groundwater table

Piezometers are placed in selected wells for monitoring the changes in the groundwater table. Manual measurements of the groundwater level were carried out in January, February, May and August 2018.

5.2.4 Geological setting and mapping

Prior to this project, Vejle Municipality had the Ny Rosborg area mapped using the geophysical methods DualEM-421 and ERT. The geophysical data, in combination with the drillings performed in this project, have been used to construct a detailed 3D geological model of the Ny Rosborg area [8].

5.2.5 Model estimation of the geothermal potential

The thermal properties of the soil affect the dimensioning of the ground source heat pump installation. I.e., the performance of the installation differs in clayey or sandy soils. To illustrate this, an example is provided. The aim of this section is to show how a preliminary dimensioning analysis can be carried out for buildings from which a monthly distributed heating and cooling need and a foundation arrangement (or footprint area) are known (inputs in Figure 3). The method, based on the model developed in [4], yields the number of energy piles required to supply the space conditioning needs of a given building under different soil conditions. This procedure will assist in the selection of a suitable heat pump to keep sustainable ground loop temperatures over the installation lifetime. The example treated here involves an office building, but this method can be applied to any type of building.

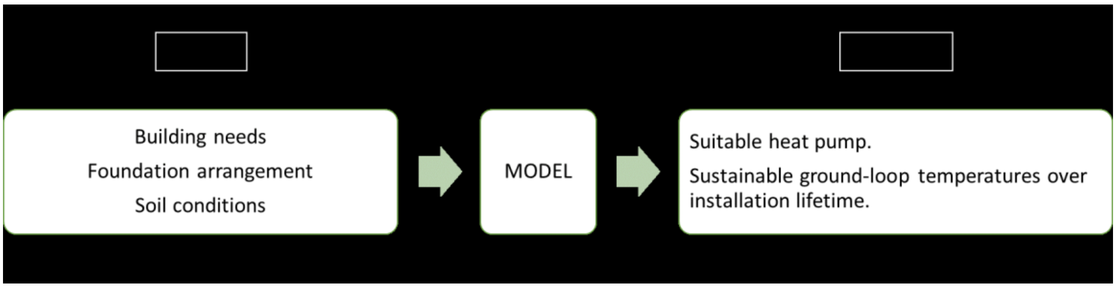


Figure 3: Preliminary dimensioning tool description.

5.3 Results

The detailed soil descriptions are provided in Appendix A. In the following, the measured soil and thermal properties are described.

5.3.1 Soil properties

The water content profiles of different drillings are provided in Figure 4. The clayey sediments (gyttja and peat) have a higher water content than the sand, typically above 50% in many cases.

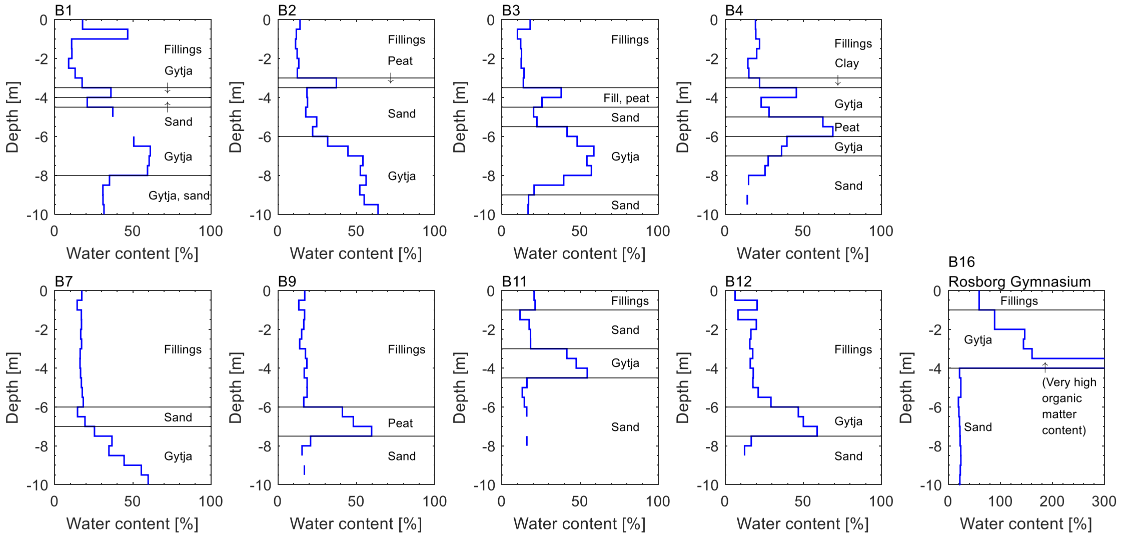


Figure 4: Water content profiles for the drillings.

Figure 5 shows the thermal property profiles for drillings B1, B4, B9 and B16.

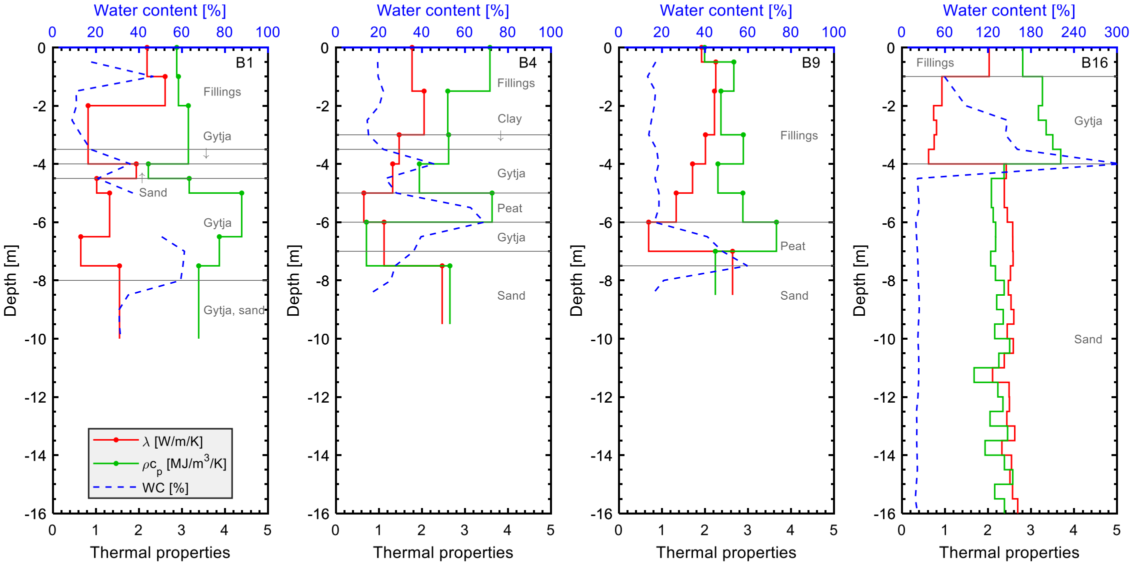


Figure 5: Thermal properties profiles for drillings B1, B4, B9 and B16. The legend is common to all the subplots.

The thermal properties vary depending on the type of soil: sand is a relatively good thermal conductor while clayey and/or organic sediments conducts heat poorly. Therefore, the thermal conductivity is fairly high in B16, due to the relatively shallow presence of the oldest sand deposits. Table 2 provides the weighted average thermal properties and bulk density values.

Table 2: Weighted average values of thermal conductivity and volumetric heat capacities.

Drilling name	**Analysed depth [m]**	**Bulk density [kg/m³]**	**Thermal conductivity [W/m/K]**	**Volumetric heat capacity [MJ/m³/K]**
B1	10	1530	1.44 ± 0.08	3.37 ± 0.37
B4	9.5	-	1.66 ± 0.09	2.51 ± 0.29
B9	8.5	-	1.91 ± 0.10	2.62 ± 0.31

B16 [9]	16	1850	2.14 ± 0.11	2.47 ± 0.29

The density of the clayey sediments is lower than the coarse-grained sediments.

5.3.2 *Mapping of the groundwater table*

The groundwater level was measured manually in January, February, May and August 2018 (Figure 6).

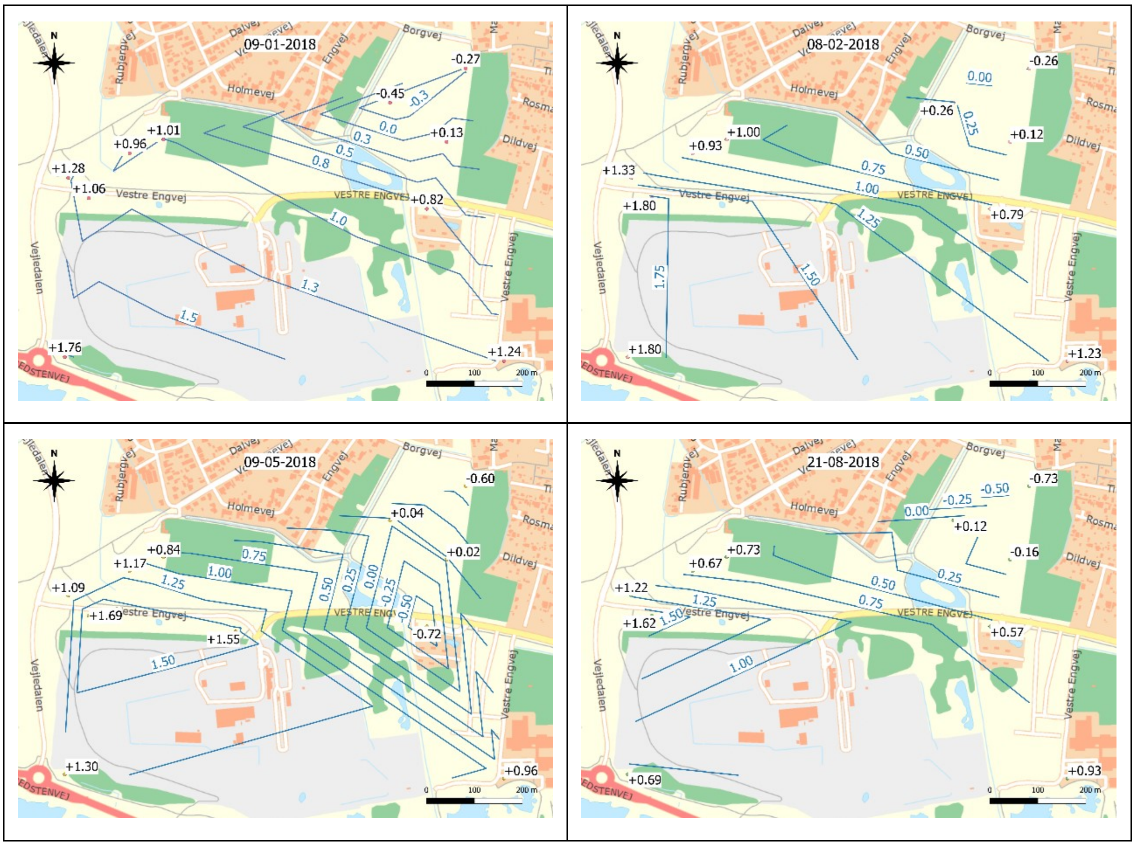


Figure 6: Recorded groundwater levels in 2018.

Groundwater levels fluctuate somewhat during the year with elevated levels during winter. The summer of 2018 was exceptionally dry and water levels in May and August were relatively low. Groundwater flows predominantly towards NE. The area is artificially drained and small-scale variations are recorded where observation wells are close indicating complex flow patterns that cannot be fully resolved with the number of observation wells available. Given the overall hydraulic gradient and typical hydraulic conductivities, Darcy velocities range between $5{\cdot}10^{-8}$ – 10^{-6} m/s.

5.3.3 *Geological setting and mapping*

Based on borehole information as well as the geophysical mapping [8] the substratum is observed to consist of glacial sediments covered by postglacial sediments. On top of the postglacial sediments, an up to 10 m thick layer of fill materials is observed (Figure 7).

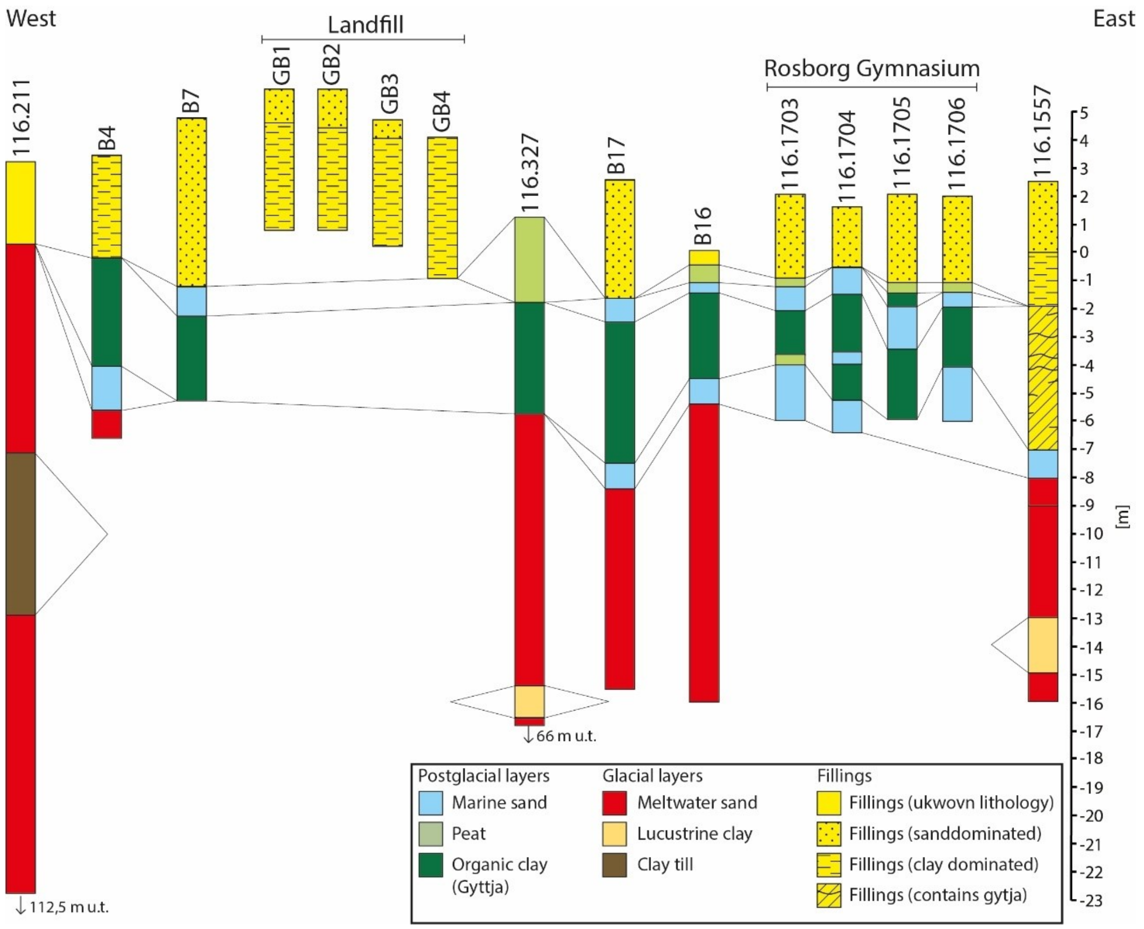


Figure 7: Geological cross section.

The glacial deposits consist of interbedded layers of clay till with thicknesses up to 5 m, meltwater deposits locally up to 15 m thick and thin lacustrine clay layers. The meltwater sand is fine to coarse-grained, poorly sorted sand with gravel. The glacial sediments were deposited when the Danish area was covered by ice during one or more of the Pleistocene glaciations. The postglacial sediments consist of layers of marine sand, organic clay (gyttja) and peat. The marine sand can be divided into an upper and lower unit. The layers are typically between 0 to 3 m in thickness and identified as fine to medium-grained sorted sand with shells. In between, the marine sand, a 2-5 m thick layer of organic clay is found. The organic clay is described as silty organic clay (Gyttja) containing plant remains and shells. Sections of peat, typically between 0 to 3 m in thickness is observed throughout the postglacial layers. All the postglacial sediments were deposited in the Holocene period starting 11.700 years ago and represent various depositions during the changes in the relative sea-level that occurred during the Holocene. The lower marine sand represents the first phase of a sea level rise in mid-Holocene, the Littorina transgression, which culminated approximately 7500 years ago. At that time the sea level was 5-10 m higher than today and the organic clay was deposited. The organic clay is allochthonous and has been formed by the reworking of organic material and inorganic material by bottom dwelling animals. The upper marine sand layer represents the beach sediments deposited during the resulting regression phase where the coastline moved back towards its present location.

The subsurface is divided in main soil units and a relation is established between measured samples and corresponding soil units. The values of the thermal properties are simple averages of all the measurements of the samples corresponding to each soil unit (Table 3).

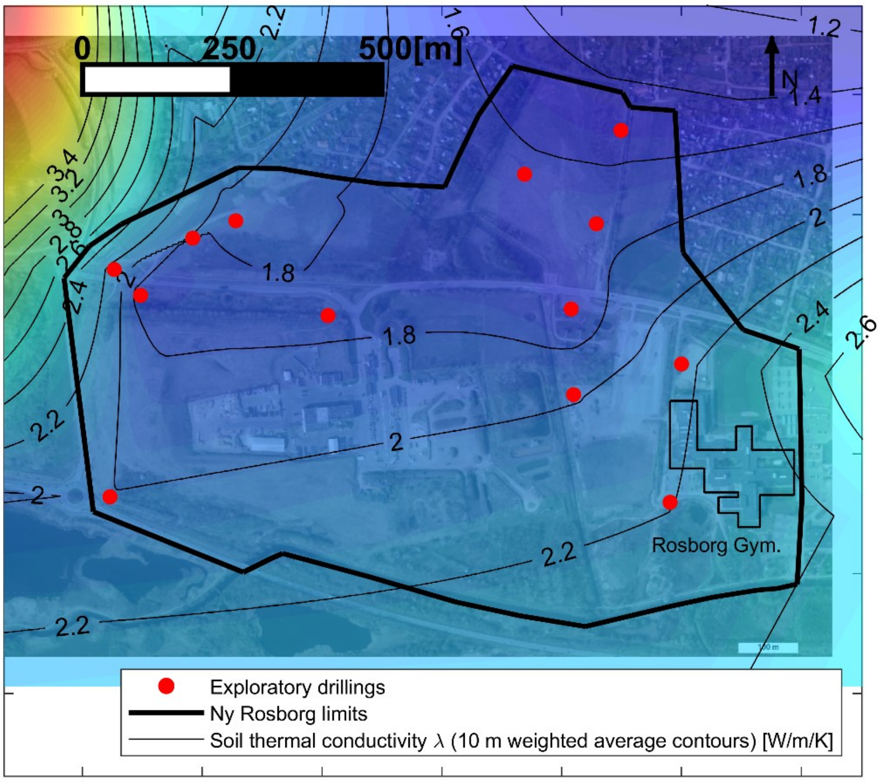
Table 3: Thermal properties of main soil units.

Unit name	**Mean thermal conductivity λ [W/m/K]**	**Mean volumetric heat capacity ρc$_p$ [MJ/m^3/K]**
Fillings	2.05	2.93
Gyttja	0.91	3.11
Peat	1.08	3.14
Clay	1.08	3.14
Sand	2.47	2.24
Gyttja-sand	1.55	3.39

The drilling locations (Figure 2) and the corresponding geological sequences are combined with the thermal properties measured for the geological units. Weighted averages are calculated and interpolated over the study area. Contour plots are shown in Figure 8, providing an overall visualisation of the expected thermal properties in the area.

Figure 8a shows an increase in the thermal conductivity towards the south east part of the area, i.e., near Rosborg Gymnasium. Here, sandy sediments emerge at 4 to 5 m below the surface (profile B16 in Figure 5). In the northern part, the thickness of the filling and organic deposits increases, yielding a lower thermal conductivity. In terms of volumetric heat capacity, fine-grained sediments show higher values, as observed in the north and north-west parts of the area (Figure 8b).

a)



b)

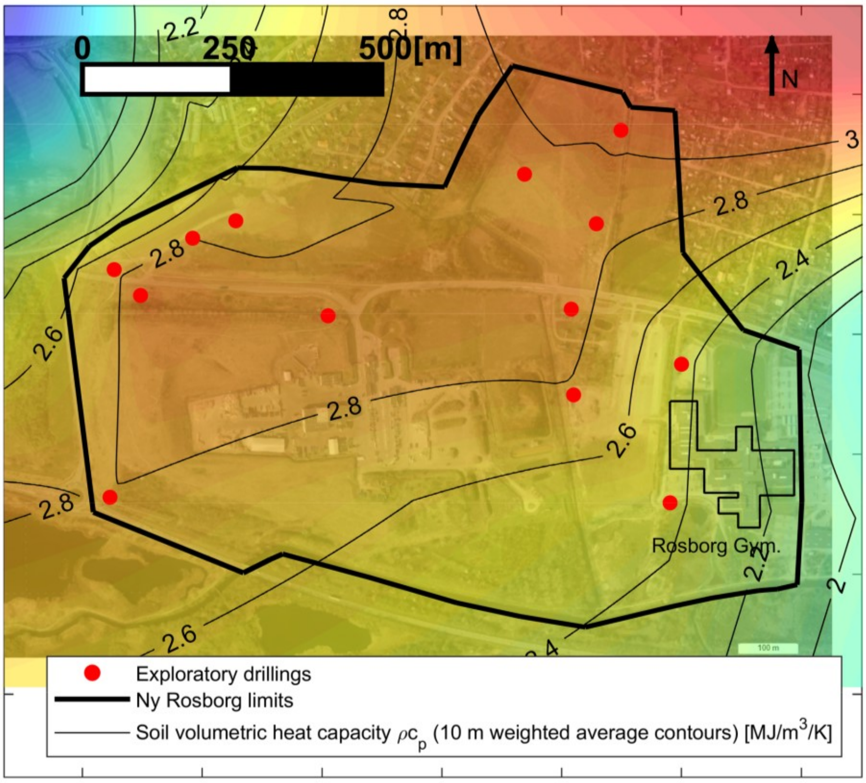


Figure 8: Contour plots of thermal conductivity and volumetric heat capacity, a) and b) respectively, in the Ny Rosborg area.

Thermal properties affect the efficiency of GSHP systems. High thermal conductivities are preferable, since the soil recovers faster. However, high volumetric heat capacities are advantageous for underground thermal energy storage, as the stored heat is retained near the source.

In terms of the geotechnical properties, fine grained deposits, such as fillings, gyttja and clays, exhibit poor strength. These sediments have been observed in all parts of the study area, with thicknesses ranging up to 10 m, suggesting pile foundations will be required and energy piles may be employed.

5.3.4 Geothermal potential for a single office building

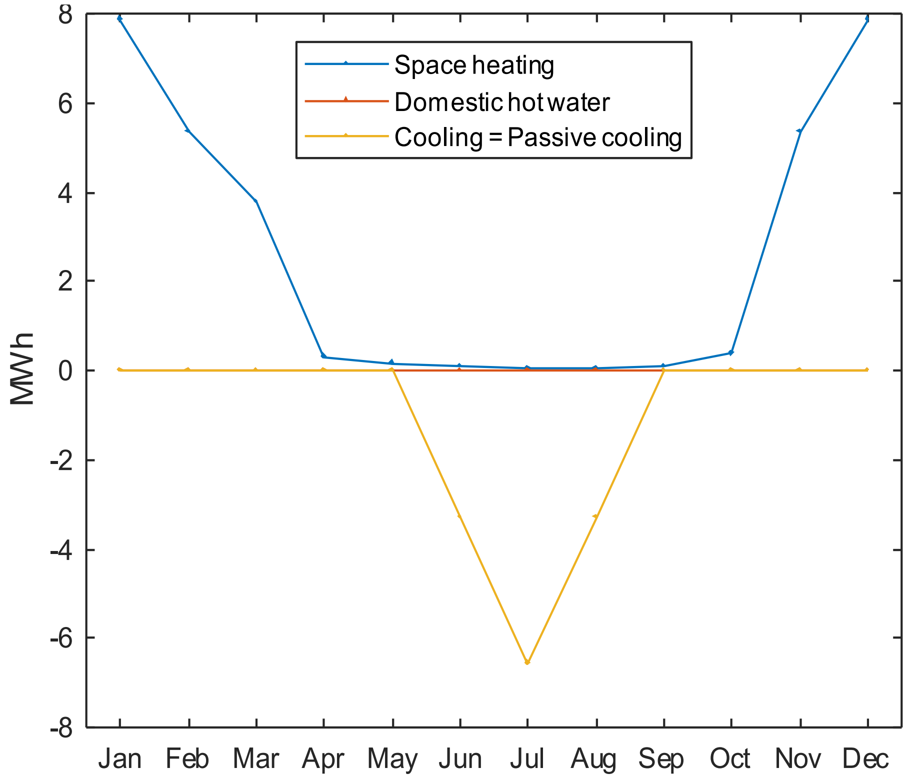
This section uses the dimensioning tool developed in [4] in an analysis of the geothermal potential for a hypothetical building. The analysed office building has the following characteristics:

- Total number of piles: 113 distributed over 750 m^2
- Energy pile active length: 15 m
- Single-U configuration
- Heat pump COP: 3
- Heat transfer fluid: water
- Passive cooling: yes
- Conditioned area: 1500 m^2
- Total heating/year: 31.5 MWh/year (based on BR15)
- Total cooling/year: 13.1 MWh/year (based on BR15)
- Peak heating: 80 kW
- Peak cooling: 20 kW
- No domestic hot water considered

- Calculated for 25 years
- Monthly resolution

The thermal load distribution is shown in Figure 9.

a)



b)

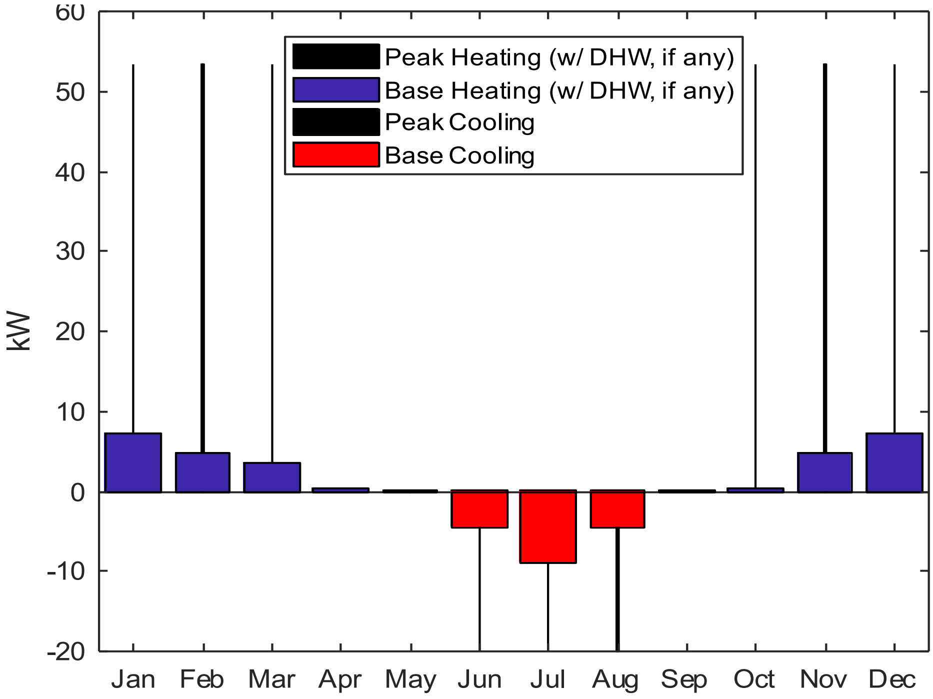


Figure 9: Building thermal needs: a) base loads, b) peak ground loads.

We carry out a parameter sweep where the thermal conductivity of the soil λ [W/m/K] and the thermal load Q [kW] are varied to analyze the sensitivity of the performance of the energy pile foundation to varying conditions (peak loads are not considered here) (Figure 10).

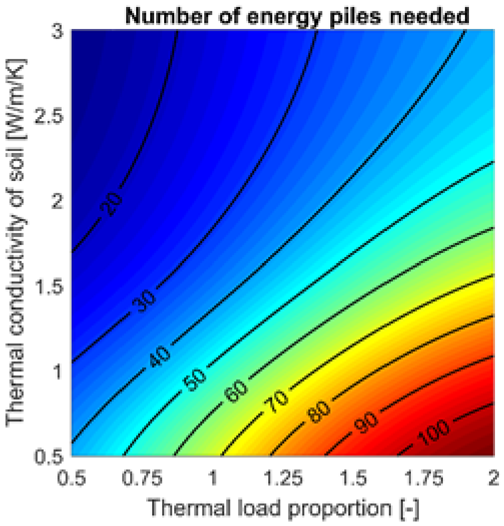


Figure 10: Parameter sweep to show the influence of thermal conductivity on the required number of energy piles

Figure 10 shows a large sensitivity of the number of energy piles to the thermal conductivity of the ground. The thermal conductivity of the soil cannot be engineered and must be determined by appropriate field or laboratory measurements such as thermal response testing during the geotechnical investigations where piles are driven to assess the depth of the foundation.

The existing groundwater flow (treated previously in this section) will increase the effective thermal conductivity of the soil, improving the performance of the ground source heat pump system, as it eases the heat transfer. On the other hand, ground water flow is not favourable for thermal energy storage.

It is common practice to design ground source heat pump installations to cover 80% of the heating load, given that peaks in demand are supplied by a complementary source. In the design process, an accumulation tank to reduce peak loads should be considered, which results in higher fluid temperatures when space heating mode is working. Moreover, heat pumps are typically fitted with a built-in electric boiler to shave peak loads in the heating demand.

Obtaining an accurate energy demand profile for a planned building is not always possible. In that case, parameter sweeps are useful for quantifying the uncertainty of the number of energy piles from having insufficient knowledge of the thermal load of the building.

For the case of the lowest thermal conductivity found in the area (1.4 W/m/K) and to cover 100% of the base and peak loads, ground loop temperatures go just below 1 °C for conservative peak requirements (few hours per month) (Figure 11). This shows that energy piles are a feasible option to supply the space heating and cooling needs of the Ny Rosborg area in the future.

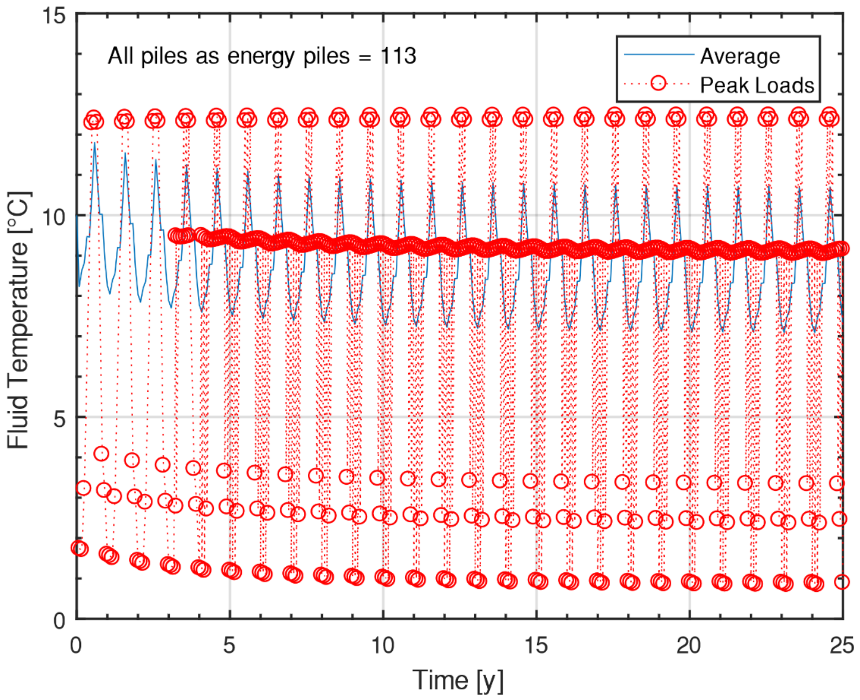


Figure 11: Ground loop temperatures during 25 years of operation, given that all piles are energy piles.

5.4 Conclusions

In this work package, a thorough mapping of the geological setting in the Ny Rosborg area has been carried. Groundwater flow and the thermal properties of the geological units have been estimated and mapped. Subsequently, the surveys form the basis for a preliminary dimensioning of an energy pile installation to supply an office building. The investigations show that energy piles are able to cover the heating and cooling needs of the studied hypothetical building in Ny Rosborg, making it suitable for energy pile applications.

6. WP3: Installation and testing of energy piles

6.1 Purpose

The purpose of WP 7 is to further characterize the thermal potential in the Ny Rosborg area and to test the performance of a new pipe configuration for the pile HE. For this, three energy piles haven been installed. A Thermal Response Test (TRT) was performed on two of them to obtain a more accurate indication of the soil thermal properties over the active length of the energy piles and to assess the efficiency of the HE. In addition, one energy pile is complemented by a monitoring drilling at a distance, where thermocouples were installed at specific depths to measure soil temperatures during the TRT.

This section is structured as follows. First, the energy piles are presented. Second, the fieldwork carried out is explained, comprising the installation of the energy piles, the drillings, the TRT setup and its execution. Third, the TRT interpretation models are described. Fourth, the Results and Discussion section provides the measurements and the TRT interpretation estimates. Finally, conclusions are drawn.

6.2 Description of energy piles

Energy piles are concrete foundation piles with built in geothermal pipes thus serving as a vertical closed-loop HEs [10]. Pile HEs vary in length from 7 to 50 m with a side length or diameter of 0.3 to 1.5 m. The methods of construction include cast-in-place concrete piles, 0.3-1.5 m in diameter; precast concrete piles with side lengths spanning 0.27-0.6 m; hollow concrete precast piles and driven steel piles.

The terms “energy pile” and “pile HE” describe a quadratic cross section pile HE with a length between 7 to 18 m, as indicated in Figure 12. An energy pile is simply a traditional foundation pile (produced by Centrum Pæle A/S), in which a single-U shaped pipe (32 mm outer diameter) has been embedded inside by fitting it to the reinforcement cage. Approximately 80 cm from the top and bottom are left without piping, implying that the active length of the energy pile is 1.6 m less than the total length of the pile.

Figure 12: a) Single-U pipe attached to the steel reinforcement cage. b) Energy pile cross section. Dimensions are given in cm.

6.3 Fieldwork

The fieldwork was carried out in the Ny Rosborg area in Vejle, as described in WP 2. The fieldwork consisted of installation of the energy piles and additional drillings and execution of TRT. The energy piles were driven the 2/05/2018.

6.3.1 Installation of energy piles and temperature sensors

Two locations have been chosen for the energy piles in the Ny Rosborg area (Figure 13). The position coordinates are given in Table 4.

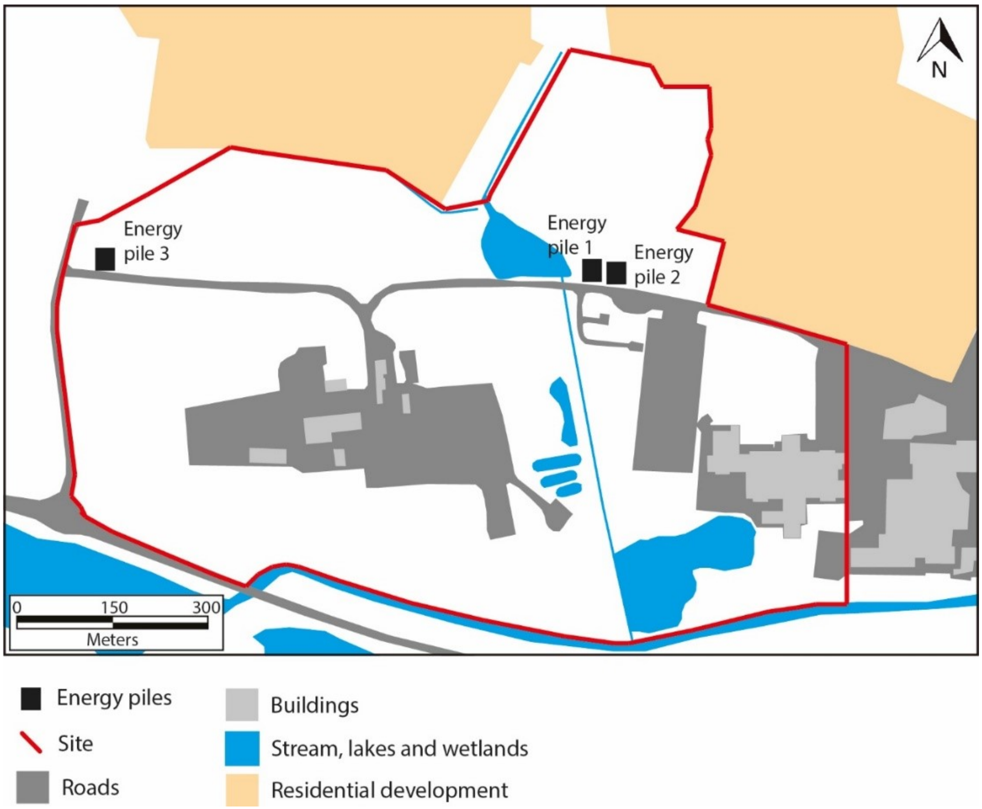


Figure 13: Energy pile locations.

Table 4: Energy pile and drilling position coordinates.

Pile	**GPS (x, y)**
Energy pile 1 (Pavilion area)	55.709571, 9.509116
Energy pile 2 (Pavilion area)	55.709571, 9.509075
Energy pile 3 (alone)	55.709929, 9.497545
Additional drilling 1	531983.007, 6173877.465
Additional drilling 2	531985.003, 6173877.194

Energy piles 1 and 2 are placed at Vejle Kommune's Pavilion area at Venstre Engvej in Vejle. In addition, two drillings were established, 18 m each, adjacent to one of the energy piles, at a distance of 2.30 and 4.00 m respectively (Figure 14). Unfortunately, drilling 1 collapsed and could not be used for testing. The complete soil descriptions are provided in Appendix B. Table 5 provides a simplified geological setting.

Figure 14: Energy pile 1 and the two additional drillings for the temperature sensors.

Table 5: Corresponding soil description for Energy Piles 1 and 2 at the Pavilion.

Depth [m]	Drilling 1	Depth [m]	Drilling 2
0.0 – 1.0	Fillings	0.0 – 1.0	Fillings
1.0 – 1.5	Clay	1.0 – 1.5	Clay
1.5 – 5.0	Sand	1.5 – 5.5	Sand
5.0 – 9.0	Gytja	5.5 – 8.0	Gytja
9.0 – 18.0	Sand	8.0 – 8.5	Peat
-	-	8.5 – 14.0	Gravel
-	-	14.0 – 18.0	Sand

The geological setting at Energy pile 3 is shown in Table 6, corresponding to drilling B5 presented in WP 2 (and appended in Appendix B).

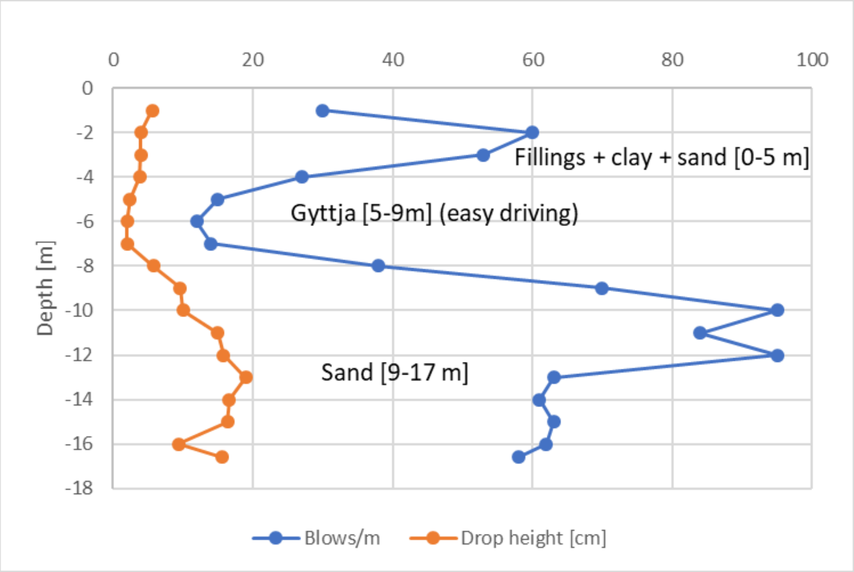
Table 6: Soil description for Energy Pile 3.

Depth [m]	B5
0.0 – 7.0	Fillings
7.0 – 7.5	Peat
7.5 – 10.0	Sand

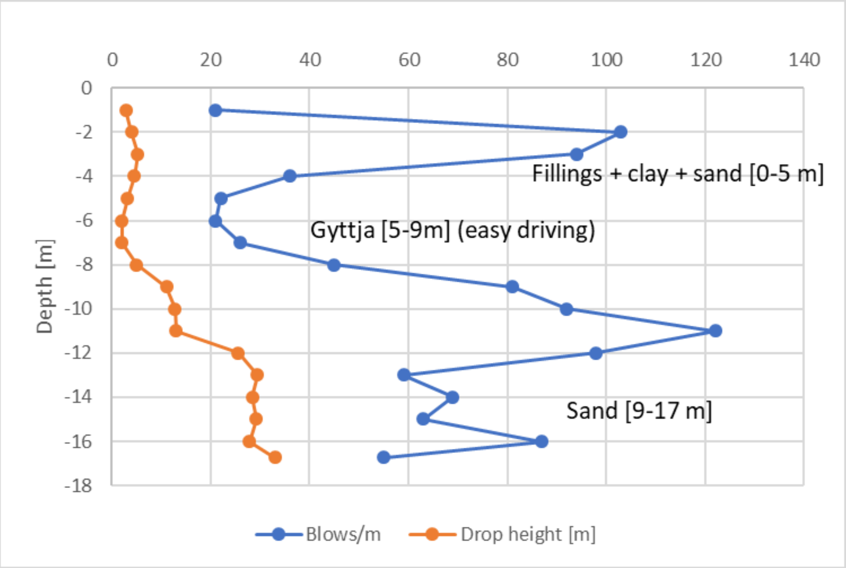
6.3.1.1 Driving logs

The driving works were carried out the 2/05/2018 by Aarsleff who also provided the driving logs. The piling rig was a Junttan PMX24, with a Junttan 70 kN hammer (maximum stroke, i.e., max. drop height is 1.5 m). Figure 15 shows the blow number required to penetrate 1 meter. The lower bearing capacity of the fillings and organic clays imply lower drop heights. The increasing drop height with depth indicates the increase of bearing capacity. The average number of blows required to penetrate 1 m into the gyttja is below 20, suggesting very easy driving.

a) Energy Pile 1



b) Energy Pile 2



c) Energy Pile 3

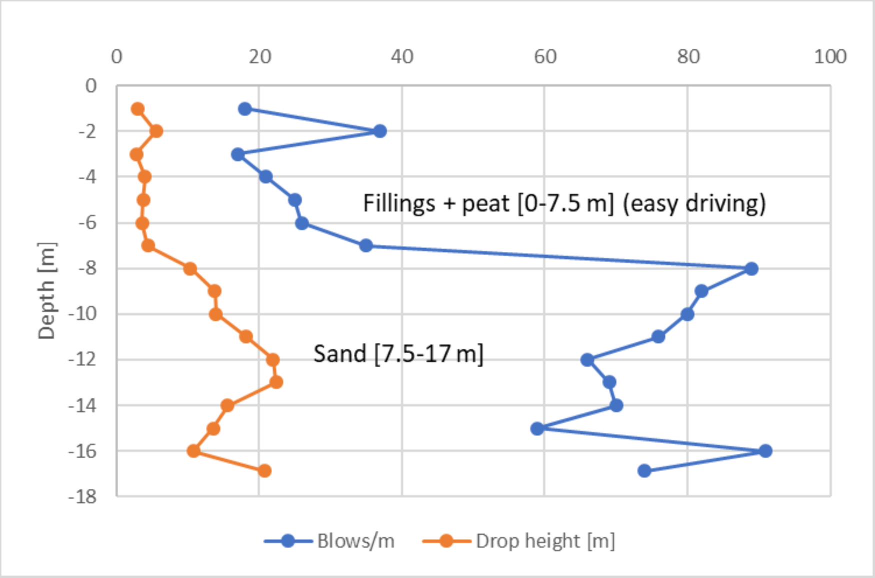


Figure 15: Driving logs containing blows/m and drop height.

6.3.1.2 Expected soil ultimate bearing capacity

The Danish pile driving formula (Equation (1)) is used to get an indication of the ultimate soil resistance.

$$Q_{dy} = \frac{\alpha W_H H}{S + 0{,}5 S_e} \tag{1}$$

$$S_e = \sqrt{\frac{2\alpha W_H H L}{AE}}$$

Where Q_{dy} is the ultimate dynamic bearing capacity of the driven pile, α is the hammer efficiency, W_H is the weight of the hammer, H is the hammer drop height, S is the inelastic set of the pile (in distance per hammer blow), S_e is the elastic set of the pile (in distance per hammer blow), L is the length of the pile, A is the pile end area and E is the elastic modulus of the pile material.

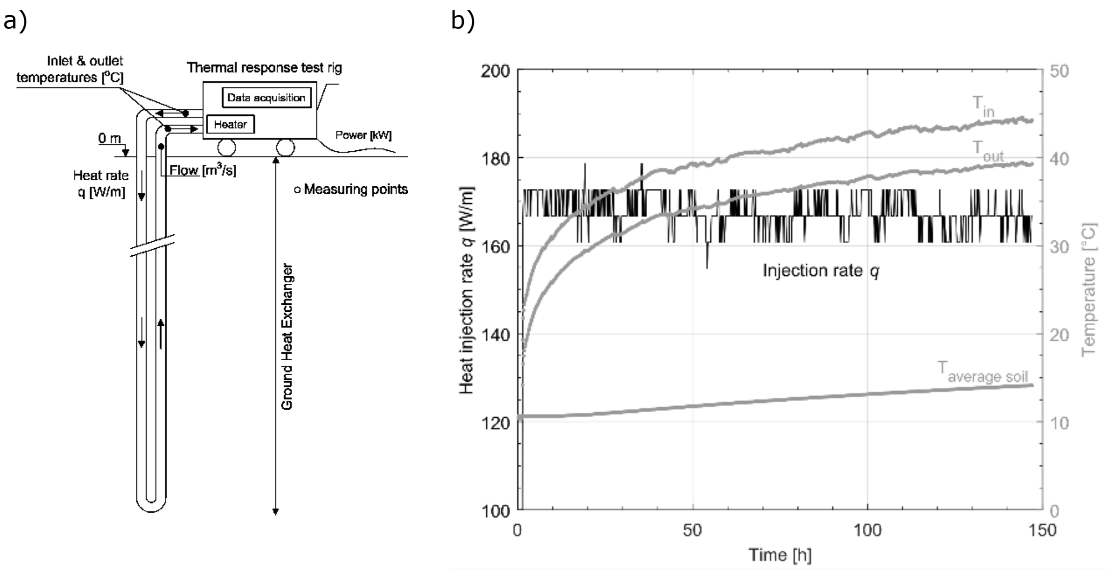
The calculated dynamic soil resistances are 750 kN, 1000 kN and 750 kN for EP1, EP2 and EP3, respectively. These ultimate capacities are not as high as required by buildings, meaning that longer joined piles might be required to reach higher capacities. Therefore, the use of foundation piles is quite necessary in the Ny Rosborg area.

6.3.2 Thermal Response Test TRT

6.3.2.1 Definition

The TRT is a field method carried out in ground HEs for estimating the soil thermal conductivity λ_s [W/m/K], ground HE thermal resistance (here concrete thermal resistance R_c [Km/W]) and undisturbed ground temperature $T_{s,0}$ [°C] [11,12].

During the TRT, the heat carrier fluid (water) is circulated in the ground HE while being continuously heated at a specified rate. Heat dissipates to the ground HE and subsequently to the ground. The test records fluid inlet-and outlet temperatures and the fluid flowrate and logs them in 10-min intervals for at least 48h. Figure 16 shows the test setup and an example of the measurements.


a)

b)

Figure 16: a) Thermal response test setup (from [12]*); b) In- and outlet TRT temperatures and weighted soil temperatures at 0.9 m from pile (all grey curves) and the power injection rate q (black curve) (from* [13]*).*

6.3.2.2 Setup

A TRT was performed on Energy Piles 1 and 2 situated in the pavilion area. The energy piles are connected in series, as shown in Figure 17(a). TRT of groups of piles have been reported in [14,15]. During the TRT, soil temperatures at a distance from Energy Pile 1 were compiled simultaneously at different depths (Figure 17(b)). The temperature sensors placed in the observation drillings, which measure the temperature change in the soil, are T type (NiCu-Ni) thermocouples. The data is collected by Testo 176T4 data loggers in intervals of 5 minutes. After the conclusion of the TRT, the two energy piles were connected to a heat pump. Further information is provided in Appendix C.

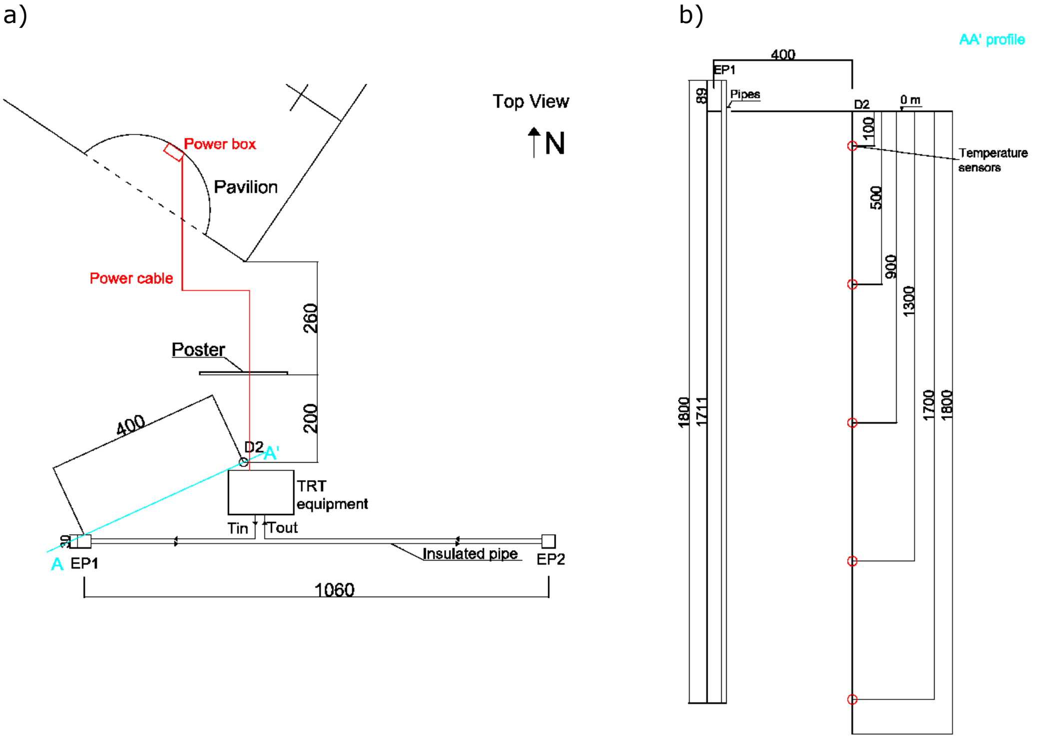

a)

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Figure 17: TRT setup at the pavilion area: a) Top view, b) AA' vertical cross section view. Cotes given in cm.

6.4 Methods for TRT interpretation

The TRT data can be interpreted with mathematically different methods. In this case, numerical and semi-empirical methods are used.

6.4.1 3D finite element model

The software COMSOL Multiphysics [16] is utilised for calculating the subsurface temperature response in and around the pile HEs. In the model, the ground is assumed to be thermally isotropic and homogeneous. The thermal interaction between the energy piles and the surrounding soil is modelled by conduction and advection in the HE pipes, in a similar way to the models developed in [9,13]. The 3D model contains five domains (Figure 18a): the soil, the two concrete piles and the HE pipe cast into each pile. The cross section of the modelled pile is given in Figure 18(b). The upper boundary is modelled as a convective heat flux boundary condition mimicking the energy exchange between the soil and the air, using a heat transfer coefficient of 50 W/m^2/K. The measured ambient air temperature is applied as the external temperature in the surface heat transfer boundary condition equation. Heat transfer due to groundwater flow is not considered.

For the thermal load, the model considers non-isothermal heat transport and fluid advection in the HE pipes. The outlet node of the first pile is connected to the inlet node of the second pile by a function for estimating conductive and convective heat losses from the pipe to the air.

The measured inlet temperature during the TRTs is specified for the inlet node of the first energy pile. The simulated outlet temperature is compared with corresponding observations. The determination of the soil thermal conductivity is carried out by manually fitting the model curve to observed temperatures.

Model tests have been conducted to ensure that modelled temperatures are independent of the chosen level of temporal and spatial discretisation and the distance to model boundaries.

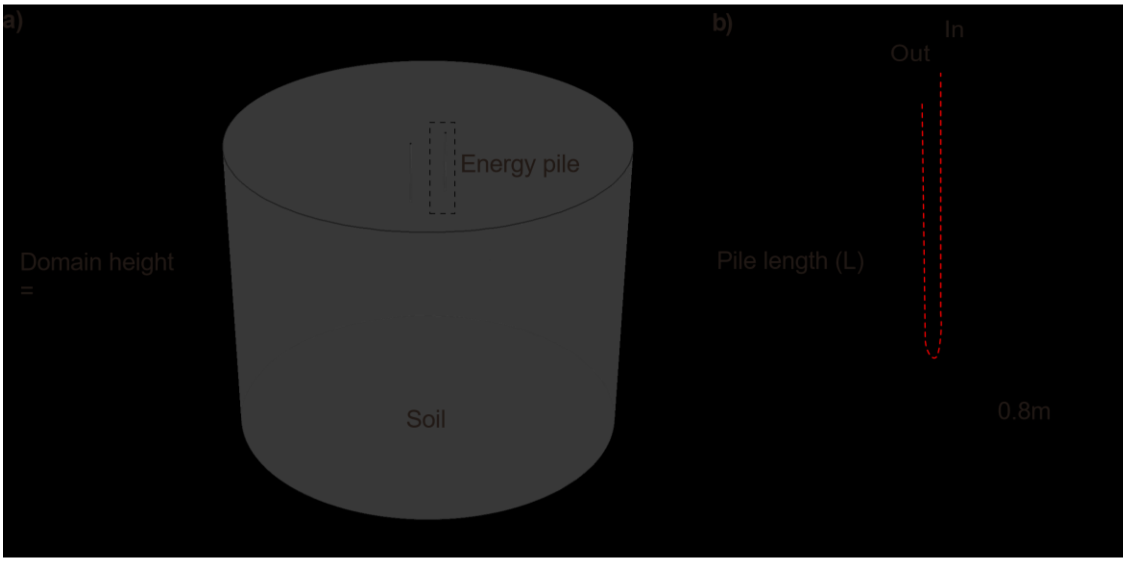


Figure 18: Description of the 3D finite element model. a) Simulated meshed domains; b) Schematic of the Single-U pile HE.

6.4.2 Semi-empirical model

The semi-empirical model used to generate the so called pile G-functions is similar to that described in [13,17], developed by the authors of this report. Satisfactory results from applying these models have been shown in [9,18]. The pipe thermal resistance R_{pipe} is estimated as suggested by [19,20], using the Gnielinski's correlation to obtain the corresponding heat transfer coefficients (see Section 7.2.1). The series configuration is considered by establishing identical fluid flow in both energy piles and assuming a total length of twice the length of a single energy pile. Heat losses are not considered in this approach.

Automated parameter estimation is employed as described in [9]. The parameter estimation is performed with PEST [21], yielding estimates of the thermal conductivity of the soil λ_s [W/m/K] and the steady state concrete thermal resistance R_c [K·m/W].

6.4.3 Pressure loss

The pressure loss (also known as head loss) of the pipes is quantified by Churchill's simplification [22] (see Section 7.2.1.). The study of the head loss is important since it will affect the running costs of the final installation. The head loss is not just affected by the piping materials, but also by the circulating flow as higher flow rates, yield larger pressure drops.

6.5 Results and discussion

In this section we present the TRT measurements and the corresponding interpretation.

6.5.1 Measurements

6.5.1.1 Undisturbed soil temperature

The undisturbed soil temperature has been measured by downhole temperature logging and after a non-heated water circulation period (Figure 19). Soil temperatures were measured only in D2. The average undisturbed soil temperature is determined to be 13.4 °C.

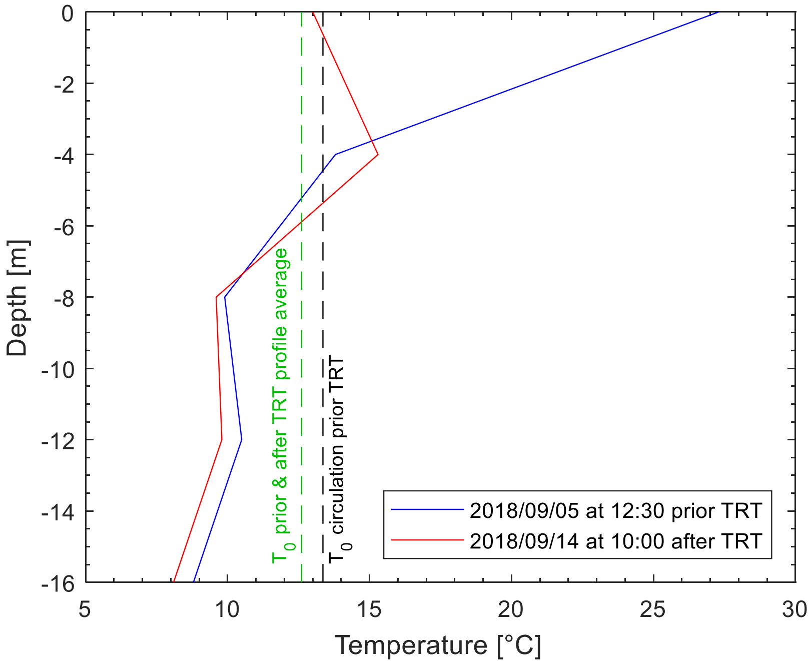


Figure 19: Undisturbed soil temperature measured in drilling D2, 4 m apart from Energy Pile 1.

6.5.1.2 TRT measurements

Table 7 summarises the main characteristics of the TRT. The quadratic cross section piles have a side length of 30 cm. the measurement interval was 10 min. The outer and inner diameters of the PE pipes are 32 mm and 26 mm, respectively and water serves as the heat carrier fluid. The piping between the TRT instrument and the tested piles (10.5 m approximately) is carefully insulated (2 cm of polyethylene foam) to reduce ambient temperature effects.

Table 7: Main TRT characteristics.

Test site	Pavilion
Pile ID	EP1 & EP2
Pipe configuration	2 piles in series, 1U
Active length/pile [m]	16.44
Aspect ratio/pile [-]	44
Undisturbed soil temperature [°C]	13.37
Flow rate [m^3/h]	0.710
Reynolds number [-]	9638
Average heat injection rate [W/m]	Ca. 45
Heat injection rate, standard deviation as % of average	3.1
TRT duration [h]	212
T_{in} – T_{out} (end) [°C]	1.84
Observed energy injected to the ground [kWh]	314
Expected energy loss in connection pipe [kWh]	10.5

Figures 20 to 22 show the measured data during the TRT. The fluid temperatures are slightly affected by the ambient temperatures. This effect is aggravated due to the relatively long pipes connecting the two energy piles (approx. 10.5 m). The soil temperature sensors placed closest to the tested piles (4 m from Energy pile 1) do not show any temperature increase, implying that the soil is thermally undisturbed by the TRT at this distance.

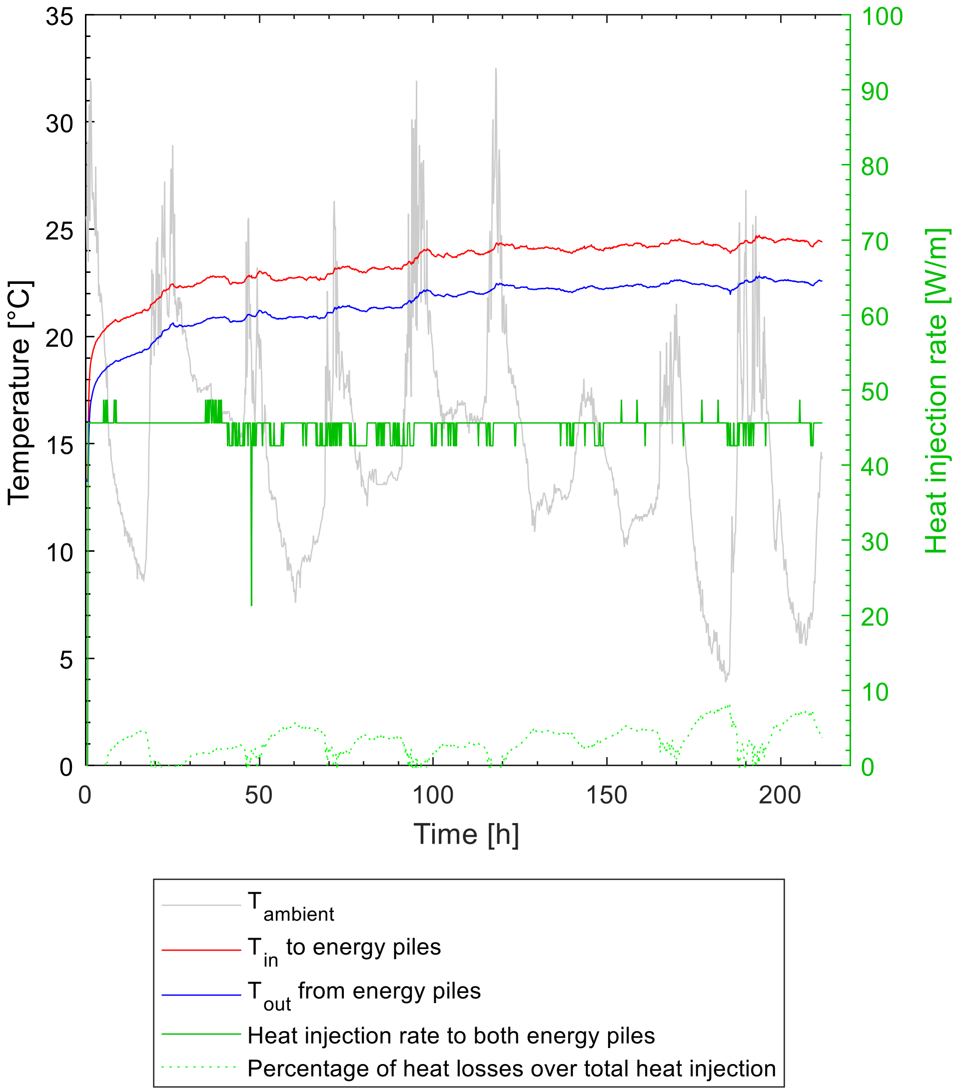


Figure 20: TRT measurements: two energy piles connected in series. Active length: 16.4 m/pile, single-U tubes.

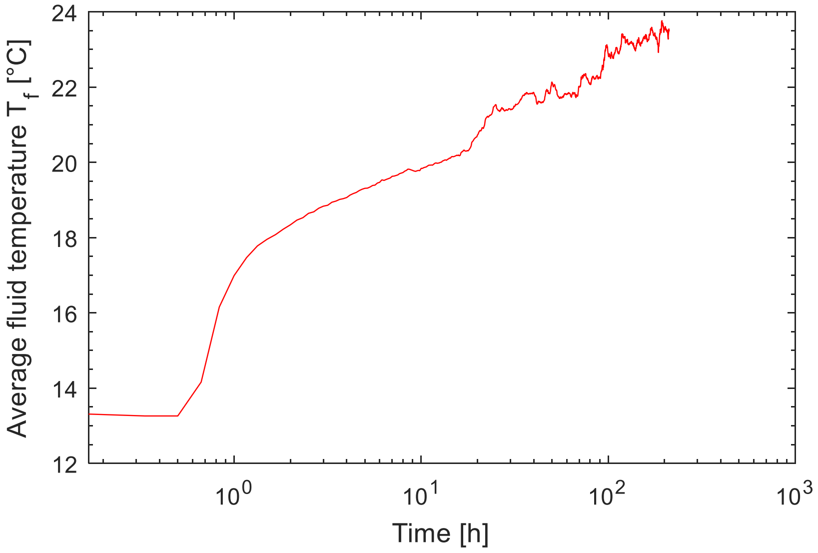


Figure 21: TRT average fluid temperature measurements plotted against logarithmic time.

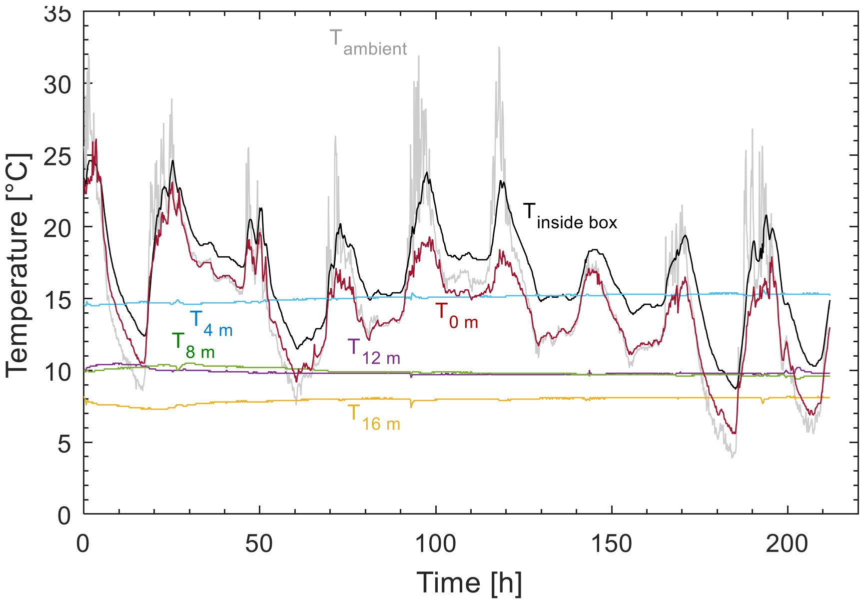


Figure 22: Soil temperature measurements at drilling D2 situated 4 meters from Energy Pile 1.

6.5.2 TRT interpretation

The TRT data has been interpreted by two methods: the numerical 3D finite element model and the semi-empirical G-function model.

6.5.2.1 3D FEM (Finite Element Model)

The parameters used in the model are listed in Table 8. The inlet temperature is imposed as measured and the outlet response is compared to the measurements. The comparison and the residuals are shown in Figure 23. The soil thermal conductivity λ_s has been manually modified to fit the observation curve.

Table 8: Best fit parameters.

Parameter [unit]	**Values**
Flow [m^3/h]	0.71
Thermal conductivity of concrete λ_c [W/m/K]	2.50
Volumetric heat capacity of concrete ρc_{pc} [MJ/m^3/K] (Average from [9])	2.00
Thermal conductivity of soil λ_s [W/m/K]	2.20
Volumetric heat capacity of soil ρc_{ps} [MJ/m^3/K] (based on initial estimate from WP2)	2.80
Thermal conductivity of pipe λ_p [W/m/K]	0.42

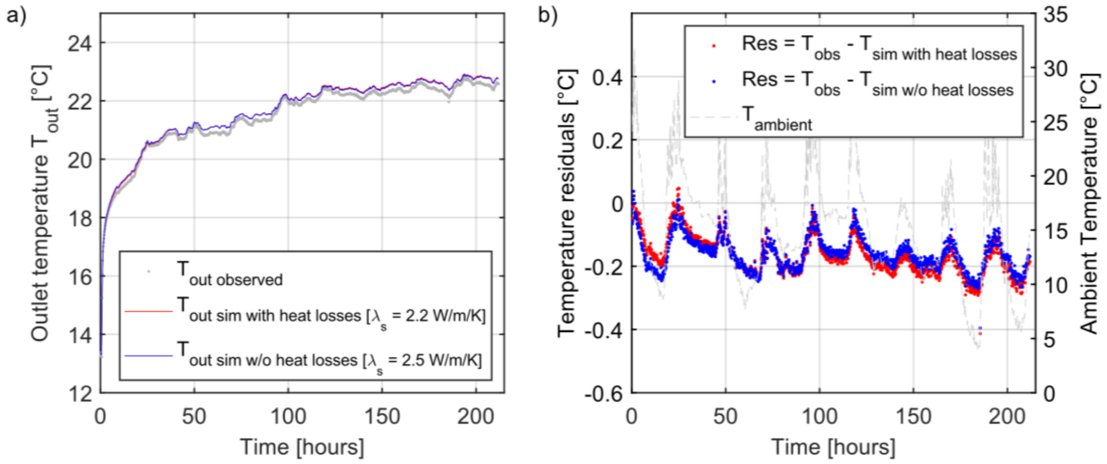


Figure 23: a) Observed and 3D FEM modelled outlet temperatures; b) Residuals, defined as the difference between the observed and the simulated temperatures and observed ambient temperatures.

Model calibration without considering the heat flux upper boundary and the heat losses yield a thermal conductivity estimate of 2.50 W/m/K. Considering the heat flux boundary and the heat losses yields a thermal conductivity estimate of the soil of 2.20 W/m/K.

The residuals are below 0.25 °C at all times and correlate with variations in the ambient temperature, as observed in [23]. The steady state pile concrete resistance R_c estimate is 0.071 K·m/W, which is within the expected range for single U piles and concrete thermal conductivity of 2.5 - 2.8 W/m/K (Figure 24).

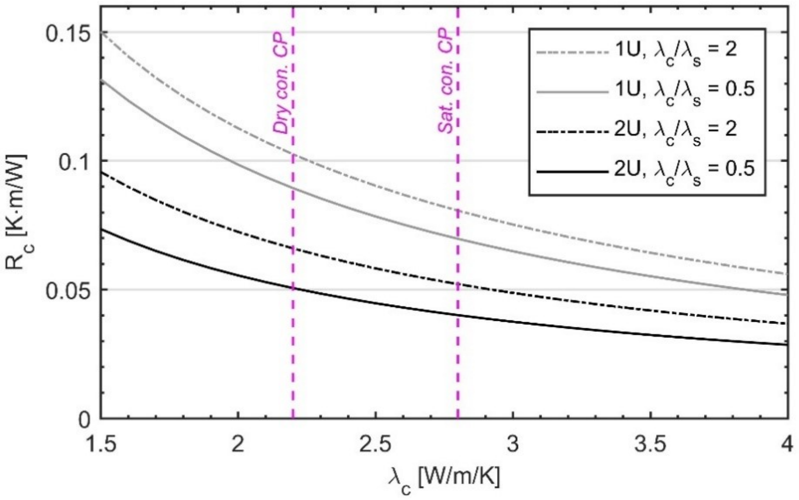


Figure 24: R_c vs thermal conductivity of the concrete λ_c. Upper and lower bounds for the concrete thermal resistance R_c for square precast pile HEs for 25x25, 30x30 and 45x45 cm^2 with 1U and W-shape pipes for a range of concrete thermal conductivities.

6.5.2.2 Semi empirical G-functions

The automatic parameter estimation yields a thermal conductivity of the soil λ_s of 2.54 W/m/K and a pile concrete thermal resistance R_c of 0.073 K·m/W. Figure 25 compares the observations and the simulations and the residuals, which also follow the ambient temperature changes.

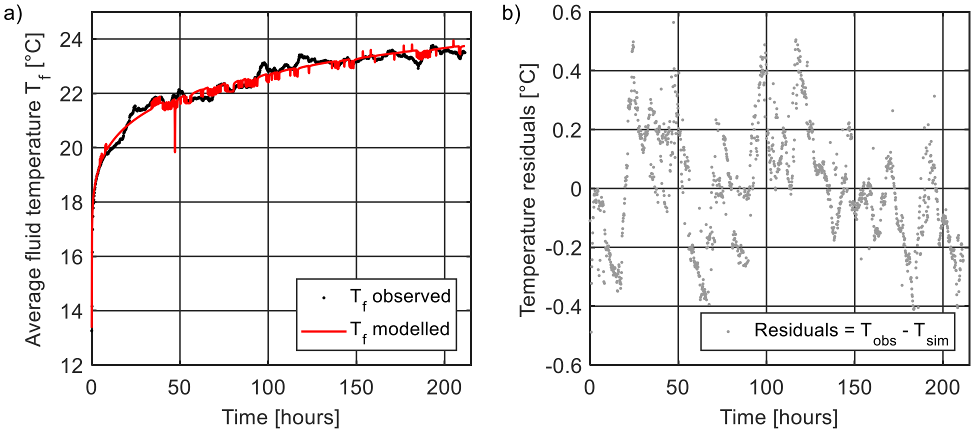


Figure 25: a) Observed and semi empirical G-function modelled average fluid temperatures; b) Residuals, defined as the difference between the observed and the simulated temperatures.

6.5.2.3 Comparison of results

Table 9 lists the estimates from both interpretation methods, which consistently agree. The discrepancy between the 3D FEM and semi-empirical estimates of R_c [K·m/W] is approx. 3%. These estimates are in line with the expected pile concrete thermal resistances computed in [9] for single-U pipe arrangements (Figure 24). This shows that the thermal resistance of the single-U configuration with the bigger diameter pipes is lower than the 0.095 K·m/W obtained for the 20 mm diameter pipes in LM1 pile in [9].

Table 9: Summary of parameter estimation.

	Thermal conductivity of soil λ_s [W/m/K]	**Pile concrete thermal resistance R_c [K·m/W]**
3D FEM	2.20	0.071
Semi-empirical	2.54	0.073
Lab-measurement based (WP2)	1.80	-

The semi-empirical model does not consider the heat losses, while the FEM model does. FEM modelling without considering the heat losses yields a thermal conductivity of the soil of 2.50 W/m/K, similar to the estimate of the semi-empirical model (Figure 23). A possible improvement could be to consider the heat losses in this semi-empirical model since the 2.50 W/m/K is somewhat high given the soil type. When heat losses are considered, the thermal conductivity estimate shows a more plausible value, 2.20 W/m/K.

Still, the thermal conductivity of the soil λ_s yielded from the TRT interpretation (2.20 W/m/K) is higher than the one expected from the laboratory measurements carried out for WP 2 (approx. 1.80 W/m/K). The higher thermal conductivity of the soil λ_s yielded from in-situ testing analysis might be due to local higher water content and heterogeneities of the soil, not considered in the extrapolation carried out in Work Package 2 (see section 5). Anyhow, it is not recommendable to use TRT of energy piles connected in series to yield thermal properties of the soil, since more complex interpretation methods are required.

Table 10 shows the observed and simulated energy injection to the ground. The discrepancy between the observed and the simulated heat injection is of 3%, which agrees with the expected heat losses of 3.5%. Max. heat loss percentage is 8% (Figure 20) of the measured Q [W], which is translated in less than 0.01 K temperature loss. Yet small, this heat loss results in a different thermal conductivity estimate, as shown in Figure 23.

Table 10: Energy injection to the ground during the 212 h of testing.

Observed energy injected to the ground [kWh]	314.0
Energy loss expected [kWh]	10.5
Simulated energy injected to the ground 3D FEM [kWh]	306.0

6.5.2.4 The effects of connecting energy piles in series

The measured heat injection rate is 45 W/m, which involves heat losses in the connection pipe. The simulated heat injection rate in the 3D FEM, where the heat losses are not considered, is 42 W/m.

The expected maximum heat loss from the insulated pipes (polyethylene pipe insulated with 20 mm thick polyethylene foam) is about 3.5% of the heat injection rate. This occurs when the difference between the ambient temperature and the average fluid temperature is the highest (during the final 48 hours of test, Figure 20), i.e., where the residuals are higher (Figure 23).

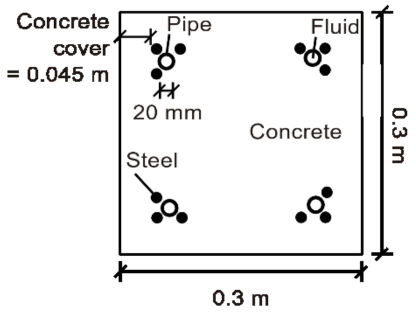
In real applications the distance between energy piles will be smaller and the heat losses will be lower. It might be recommendable to couple two piles in series, as more heat is dissipated per pile. Essentially, two energy piles connected in series can mimic a long energy pile twice the active length. However, the longer pipe sections require an analysis on the pressure drop (see Section 6.5.3).

6.5.3 Effect of new Single-U pipe HE

The energy piles used at Rosborg Gymnasium, have W-shaped piping with a smaller diameter [9,13] (Figure 26). The W-shaped HE gives the energy pile a lower pile concrete resistance, implying a better heat exchange with the surrounding soil. However, the W-configuration is relatively expensive to produce and the small inner diameter (0.016 m) of the piping causes high pressure loss and additional problems when flushing the circuit.

The new HE consists of a prefab pipe ensemble prepared for the corresponding pile length. The new pipes are shorter and have a larger diameter, which increases the pile concrete thermal resistance (0.071 K·m/W against the average 0.045 K·m/W for the W-shape [9]). The following analysis compares both pipe configurations in terms of heat transfer efficiency and pressure drop.

a)



b)

Figure 26: a) W-pipe HE used in previous projects; b) Single-U pipe HE used in the current project.

6.5.3.1 Pipe thermal resistance

The pipe thermal resistance R_{pipe} [K·m/W] is calculated for a number of pipe configurations, pipe diameters and a range of Reynolds numbers (Figure 27). Changing the flow regime from transitional to full turbulence does not yield a significant improvement in the pipe thermal resistance R_{pipe}.

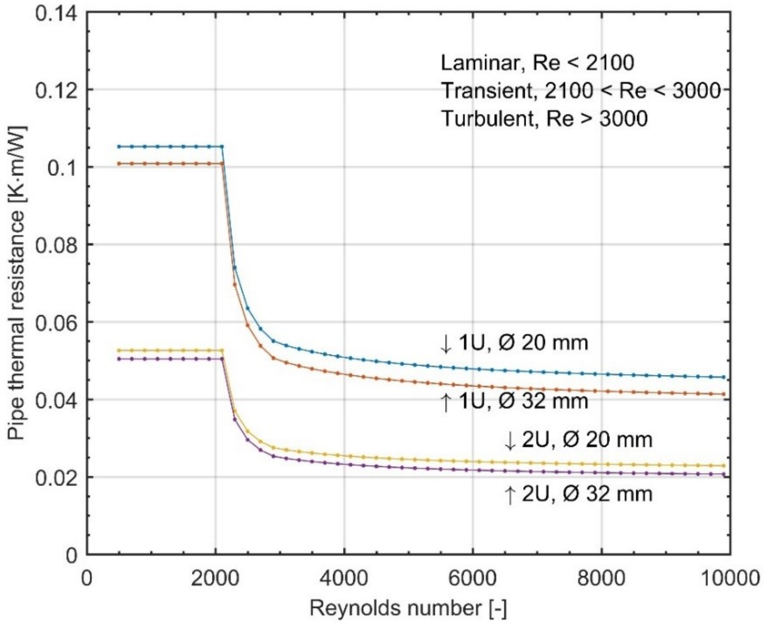
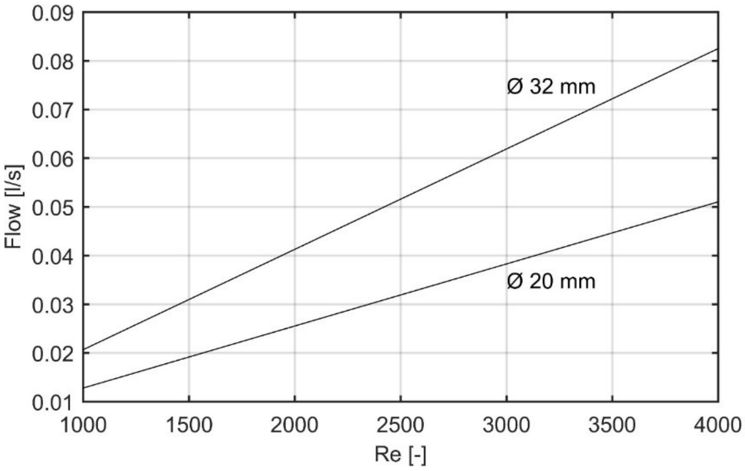


Figure 27: Pipe thermal resistance R_p vs Re for different pipe diameters and number of pipes in the pile cross section.

6.5.3.2 Pressure drop

Finally, a short study considering the head loss in the PEX pipes is carried out. International recommendations recommend that the head losses should be between 0.098 kPa/m and 0.294 kPa/m, in order to strike a balance between the heat transfer in the transitional and turbulent flow regime and the pumping costs [24].

a)



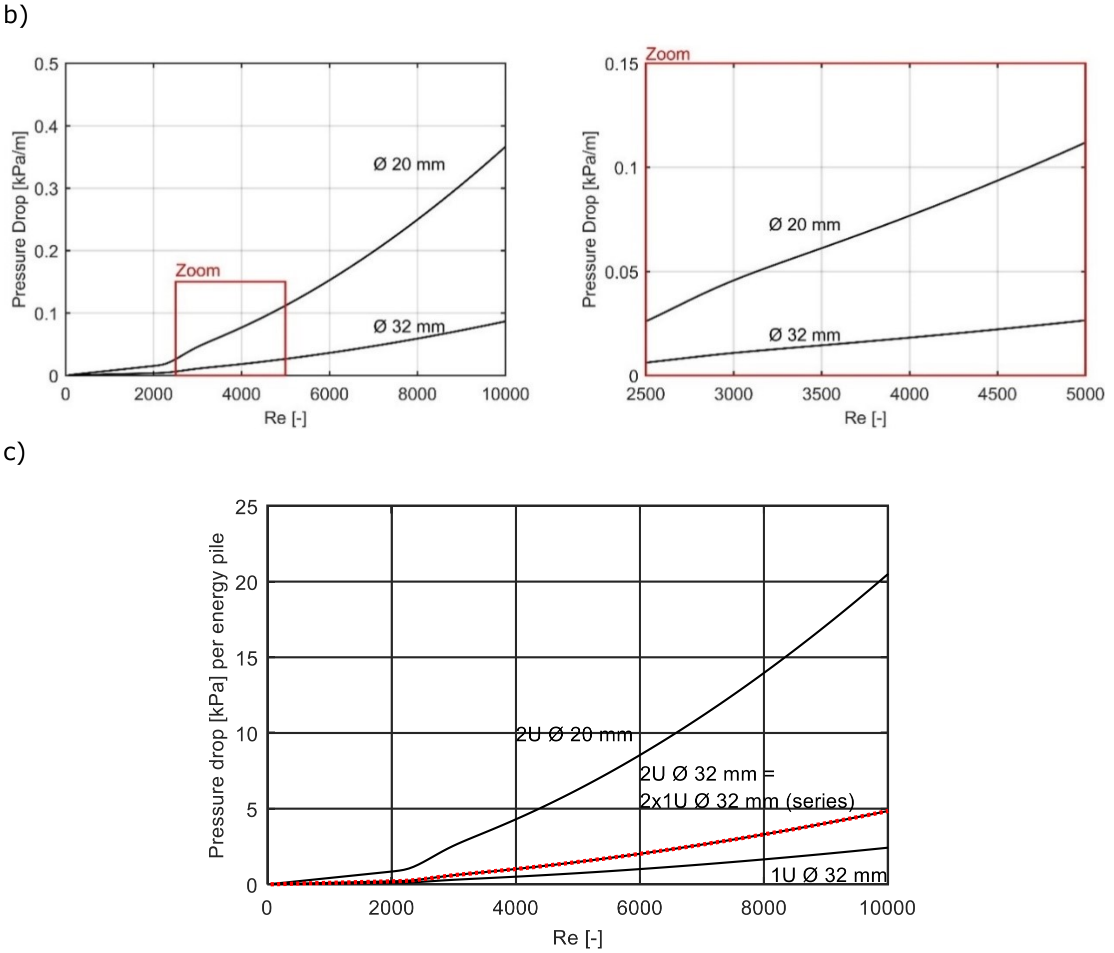


Figure 28: a) Evolution of flow vs the Reynolds number for the considered pipe diameters (Ø 20 and 32 mm). b) Evolution of pressure drop/head loss with Reynolds number for the considered pipe diameters. c) Development of pressure drop with Reynolds number for the considered pipe diameters and pipe arrangements for a 14 m energy pile.

As Figure 28a, b shows, the head loss increases dramatically with the flow. The laminar, transition and turbulent flows close to a Reynolds number of 3000 are targeted for an optimal pressure drop condition. For example (following Figure 28c), Reynolds numbers of 8000 provoke high pressure drops, up to 14 kPa for a 14 m long 2U energy pile with Ø20 mm pipes while for a Reynolds number of 3000 the head loss falls to 3 kPa per pile. In addition, the circulation effort required for operating two energy piles in series (Ø 32 mm) is less than that of a circulating fluid in a single W-shaped energy pile.

A balance between optimal head loss and heat transfer efficiency must be striked. In order to fulfil the pressure drop constraints in operational conditions, Reynolds numbers corresponding to transitional and low turbulent flow regimes are recommended.

6.6 Conclusions

Three energy piles have been driven at the Ny Rosborg area and the geotechnical conditions imply that foundation of buildings in the Ny Rosborg area requires foundation piles.

A Thermal Response Test was carried out in two energy piles connected in series. The temperature data is interpreted with two models (one numerical and the other, semi-empirical). The results show that TRT of piles in series are not suitable for accurate determination of soil thermal conductivity unless heat losses are considered.

However, the series configuration of the single U configuration piles can be beneficial for the installation performance as the temperature difference between the inlet and the outlet to the heat pump can increase to 2-3 °C.

The W-shaped HE energy piles have a 40% lower concrete resistance relative to the new single-U HE but the former are also more costly to produce. In addition, head losses are higher, which usually create problems when flushing the circuit and increases the pumping costs.

It has been demonstrated that changing the flow regime from transitional to full turbulence does not significantly improve the heat transfer between the fluid and the concrete. In other words, the increased pumping costs from imposing full turbulence are not matched by a corresponding increase in the heat abstraction with the energy pile.

7. WP4: Energy calculations

7.1 Purpose

Cold District Heating (CDH) includes an uninsulated, horizontal distribution network for supplying heat to consumers connected to the network by means of individual ground source heat pumps. The network has a supply manifold that distributes fluid and energy from the *energy producers* to the *energy consumers* on the network. The return flow manifold directs the flow back to the energy producers once the energy is delivered at the consumers as illustrated in Figure 29.

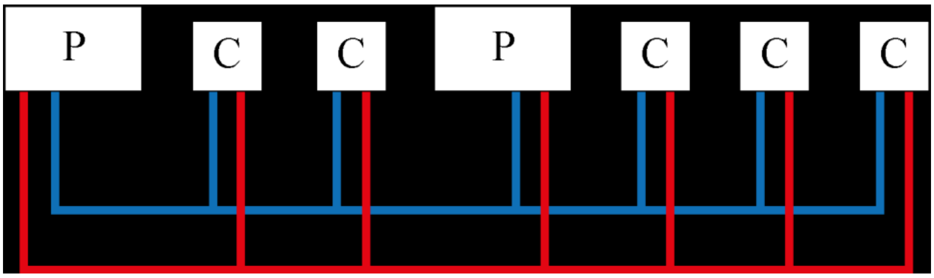


Figure 29: Topology of the CDH network exemplified with two connected energy producers (P) and five energy consumers (C). Red and blue indicate flow manifolds to and from the consumers in heating mode.

Energy producers include energy piles (EP), BHEs, solar panels, return flow from a traditional district heating network, industrial waste heat, buildings with cooling demand etc.

During the hot season, the CDH is used for passive cooling of the connected buildings, by rejecting excess heat to the relatively cold ground. Therefore, heat is stored for later use in the cold season, improving the efficiency of the heat pump.

There are several vital performance metrics for the CDH network that are currently difficult to assess. This is due to 1) a lack of operational experience with CDH networks used for both heating and cooling and 2) a lack of holistic energy models for CDH networks.

Some important considerations and open questions for a specified CDH network are:

1) The heating and cooling capacity of the network. This depends on the complex interplay between the deep heat sources such as EPs or BHEs and the shallow distribution network that exchanges heat with the surroundings and is affected by seasonal variations in the surface temperatures.
2) Fluid temperatures in the network during peak energy loads in the summer and winter. Do they exceed the lower and upper energy pile geotechnical limits of 2°C and 30°C, respectively? This depends simultaneously on the average heating and cooling loads and the corresponding peaks. Proper assessment of the cooling and heating demand of the connected buildings is vital for addressing this question.

3) The impact of seasonal heat storage on the efficiency of the heat pump. Heat is stored for winter, increasing the fluid temperatures to the heat pump, thus improving the COP.

4) The impact of heat consumption on the capacity for passive cooling. Passive cooling depends on low ground temperatures. This is achieved by removing heat from the ground during winter – that is – by using the heat pump to cover the heating demand.

5) The impact of seasonal surface temperature variations on the heating and cooling capacity of the shallow distribution network. Due to the shallow burial depth of approximately 1 m, the distribution network is affected significantly by seasonal variations in the surface temperature.

The above considerations are difficult to address without a full calculation of the heat transport in the CDH network. Thus, in work package 4, we carry out a full simulation of the heat transport for a case study of Rosborg Ø which is a small residential sub area of Ny Rosborg.

In the early stages of the project it was decided that the modelling tool was to be developed from scratch. The primary motivation for this, is that earlier attempts to model such CDH systems with the commercial software TERMIS had failed to provide answers to the questions listed above. It seems that a model code tailored for simulating energy transport on CDH networks is required.

In the following sections we outline the theoretical basis and composition of the model framework.

7.2 Methods

The calculation of temperatures in the CDH network involves a two-stage simulation of corresponding network fluid flow and heat transport, respectively. For a given fluid flow, the energy transport model consists of three main parts as indicated in Figure 30.

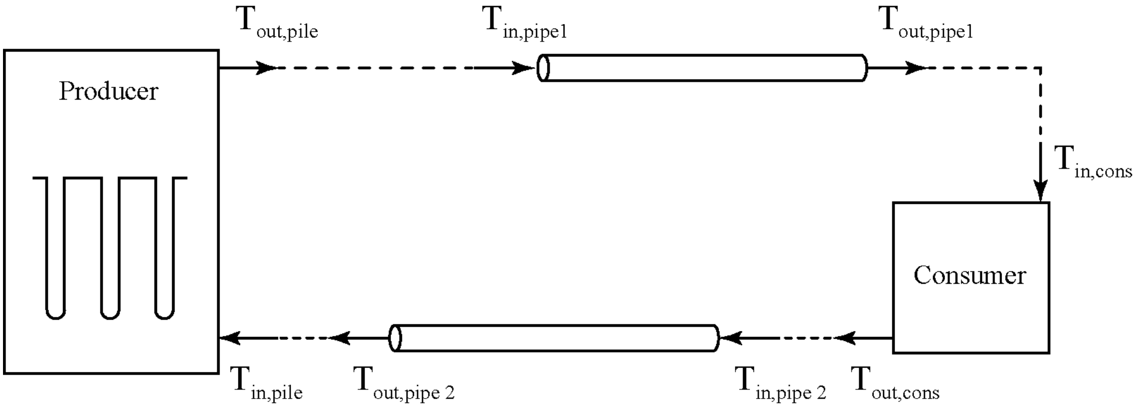


Figure 30: Schematic model overview for a simplified network with one producer and one consumer. The energy pile model, horisontal pipe model and consumer models are coupled through fluid temperatures.

At the producer building, an energy pile model simulates the fluid temperatures based on the total energy demand of the system. The simulated energy pile outlet temperature is passed as the inlet temperature to a horisontal pipe model, that simulates the thermal interaction of the fluid in the uninsulated pipes with the ground. The outlet temperature of the pipe serves as the inlet temperature for the consumer model, and the outlet temperature at the consumer is finally passed through the horisontal pipe model before reconnecting with the pile model at the production building. An overall energy balance is enforced to ensure consistent temperatures as will be disussed in a later section.

In the following we shall describe in detail the different model components outlined above, as well as the total energy demand necessary to drive the model. Finally we discuss the overall model coupling as well as simulation results.

7.2.1 Pipe flow

For the energy pile and horizontal pipe calculations, it is necessary to estimate the heat transfer coefficient and in some circumstances the head loss. The flow regime (laminar, transitional or turbulent) is determined by the dimensionless Reynolds number:

$$\mathrm{Re} = \frac{\mathrm{w} \cdot \mathrm{d}}{\mathrm{\nu} \cdot \mathrm{A}} \tag{2}$$

Where w [m^3/s] is the fluid flow rate, d [m] is the pipe diameter, υ [m^2/s] is the kinematic viscosity and A [m^2] is the cross-sectional area of the pipe.

From the Reynolds number, the friction factor is [25]:

$$\frac{2}{\mathrm{f}} = \left(\frac{1}{\left[\left(\frac{8}{\mathrm{Re}} \right)^{10} + \left(\frac{\mathrm{Re}}{36500} \right)^{20} \right]^{1/2}} + \left[2.21 \ln \left(\frac{\mathrm{Re}}{7} \right) \right]^{10} \right)^{1/5} \tag{3}$$

The heat transfer coefficient can then be estimated from the Gnielinsky correlation, using the Nusselt and Prandtl numbers. For transitional and turbulent flow:

$$\mathrm{Nu} = \frac{(\mathrm{f}/2)(\mathrm{Re} - 1000)\mathrm{Pr}}{1 + 12.7(\mathrm{f}/2)^{1/2}(\mathrm{Pr}^{2/3} - 1)} \tag{4}$$

$$\mathrm{Pr} = \frac{\nu}{\alpha} \tag{5}$$

where α [m^2/s] is the fluid thermal diffusivity. The heat transfer coefficient may then be evaluated as:

$$\mathrm{h} = \frac{\mathrm{Nu} \cdot \lambda_\mathrm{f}}{\mathrm{d}} \tag{6}$$

where λ_f [W/m/K] is the fluid thermal conductivity.

When choosing the pipe dimensions, it is important that the head loss due to friction along the length of the pipe is not too large (see Section 6.5.3). The head loss ΔH can be estimated by the empirical Darcy–Weisbach equation (see e.g. [26]):

$$\Delta\mathrm{H} = \mathrm{f} \cdot \frac{8\mathrm{L}}{\pi^2 \mathrm{g} \mathrm{D}^5} \cdot w^2 \tag{7}$$

where L [m] is the length of the pipe and g [m/s^2] is the local acceleration due to gravity.

7.2.2 Energy piles

The energy pile thermal model developed in [4], is used to simulate the thermal behaviour of the single and multiple energy piles treated in this report. Further details can be found in the cited thesis and the corresponding journal papers.

The average energy pile fluid temperature T_f [°C] is defined as [27]:

$$\mathrm{T_f} = \mathrm{T_{s,0}} + \frac{\mathrm{q}}{2\pi\lambda_\mathrm{s}} \mathrm{G_g} + \mathrm{q R_c G_c} + \mathrm{q R_{pipe}} \tag{8}$$

where $T_{s,0}$ [°C] is the undisturbed soil temperature, q [W/m] is the heat transfer rate per metre of pile HE, λ_s [W/m/K] is the thermal conductivity of the soil, G_g [-] is the G-function describing the dimensionless ground temperature response, R_c [K·m/W] is the steady state concrete thermal resistance, G_c [-] is the concrete G-function describing the transient concrete response and R_{pipe} [K·m/W] is the thermal resistance of the pipes.

The model is based on the calculation of G-functions which are dimensionless response factors that describe the change in temperature with time in the ground around the HE due to an applied thermal load [28]. It is conventional to introduce dimensionless temperature and time:

$$T_{Db} = \frac{2\pi\lambda_s}{q}\left(T_b - T_{s,0}\right) \tag{9}$$

$$t_D = \frac{\alpha_s t}{r_b^2} \tag{10}$$

where T_b [°C] is the average pile wall temperature, α_s [m^2/s] is the thermal diffusivity of the soil, i.e., the ratio between the thermal conductivity and the volumetric heat capacity of the soil c_s [$J/m^3/K$], and r_b [m] is the energy pile equivalent radius. The equivalent radius is defined as the radius that provides the equivalent circumference to the square perimeter:

$$r_b = \frac{4 \cdot b}{2\pi} \tag{11}$$

where b [m] is the pile side length.

For a single pile, the pile wall temperature depends on time and the aspect ratio, i.e. the ratio between the active length L [m] and the equivalent radius. The wall temperature is determined by:

$$T_b = T_{s,0} + \frac{q}{2\pi\lambda_s} \cdot G(t_D, \frac{L}{2r_b}) \tag{12}$$

The G-function can be obtained by analytical, numerical or empirical methods. In [4], validated transient Finite Element Method (FEM) modelling is employed to compute dimensionless temperature response curves (also known as semi-empirical G-functions) for the single energy pile considered in this report.

The concrete G-function G_c, as defined by [27,29], describes the transient thermal resistance of the pile HEs. To incorporate the transient response of the pile concrete into the overall temperature response function (Equation (8)), the proportion of the steady state thermal resistance that has been achieved at a given value of time needs to be determined:

$$R_c = \frac{T_p - T_b}{q} \tag{13}$$

where T_p [°C] is the average temperature on the outer wall of the pipe.

The pipe thermal resistance R_p [K·m/W] is defined as the sum of a convective and conductive contribution, respectively:

$$R_p = \frac{1}{2n\pi r_i h} + \frac{1}{2n\pi\lambda_p}\ln\left(\frac{r_o}{r_i}\right) \tag{14}$$

where n is the number of pipes in the pile HE cross section, r_i [m] is the inner radius of the pipe, r_o [m] is the outer radius of the pipe, h [$W/m^2/K$] is the heat transfer coefficient (see Equation (6)) and λ_p [W/m/K] is the thermal conductivity of the pipe material. The model assumes instant steady-state heat conduction in the geothermal piping material.

In the long-term performance, energy pile foundations must consider the thermal interaction between piles. The multiple pile G-functions provide the change in the average pile wall temperature over time from the individual contributions from all the piles in the energy foundation. That is, the G-function provides the pile wall temperature for a specific foundation configuration due to a constant heat input rate [30]:

$$T_b = T_{s,0} + \frac{q}{2\pi\lambda_s} \cdot G(t_D, \frac{L}{2r_b}, \frac{S}{2r_b}) \tag{15}$$

where T_b [°C] is the pile wall temperature common to all piles, G [-] is the multiple pile G-function. As shown in Equation (15), for the case of pile HE foundations, the multiple pile G-functions depend on three non-dimensional parameters: the dimensionless time, the pile aspect ratio, and the foundation aspect ratio $S/2r_b$, where S [m] is the centre to centre pile spacing, as defined in [29].

The multiple pile HE G-functions presented in [4] are based on the temperature fields extracted from a single 3D FEM model. In addition to the pile wall temperature, soil temperatures at radial distances corresponding to typical pile spacings are extracted from the FEM simulation. The computed temperatures are fitted with a 9th degree polynomials in order to obtain the temperature response functions in a similar way to the methods presented in [27,31]. Several pile aspect ratios and pipe configurations were considered and tabulated type curves are available in [18].

The multiple pile G-function can be calculated by applying temporal and spatial superposition of the single pile G-function and radial temperatures. This principle relies on the linearity of the heat conduction equation and boundary conditions [30].

In the spatial superposition, the temperature contributions from the energy pile itself and all neighbouring piles are summed in order to calculate the temperature variation at the pile wall [32]:

$$\Delta T_b(t) = \frac{1}{n_p} \sum_{i=1}^{n_p} \sum_{j=1}^{n_p} \Delta\bar{T}(d_{ij}, t) \tag{16}$$

$$d_{ij} = \begin{cases} r_b, & i = j \\ \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}, & i \neq j \end{cases} \tag{17}$$

where ΔT_b [K] is the average temperature variation at the pile HE wall, i.e., $\Delta T_b = T_b - T_{s,0}$, (x_i, y_i) [m] are the coordinates of the ith pile HE, n_p is the number of pile HEs in the foundation and d_{ij} [m] is the distance between piles *i* and *j*, and $\Delta\bar{T}$ is the average temperature variation at a distance d_{ij} from the centre of the HE.

Time variations can be applied by deconvolution of the time varying heat transfer rate [30]. The temperature at discrete time steps in the pile HE foundation is found as [27,30]:

$$\Delta T_n = \sum_{i=1}^{n} \frac{q_i}{2\pi\lambda_s} \left(G(t_{D,n} - t_{D,(i-1)}) - G(t_{D,n} - t_{D,i}) \right) \tag{18}$$

where n denotes the time step at which the superposition is evaluated.

The model assumes that energy piles are connected in parallel, assuming uniform and equal heat extraction rates for all energy piles. Due to the spatial superposition, the average temperatures along the length of all the piles are unequal. Hence, the average of the mean pile wall temperatures is used in the evaluation of the G-function.

7.2.3 Energy demand model

The starting point for a full simulation of the energy flow in a CDH network is the heating and cooling demand of the connected consumers. In the following we consider one part of the Ny Rosborg area: Rosborg Ø (see Figure 31). Calculations for the remaining areas would follow along the same lines.

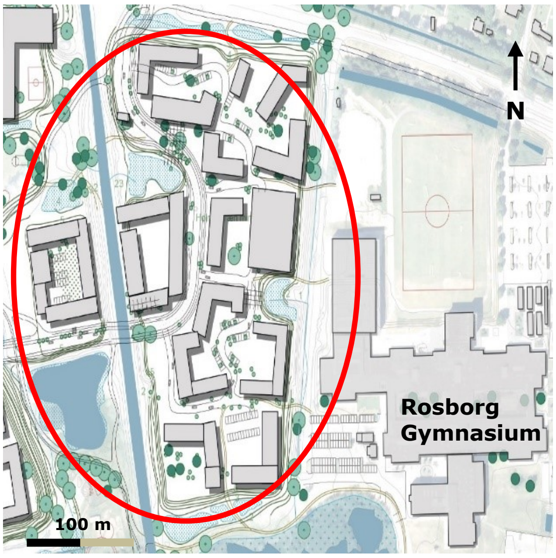


Figure 31: Rosborg Ø indicated in red. The proposed total living space for the area is 95,000 m^2. The total building footprint is 16,950 m^2.

A variety of building scenarios are considered for the Ny Rosborg area with a mix of low and taller buildings. In the following we address the heating and cooling needs of buildings with two, four and eight floors. An EnergyPlus [33] building energy model was set up in DesignBuilder to estimate the total heating and cooling demand for each building type. The construction U-value template was implemented following the Danish building regulation BR18 minimum requirement [34]. An opening percentage of 30% was assumed for the southern facade, 15% for the east and west facade, while the north facing walls are considered without windows. The template "Denmark" adapted according to BR18 was used for the glass characteristics.

The default activity template "Residential-Dwellings" was modified setting the heating set point to 22 °C and the cooling set point to 26 °C. Operational hours from the "Residential Occupancy" template were used (see Table 11).

Table 11: Occupancy schedule for the building energy model.

Weekdays		**Saturdays**		**Sundays and Holidays**	
Until	**Occ %**	**Until**	**Occ %**	**Until**	**Occ %**
5.00	100%	7.00	100%	7.00	100%
6.00	80%	8.00	80%	8.00	80%
8.00	75%	9.00	75%	9.00	75%
9.00	50%	10.00	50%		
15.00	43%	15.00	43%		
18.00	50%	18.00	50%		
21.00	75%	21.00	75%		
24.00	80%	24.00	80%		

Hourly weather data for Billund from the ASHRAE/IWEC database [35] were used as boundary conditions for the building energy simulation. The simulation was run with daily resolution for the three different building heights. The demand profiles were found to be similar for the three buildings considered, so for simplicity a simple average of the three profiles will be used in the following regardless of the building height.

The network indicated in Figure 29 implies a surplus of energy for the producers which may be shared with the consumers. An important consideration is how many consumers can be accommodated by a given set of producers. In other words, for a given number of energy piles, how many residential square meters can the network supply.

To address this question, the ground load found in the preceding section is used to simulate the energy pile fluid temperatures using Equation (8) for a square of 16,950 m^2 energy pile foundation with a pile spacing of 3.0 m. The contribution of the horizontal distribution pipes is neglected for now, we return to this issue in Section 7.2.4. The simulation is run for 25 years, and the minimum fluid temperature recorded. Keeping the building energy requirement fixed we successively reduce the energy pile foundation area (and hence the number of energy piles) in the simulation until the minimum simulated fluid temperature reaches the lower limit of 2 °C.

7.2.4 Heat transport in horizontal pipes

The horizontal pipes that comprises the heating and cooling distribution network are uninsulated and exchange energy with the surrounding soil as illustrated in Figure 32.

Figure 32: Cross section of the geothermal pipe in heating mode (left) and cooling mode (right). Arrows indicate the direction of heat conduction.

The heat flow equation in the soil for a cylindrically symmetric problem is:

$$\frac{\partial T_s}{\partial t} = \frac{\lambda_s}{c_s}\frac{\partial^2 T_s}{\partial r^2} + \frac{1}{r}\frac{\partial T_s}{\partial r} \tag{19}$$

where T_s [K] is the soil temperature; t [s] is the time; λ_s [W/m/K] is the soil thermal conductivity, c_s [J/m^3/K] is the volumetric heat capacity, and r [m] is the radial distance measured from the center of the pipe.

We introduce dimensionless time, radial distance, axial coordinates and soil temperature:

$$t_D = \frac{\lambda_s \cdot t}{c_s \cdot r_{po}^2} \tag{20}$$

$$r_D = \frac{r}{r_{po}} \tag{21}$$

$$x_D = \frac{x}{L} \tag{22}$$

$$\mathrm{T_{Ds}} = \frac{2\pi\lambda_s \mathrm{L}}{\mathrm{Q}}\left(\mathrm{T_s} - \mathrm{T_{s,0}}\right) \tag{23}$$

where r_{po} [m] is the pipe outer radius, L [m] the length of the pipe, Q [W] the heat injection rate for the fluid, and $T_{s,0}$ [K] the undisturbed soil temperature. In these dimensionless variables Equation (19) becomes:

$$\frac{\partial \mathrm{T_{Ds}}}{\partial \mathrm{t_D}} = \frac{\partial^2 \mathrm{T_{Ds}}}{\partial \mathrm{r_D^2}} + \frac{1}{\mathrm{r_D}}\frac{\partial \mathrm{T_{Ds}}}{\partial \mathrm{r_D}} \tag{24}$$

By considering the energy balance for an infinitesimal section of the pipe we arrive at the following differential equation for the dimensionless fluid temperature:

$$\frac{\mathrm{A_D} \cdot \mathrm{H_f} \cdot \mathrm{N_s}}{2}\frac{\partial \mathrm{T_{Df}}}{\partial \mathrm{t_D}} + \frac{\partial \mathrm{T_{Df}}}{\partial \mathrm{z_D}} + \mathrm{N_{fs}}\left(\mathrm{T_{Df}} - \mathrm{T_{Ds}}\big|_{\mathrm{r_D}=1}\right) = 0 \tag{25}$$

In Equation (25) we have introduced:

$$\mathrm{A_D} = \frac{\mathrm{r_{pi}^2}}{\mathrm{r_{po}^2}} \tag{26}$$

$$\mathrm{H_f} = \frac{\mathrm{c_f}}{\mathrm{c_s}} \tag{27}$$

$$\mathrm{N_s} = \frac{2\pi\lambda_s \mathrm{L}}{\mathrm{w} \cdot \mathrm{c_f}} \tag{28}$$

$$\mathrm{N_{fs}} = \frac{\mathrm{L}}{\mathrm{w} \cdot \mathrm{c_f} \cdot \mathrm{R_{fs}}} \tag{29}$$

where r_{pi} [m] is the pipe inner radius, c_f [J/m^3/K] the fluid volumetric heat capacity, and w [m^3/s] the fluid flow rate. The thermal resistance between the fluid and the soil may be evaluated by Equation (14) with n=1.

7.2.4.1 Boundary conditions

Equations (24) and (25) are subject to the following boundary conditions. Continuity of heat flow at the pipe/soil interface requires:

$$\frac{\mathrm{N_{fs}}}{\mathrm{N_s}}\left(\mathrm{T_{Ds}}\big|_{\mathrm{r_D}=1} - \mathrm{T_{Df}}\right) = \frac{\partial \mathrm{T_{Ds}}}{\partial \mathrm{r_s}}\Big|_{\mathrm{r_D}=1} \tag{30}$$

The soil temperature should approach the undisturbed value for $\mathrm{r_D} \to \infty$:

$$\lim_{\mathrm{r_D}\to\infty}(\mathrm{T_{Ds}}) = 0 \tag{31}$$

Both the soil and fluid temperature should equal the undisturbed $T_{s,0}$ at *t=0*, i.e.:

$$\mathrm{T_{Df}}\big|_{\mathrm{t_D}=0} = 0 \tag{32}$$

$$\mathrm{T_{Ds}}\big|_{\mathrm{t_D}=0} = 0 \tag{33}$$

Finally, from the fluid heat injection rate we require:

$$\mathrm{N_s} = \mathrm{T_{Df}}\big|_{\mathrm{z_D}=0} - \mathrm{T_{Df}}\big|_{\mathrm{z_D}=1} \tag{34}$$

7.2.4.2 Solution

Equations (24) and (25) subject to the above boundary conditions are solved analytically in the Laplace domain following a strategy similar to [25].

The dimensionless fluid temperature in the Laplace domain $\overline{T}_{Df} = \mathcal{L}(T_{Df})$ is:

$$\overline{T}_{Df} = c_1 e^{-a_1 x_D} \tag{35}$$

where we introduce:

$$c_1 = \frac{N_s}{s(1 - e^{-a_1})} \tag{36}$$

$$a_1 = \frac{A_D \cdot H_f \cdot N_s \cdot s}{2} + N_{fs} \cdot c_0 \tag{37}$$

$$c_0 = 1 - \frac{1}{1 + \sqrt{s} \cdot \frac{N_s}{N_{fs}} \cdot \frac{K_1(\sqrt{s})}{K_0(\sqrt{s})}} \tag{38}$$

Here, s is the Laplace transform variable, and K_1 and K_0 are the modified Bessel functions of order 1 and 0, respectively.

The dimensionless fluid temperature in the time domain may finally be evaluated by applying the numerical inverse Laplace transform to Equation (35).

$$T_{Df} = \mathcal{L}^{-1}(\overline{T}_{Df}) \tag{39}$$

Note the fluid temperature depends on the fluid heat injection rate through Equation (23). This is appropriate for evaluating thermal response test data where the heat rate is known. In order to evaluate the fluid outlet temperature, $T_{f,o}$, from a given inlet temperature, $T_{f,i}$, we combine Equation (23) with the dimensional version of Equation (34) to obtain:

$$T_{f,o} = \frac{(T_{f,i} - T_{s,0}) \cdot c_f \cdot w}{2\pi \cdot \lambda_s \cdot L + c_f \cdot w \cdot T_{Df,o}} \cdot T_{Df,o} + T_{s,0} \tag{40}$$

From the above derivation we may calculate the fluid outlet temperature for a buried pipe given the inlet temperature and flow rate as well as thermal properties for the fluid, pipe and soil as indicated in Figure 33.

Figure 33: Geothermal pipe in the ground of length L with inlet and outlet temperature $T_{f,i}$ and $T_{f,o}$, respectively. In this illustration, the pipe absorbs heat from the ground, elevating temperature at the outlet.

7.2.4.3 Model evaluation

To demonstrate the applicability of the model, we compare simulated fluid outlet temperatures to thermal response test data of a 100 m geothermal pipe buried at shallow depth (approx. 1 m) in the EUDP-project "Demonstration af nyt fuldskala teknologisk koncept med en kombineret jordvarmeslange- og faskineløsning" journal no. 64015-0526 (see Figure 34).

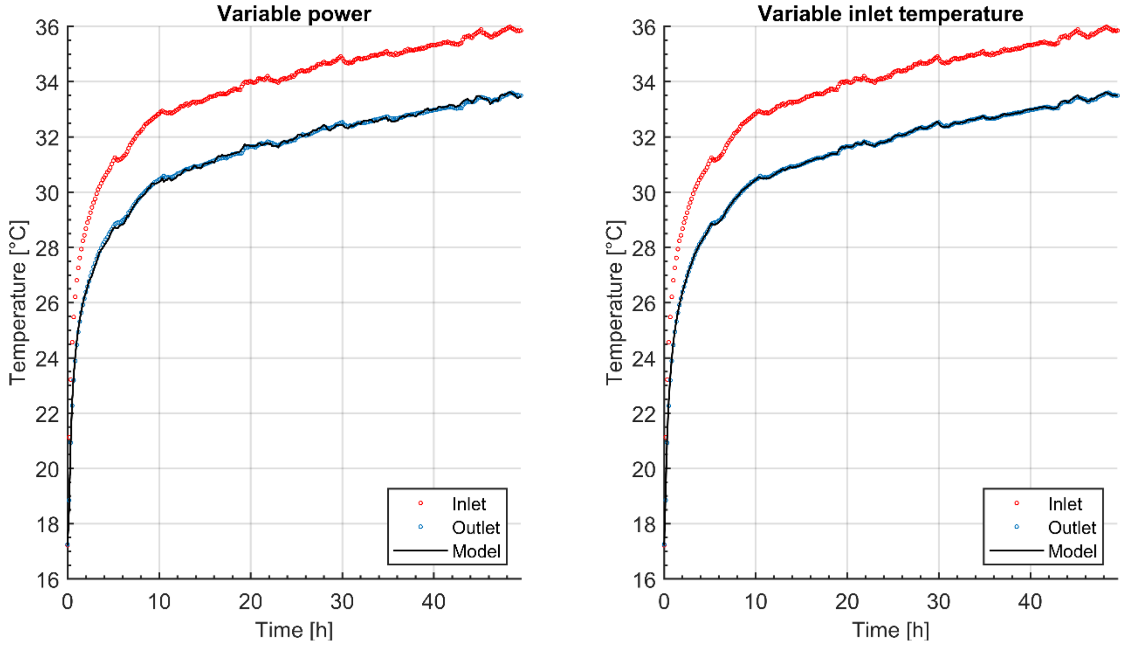


Figure 34: Measured and computed TRT outlet fluid temperatures. The outlet temperature is evaluated by superposition of the variable injected power (left) and using Equation (40) (right).

For reference, we use the ”Tør test, Grusfaskine” data set and the model parameters specified in Appendix 6 of [36].

The fluid outlet temperature is calculated in two different ways. First, the dimensionless fluid temperature T_{Df} is evaluated using Equations (35) and (39) and converted to real fluid temperature using Equation (23) and applying temporal superposition of the varying heat rate Q [30]. Second, the outlet temperature is evaluated using Equation (40). Both approaches model the observed outlet temperatures well. However, specifying the inlet temperature appears to produce the best fit. In the CDH model, the second approach is employed to calculate outlet temperatures for pipes in the network.

7.2.4.4 Accounting for seasonal temperature variations

Seasonal variations in the atmospheric temperature propagate into the ground. Surface temperatures are damped exponentially, and phase shifted linearly with depth, depending solely on the thermal diffusivity of the ground. The temperature at depth *z* below the surface is given by:

$$T(z,t) = T_0 + A \cdot \exp\left(-z\sqrt{\frac{\omega}{2\alpha}}\right) \cdot \cos\left(\omega t - z\sqrt{\frac{\omega}{2\alpha}}\right) \tag{41}$$

The depth-averaged, undisturbed temperature along different types of ground HEs is shown in Figure 35.

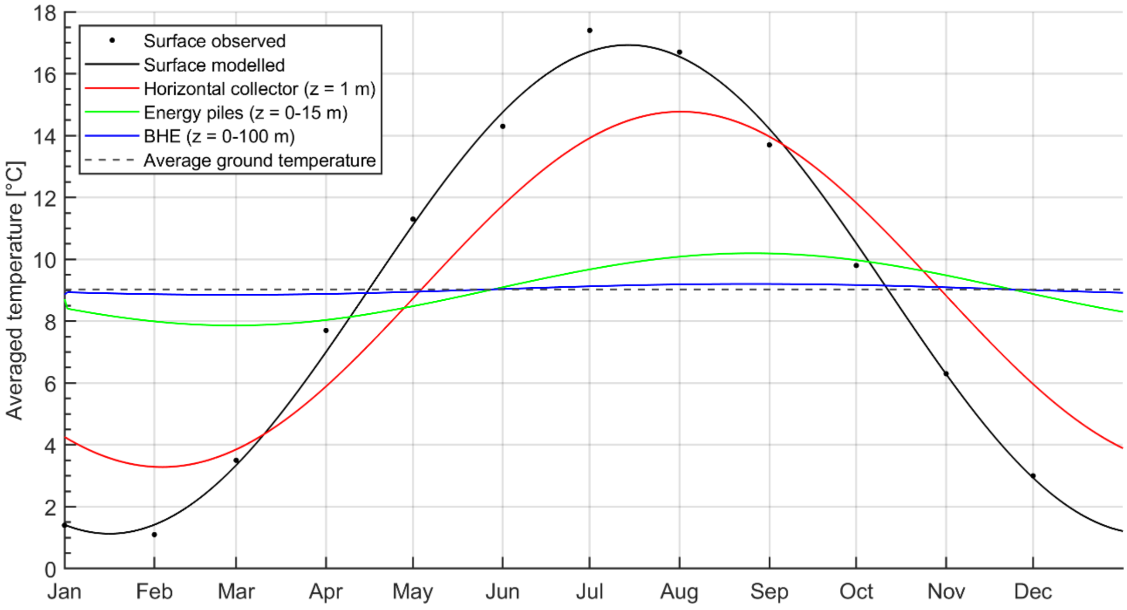


Figure 35: Monthly mean temperatures in Denmark for the period 2006-2015 are shown with black dots (www.dmi.dk). In addition, a trigonometric fit to the observed surface temperature (black), and and the temperature at depth z = 1m (red) calculated using Equation (41). The green and blue curves represent the depth averaged temperature for an energy pile and BHE respectively, while the dashed black curve is the average undisturbed ground temperature. The thermal diffusivity is in all cases $\alpha = 1.0 \cdot 10^{-6}$ *m^2/s.*

In order to include this seasonal variation in the model simulation, the static undisturbed soil temperature $T_{s,0}$ used to calculate the fluid outlet temperature is replaced by Equation (41).

7.2.5 Consumer model

The consumer requires heating in the winter as well as cooling during summer as indicated in Figure 32. Heating is provided by heat pumps installed in the consumer buildings. For a given heating demand Q_H, the heat extracted from the ground loop fluid, Q_C is given by:

$$\mathrm{COP} = \frac{|Q_H|}{W} = \frac{|Q_C| + W}{W} \tag{42}$$

where W is the work done by the heat pump and COP is the dimensionless coefficient of performance. As discussed previously we assume a constant COP of 3. For a given demand the change in the fluid temperature is found from:

$$Q_C = w \cdot c_f \cdot \Delta T_f \tag{43}$$

For cooling the situation is a little different as we assume passive cooling, that is the ground loop fluid is used directly, bypassing the heat pump. This means there is no reduction in the ground load compared to the building cooling load as can be seen in Figure 32. In addition, the cooling process cannot be forced by the heat pump as is the case for heating. Instead, an available cooling capacity is calculated and compared to the required cooling load. For fluid circulated through the under-floor heating pipes the available power is given by [37]:

$$T_a - T_f = q_a \cdot R_{fa} \tag{44}$$

where T_a [K] and T_f [K] are the ambient air temperature and average fluid temperature [K] respectively. The available cooling power is q_a [W/m^2] and R_{fa} [K·m^2/W] is the fluid to air thermal resistance. The thermal resistance can be broken down in three contributions. First, the thermal resistance between the air and floor surface. Second, the thermal resistance between the floor upper and lower surfaces i.e. the resistance of the flooring material itself. This depends on the chosen material [38]. Finally, the thermal resistance between the lower surface of the flooring material and the fluid, this includes the resistance of the concrete decking as well as the pipe material. The last two of these contributions are equal for heating and cooling, while the first is slightly higher for cooling due to reduced natural convection [39]. A suitable value for the total fluid-air thermal resistance is 0.34 K·m^2/W [38][39].

The fluid outlet temperature for the consumer side is evaluated as follows. For a given cooling demand $\mathrm{Q_c}$, the required fluid temperature change is calculated from Equation (43). Given the ground loop fluid inlet temperature at the consumer, the available cooling capacity is calculated from Equation (44). For simplicity we employ a constant ambient air temperature of $\mathrm{T_a = 26° C}$ for the entire cooling season. The required cooling capacity is calculated as:

$$\mathrm{q_{req}} = \frac{\mathrm{Q_c}}{\mathrm{A_c}} \tag{45}$$

where $\mathrm{A_c}$ is the total floor area of the consumer building [m^2]. The required cooling capacity is capped by the available capacity and the consumer outlet fluid temperature is finally calculated from Equation (43).

In the above treatment, we assume cooling is delivered through a traditional underfloor heating system. The model can easily be adapted to deal with cooling delivered by means of a ventilation system, which may be more suitable in larger non-residential buildings. In this case the fluid to air thermal resistance in Equation (44) should be modified accordingly and the floor area in Equation (45) should be replaced by the area of the cooling plate.

7.2.6 Overall model

The overall cold district heating system is modelled by combining the components described in the preceding sections. In the following we consider the case of Rosborg Ø with a total living area of 95,000 m^2. As indicated in Figure 29 we must distinguish between producing and consuming areas. In order to simplify the simulation we aggregate all production areas into a single large producer and all consumer areas into a single consumer. We assume a producer area of 14,250 m^2 and a consumer area of 95,000 m^2. From the demand profile calculated by the method outlined in Section 7.2.3 we find the separate demands of the producer and consumer buildings. In each time step, the simulated energy pile outlet temperature from the previous time step is used as the inlet temperature for the forward pipe (see Figure 36).

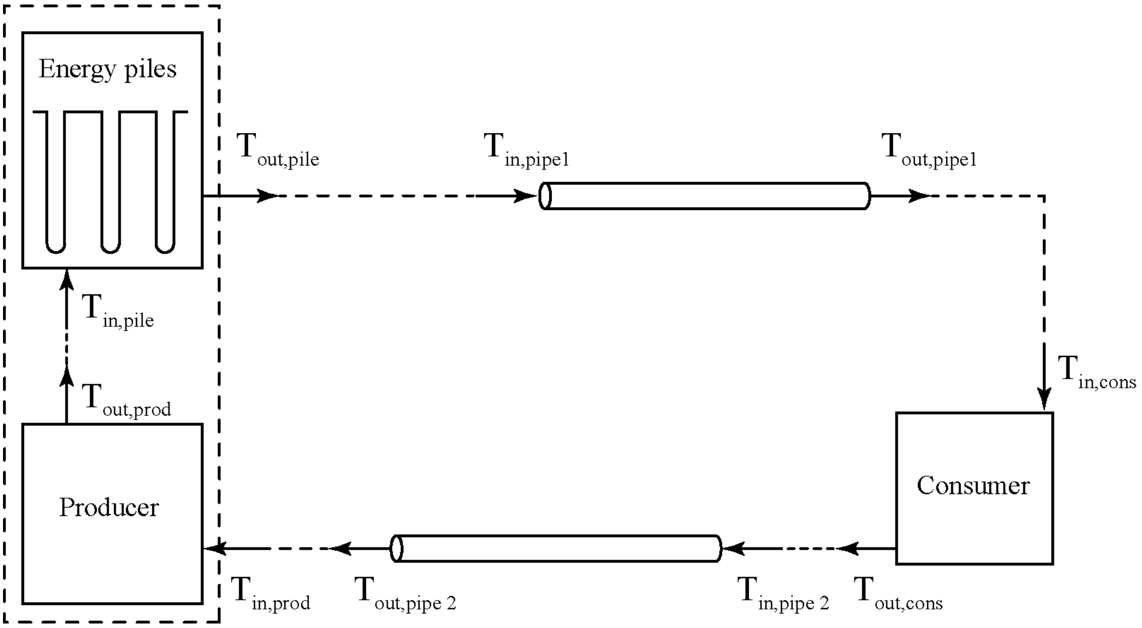


Figure 36: Mode topology for a single aggregated producer and consumer. Note the producer indicated with the dashed outline is responsible for both the energy production from the piles as well as part of the total system load.

Using the pipe model described in Section 7.2.4 we calculate the forward pipe outlet temperature, as well as the energy transfer between the fluid and the surrounding soil. The pipe outlet temperature is passed as the inlet temperature to the consumer model described in Section 7.2.5. The consumer outlet temperature is passed as the inlet temperature to the horizontal pipe model of Section 7.2.4 to calculate the return pipe outlet temperature as well as the heat transfer between the uninsulated pipe and surrounding soil. Finally, we must include the load of the production building, i.e. the return pipe outlet temperature is passed as the input to the consumer model of Section 7.2.5. Finally, an energy balance is enforced for the time step in question that is the actual load in Equation (8) is calculated as the sum of the contributions from the forward pipe, the consumer, the return pipe and the producer. For the Rosborg Ø area a characteristic pipe length of 700 m is employed for both the forward and return pipes, with an outer diameter of 200 mm. We assume a soil thermal conductivity of 2.0 W/m/K and an energy pile active length of 15 m.

7.3 Results

7.3.1 Demand profile

The simulated annual energy demand of the buildings on Rosborg Ø is estimated to be 45 kWh/m^2/yr of heating and 11 kWh/m^2/yr of cooling (Figure 37).

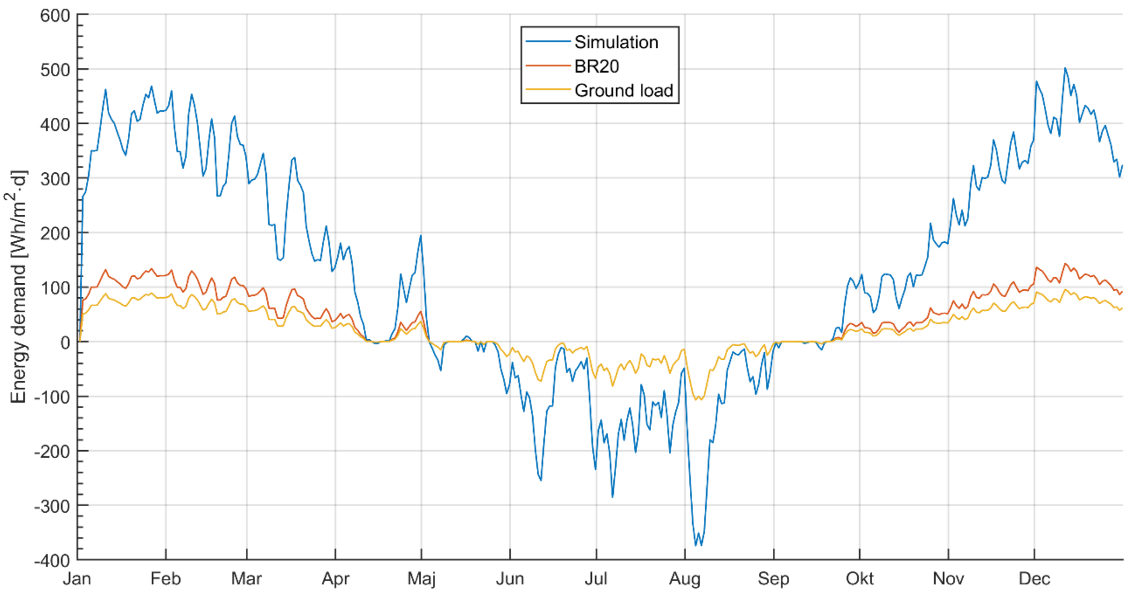


Figure 37: Simulated building energy demand (blue) together with the reduced demand corresponding to 20 kWh/m^2·y (red). For the energy pile simulation, the heating load must be reduced by the COP (yellow).

The new Danish building regulation BR20 [40] constrains total energy consumption to 20 kWh/m^2 for heating, cooling and electricity. The actual energy transfer between the ground and the building must take into account the contribution of the heat pump during the heating season. The heat injection rate for the energy pile model (see Equation (8)) is reduced compared to the building heating requirement assuming a constant COP of 3.

7.3.2 CDH simulation

The model described in the preceding section is run for 25 years with a time step of one day. The simulated energy pile fluid temperatures for the final year of the simulation are shown in Figure 38.

Figure 38: Simulated energy pile fluid temperatures for the 25th simulation year for the Rosborg Ø area.

The minimum and maximum energy pile fluid temperatures found in the simulated period are 4.4 °C and 15.2 °C. This is well within the allowable lower and upper limits for the energy piles of 2°C and 30°C respectively. In fact, the energy pile foundation area can be reduced to 11 %

of the total liveable area before fluid temperatures reach the lower limit of 2°C. In other words, one square meter of energy pile foundation can supply at most nine square meters of living space. This can either be in the form of additional stories or separate buildings.

The energy pile model is coupled to the rest of the system by feeding the simulated energy pile outlet temperature in time step *n-1* to the horizontal pipe model in time step *n*. Similarly for the producer building outlet temperature and energy pile inlet temperature as indicated in Figure 37. This procedure incurs an error in the overall energy balance which should be small if the model is to be consistent. In order to quantify this effect, we calculate the mean absolute error between the energy pile outlet temperature and inlet temperature for the forward distribution pipe for the full simulation period, similar for the producer outlet temperature and energy pile inlet. In both cases we obtain a mean absolute error of 0.17 °C.

In order to investigate the thermal capacity of the horizontal network of distribution pipes we compare the total energy supplied to the Rosborg Ø area to the energy supplied by the energy piles and horizontal pipes in Figure 39.

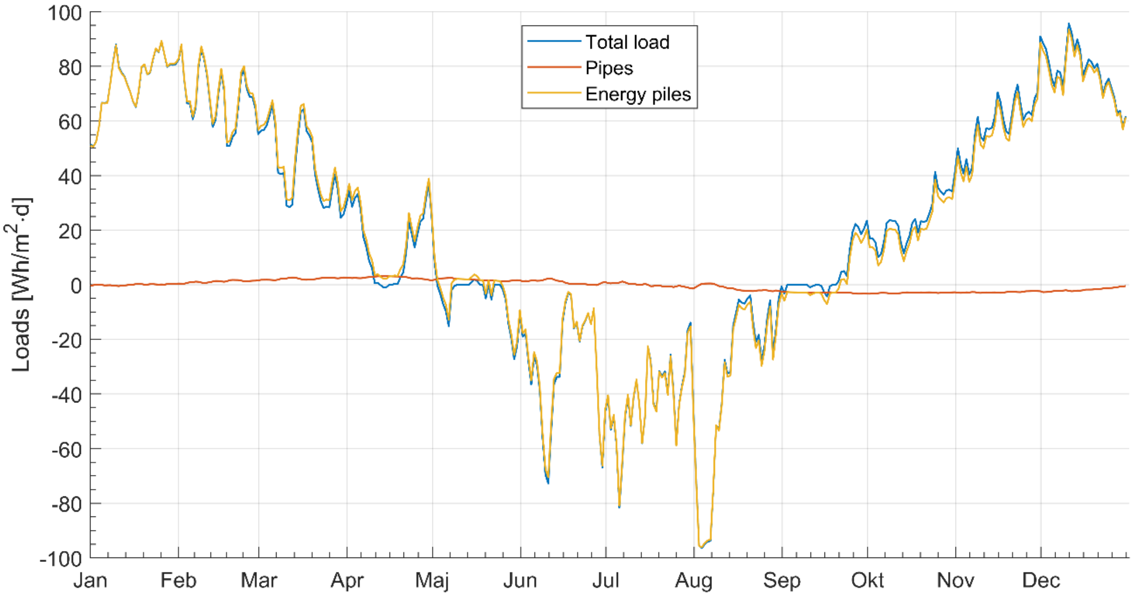


Figure 39: Total energy demand for the 25th simulation year for the Rosborg Ø area (blue), compared to the load supplied by the energy piles (yellow) and pipes in the distribution network (red).

In the case considered here, the capacity of the energy piles is significantly larger than that of the distribution network. Note that for most of the autumn the energy piles are in fact supplying less heating than is required by the connected buildings, the difference is made up by the pipe network. It would be possible to amplify this effect by deliberately laying out more horizontal pipes and actively harnessing the capacity of such a horizontal HE system. Care should obviously be taken that the opposite effect does not dominate during spring that is the pipe network should not cause the energy piles to deliver significantly more heating than required by the consumers.

Finally, we consider the simulated cooling capacity. Recall from Section 7.2.5 that the available capacity calculated from Equation (43) is limited by the fluid temperatures. We find that the cooling demand exceeds the capacity for 4 days per year. It should be noted that this estimate is based on average daily energy demands. The proportion of operational hours where there is insufficient available cooling will be higher when peak loads are taken into account.

7.3.3 *Outlook and further work*

The results obtained in the present work indicate that it is indeed feasible to supply heating and cooling with a CDH energy supply. A number of issues would be interesting to explore further in future projects. In the following we indicate some future avenues of further inquiry as well as some issues raised in the current work.

There is a significant mismatch between the estimated building energy demand following the current Danish building regulation BR18, and the energy limit imposed by the upcoming BR20. In the current work we have chosen to abide by the limit set by the upcoming building regulation, but it is currently unclear how this limit is to be met. To investigate consequence of varying the energy requirements we have repeated the simulation of the Rosborg Ø area for different values of the yearly energy demand and recorded the minimum energy pile fluid temperature, see Table 12.

Table 12: Minimum fluid temperature dependence on building energy demand.

Energy demand [kWh/m^2/y]	20	25	27	30
Minimum temperature [°C]	4.4	3.0	2.4	1.5

The minimum fluid temperature is clearly quite sensitive to the yearly load. In a scenario with no backup heating system, careful attention will have to be paid to the allowed ratio of producing to consuming areas.

When calculating the ground load for the energy pile model we assumed a constant COP of 3. In fact, the coefficient of performance is expected to vary over the year depending on operating conditions. It would be interesting to estimate the effect of this time variation on the performance of the entire system.

In order to keep the model as simple as possible we have aggregated all consumers into one, same for the producers. In order to investigate the effect of the horizontal distribution network further it would be interesting to increase the complexity of the network topology, that is to explicitly include multiple consumers and producers as well as the horizontal network of distribution pipes. The model described in Section 7.2.6 is straightforward to extend to a more complicated geometry. At all junctions in the network outlet temperatures may be calculated by enforcing conservation of energy.

In the same spirit of keeping the model simple, we have used simulated outlet temperatures for preceding time steps as inputs for model components, thereby incurring an error in the overall energy balance. An alternative approach would be to implement an iterative procedure to evaluate consistent temperatures in each time step, albeit at the cost of increased simulation times. Further research is necessary to estimate the magnitude of this effect in more detail.

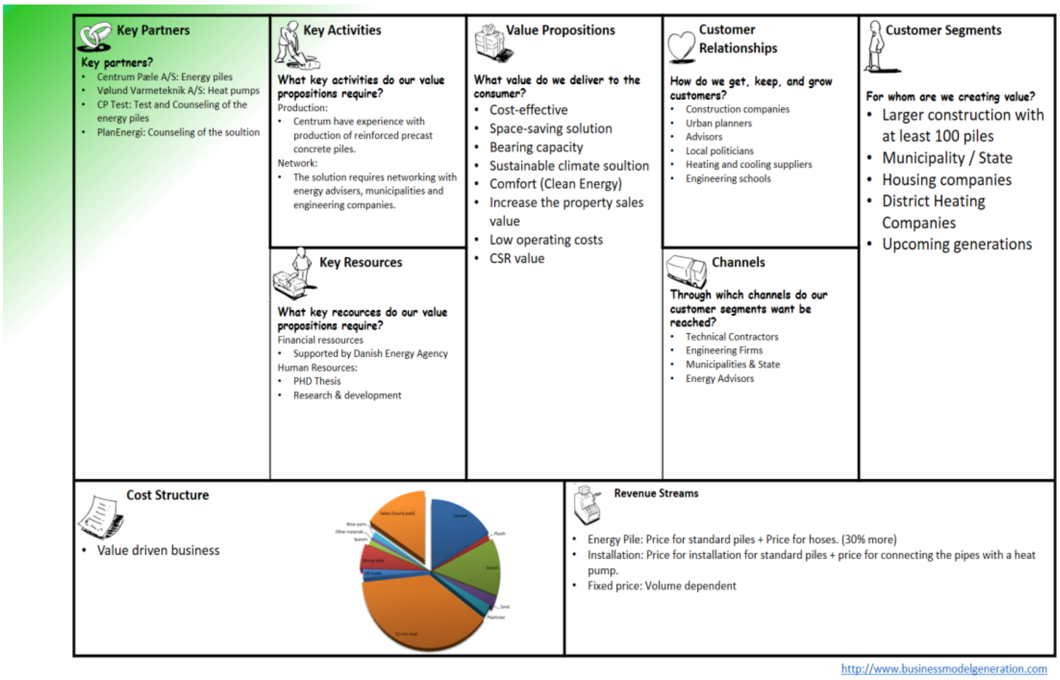
The simulations performed in the preceding section were based on daily time steps and average daily loads. While we found that the required cooling capacity can be met almost all of the time using this model, it is an open question what the effect of considering peak loads would be. In times where passive cooling cannot supply the entire cooling demand, the possibility of using reversible heat pumps for shaving peak demands in cooling could be explored. Active cooling has ramifications for the energy efficiency ratio, which is a key factor in calculating the payback period for a given case.

Finally, in the effort to improve the developed CDH model, real world operational data are necessary. In the event that systems of this kind are put into operation in the coming years, it is vital that the instrumentation and data acquisition focus not only on the minimum requirements for operating the system, but also take into account which data are necessary to validate and improve the model further.

8. WP5: Business model

Following the computational work in WP 4, the estimated total liveable area in Rosborg Ø has been lowered from 95,000 m2 to 77,440 m^2 by Vejle municipality. It is expected to be reduced even further but there is no information available on this issue as of now. In the calculation of payback time in this section, the updated estimate of the liveable area of 77,440 m^2 is used.

During a series of five half-day meetings, the commercial partners have defined a business model to support the realization of the energy pile system. The Business Model Canvas for energy piles is shown in Figure 40.



Key Partners

Key partners?
- Centrum Pæle A/S: Energy piles
- Vølund Varmeteknik A/S: Heat pumps
- CP Test: Test and Counseling of the energy piles
- PlanEnergi: Counseling of the soultion

Key Activities

What key activities do our value propositions require?
Production:
- Centrum have experience with production of reinforced precast concrete piles.

Network:
- The solution requires networking with energy advisers, municipalities and engineering companies.

Key Resources

What key recources do our value propositions require?
Financial ressources
- Supported by Danish Energy Agency

Human Resources:
- PHD Thesis
- Research & development

Value Propositions

What value do we deliver to the consumer?
- Cost-effective
- Space-saving solution
- Bearing capacity
- Sustainable climate soultion
- Comfort (Clean Energy)
- Increase the property sales value
- Low operating costs
- CSR value

Customer Relationships

How do we get, keep, and grow customers?
- Construction companies
- Urban planners
- Advisors
- Local politicians
- Heating and cooling suppliers
- Engineering schools

Channels

Through wihch channels do our customer segments want be reached?
- Technical Contractors
- Engineering Firms
- Municipalities & State
- Energy Advisors

Customer Segments

For whom are we creating value?
- Larger construction with at least 100 piles
- Municipality / State
- Housing companies
- District Heating Companies
- Upcoming generations

Cost Structure
- Value driven business

Revenue Streams
- Energy Pile: Price for standard piles + Price for hoses. (30% more)
- Installation: Price for installation for standard piles + price for connecting the pipes with a heat pump.
- Fixed price: Volume dependent

http://www.businessmodelgeneration.com

Figure 40: Business Model Canvas for energy piles.

The model is based on system thinking and collaboration between the partners participating in the model. No value will be created unless there is a trust and understanding between the partners. Only through collaboration between the key partners, is it possible to realize the value proposition.

Therefore, a new value proposition has been worked out during the work regarding the business model supporting the solution. The value proposition is *”Energy piles are a vital source to effective and efficient climate solutions in building sustainably by the use of the earths renewable resources”.* The value proposition canvas is shown in Figure 41.

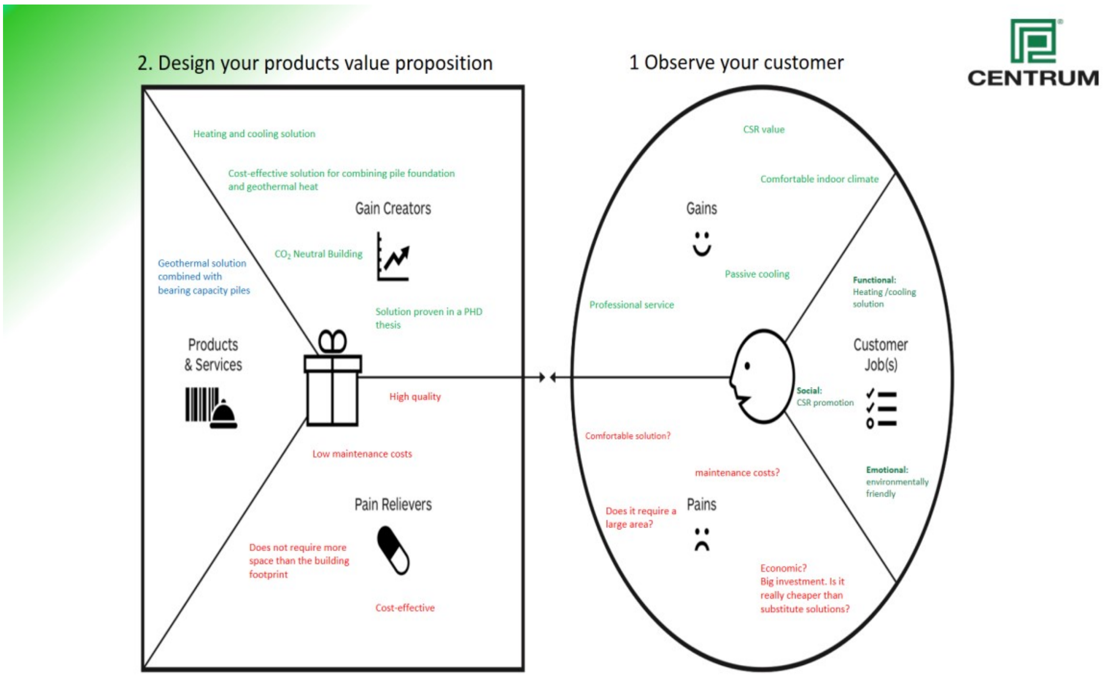


Figure 41: The Value Proposition Canvas for energy piles.

The business model is tested on the residential are Rosborg Ø in Ny Rosborg to test its profitability. The variables in the model are:

- Cost of piles.
- Cost of assembly of the system.
- The thermal capacity of the piles. The length of the pile and the ground conditions.
- COP values realized versus computed.
- The thermal capacity of the ground calculated with the simulation tool versus reality.
- Consumption (cooling/heating) from building calculated versus reality.
- Cost of energy (electricity).
- Endurance and effectiveness of heat pumps.
- Development in the interest rate.

The solution provides green, cost effective energy (heating and cooling) at low operational and maintenance costs. This is achieved without the requiring additional outdoor areas for the ground heat exchangers as the energy piles are placed under the building.

The business case parameters for the Rosborg Ø case study are listed in Table 13.

Table 13: Business case parameters for Rosborg Ø.

Information	**Unit**	**Value**
Building size	m2	16,942
Living area	m2	77,740
Heat need	kWh/year	2,720,900
Cooling need	kWh/year	680,225
Electricity	kr./kWh	0.619
Discount rate	%	1.00

We assume a depreciation period of 20 years and an interest rate of 1%.

The energy pile costs are summarized in Table 14.

Table 14: Initial and variable costs associated with energy pile based CDH.

Capital cost	Price	Depriciation in years	Dep/year	***Runnin costs***	
Price energy piles	3.698.000,00 kr.	20	204.926 kr.	Heatproce/year	481.210,60 kr.
Intallation pile to heat pump	3.964.256,00 kr.	20	219.680 kr.	Coolingprice/year	21.052,96 kr.
Heat pump and installation	9.349.338,00 kr.	20	518.097 kr.		
Thermonet plus installation	4.426.608,00 kr.	20	245.302 kr.		
Total	21.438.202 kr.	Tortal depriciation	23.760.094 kr.	Total	502.263,56 kr.

For comparison we list the costs associated with traditional District heating in Table 15.

Table 15: Initial and variable costs of traditional district heating and air conditioning.

Captital cost	Price	Depriciation in years	Dep/year	***Runnin costs***	
District heating solution	8.292.396,82 kr.	20	459.526 kr.	Heatproce/year	2.433.323,32 kr.
Main line	5.750.000,00 kr.	20	318.638 kr.		
Total	14.042.396,82 kr.	Tortal depriciation	15.563.277 kr.	Total	2.433.323,32 kr.

Using the information provided in Table 15 the payback period is estimated (Table 16).

Table 16: Calculation of payback period for CDH in Rosborg Ø, Ny Rosborg, Vejle, Denmark.

Energy piles price per year	502,263.56 kr.
District heating price per year	2,433,323.32 kr.
Saving from energy pile per year	1,931,059.76 kr.
Payback time	**4.24 years**

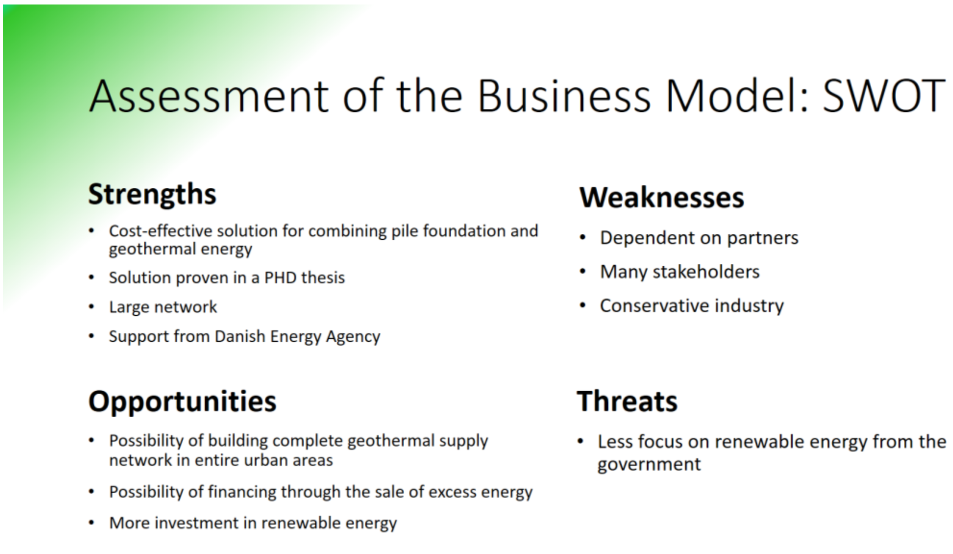
The business case shows that the cost of energy pile based CDH is returned in variable cost savings in 4.24 years relative to traditional DH. The numbers are based on the prospect from Vejle kommune on Ny Rosborg, the internal cost calculations from Vølund Varmeteknik and Centrum Pæle. Vølund Varmeteknik has dimensioned the piping in the CDH network. On that basis, Søren Skjold Andersen from Geodrilling, who deploy and operate CDH networks in Denmark, kindly estimated the cost of establishing the horizontal piping for the CDH distribution network at Rosborg Ø. The economic figures for district heating are based on information from the Vejle DH company. Energy prices are provided by PlanEnergi and takes different accounting and taxation policies and rules into consideration. The validity of the numbers should therefore be high.

Regarding the customer segment then Centrum Pæle estimates that the maximum potential is equivalent to a scenario where all buildings in areas with beneficial thermal conductivities are founded on energy piles.

This would amount to roughly 400,000 meters of energy piles per year. However, realistically, Centrum Pæle has an expectation that this number would be closer to 200,000 meters – or 10,000 piles in total in the Danish market alone.

Then there is potential in technology transfers and licensing solutions. Both as an export item since energy piles do not transport very far. The size of that part of the business can have a very high potential and dialogue is already established with several companies.

The model is also tested for the strength and weaknesses in a SWOT analysis (Figure 42).



Assessment of the Business Model: SWOT

Strengths

- Cost-effective solution for combining pile foundation and geothermal energy
- Solution proven in a PHD thesis
- Large network
- Support from Danish Energy Agency

Weaknesses

- Dependent on partners
- Many stakeholders
- Conservative industry

Opportunities

- Possibility of building complete geothermal supply network in entire urban areas
- Possibility of financing through the sale of excess energy
- More investment in renewable energy

Threats

- Less focus on renewable energy from the government

Figure 42: SWOT analysis for energy piles.

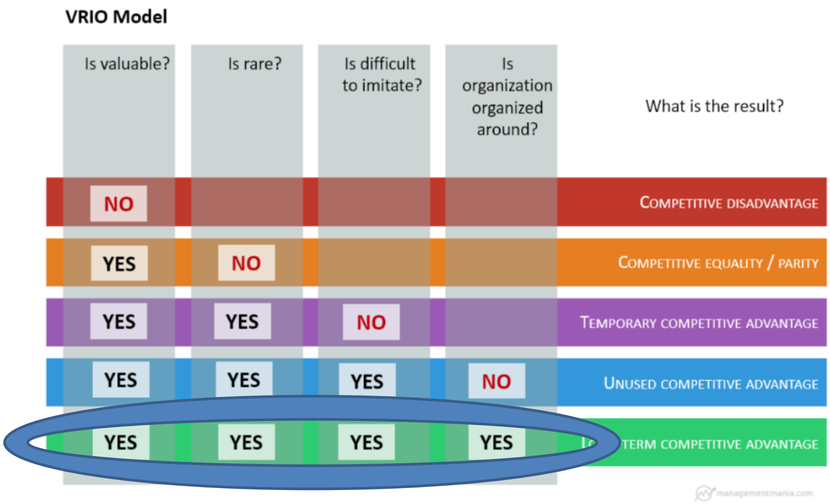
It is a proven cost-effective solution that could change the way the industry thinks and act. It demands togetherness as a basis thinking with can be challenging in a industry where each often acts alone. It supports the global climate goals for sustainability (https://www.globalgoals.org/) but still depends on local government polices favouring these type of solutions. Especially goal 7,11 and 13 are in focus with the solution (Figure 43).

Figure 43: Sustainable Development Goals (SDGs) related to energy piles.

The model is also tested in the VRIO framework (Barney, J. B., & Hesterly, W. S. (2010). VRIO Framework. In Strategic Management and Competitive Advantage (pp. 68–86). New Jersey: Pearson)

The following question is addressed: **The Question of Value:** "Is the firm able to exploit an opportunity or neutralize an external threat with the resource/capability?" **The Question of Rarity:** "Is control of the resource/capability in the hands of a relative few?" **The Question of Imitability:** "Is it difficult to imitate, and will there be significant cost disadvantage to a firm trying to obtain, develop, or duplicate the resource/capability?" **The Question of Organization:** "Is the firm organized, ready, and able to exploit the resource/capability?" "Is the firm organized to capture value?"[1]

The VRIO analysis of energy piles is shown in Figure 44.


VRIO Model

Is valuable?	Is rare?	Is difficult to imitate?	Is organization organized around?	What is the result?
NO				Competitive disadvantage
YES	NO			Competitive equality / parity
YES	YES	NO		Temporary competitive advantage
YES	YES	YES	NO	Unused competitive advantage
YES	YES	YES	YES	term competitive advantage

Figure 44: The VRIO model for energy piles.

There is strong evidence that energy piles have a long-term competitive advantage based on the VRIO framework test.

The calculation possibilities from the Ph.D. has resulted in a dimensioning tool that will be very hard to imitate. The payback time is short and the solution is green. It can be imitated but it takes an organization that provides a system solution.

The biggest hurdle to overcome is the acceptance of the solution. The Danish construction industry market is renowned for its extreme conservativeness with a one eyed focus on price (https://advantage-marketline-com.ez-aaa.statsbiblioteket.dk:12048/Analysis/ViewasPDF/denmark-construction-69841) as shown in the Degree of Rivalry analysis in Figure 45.

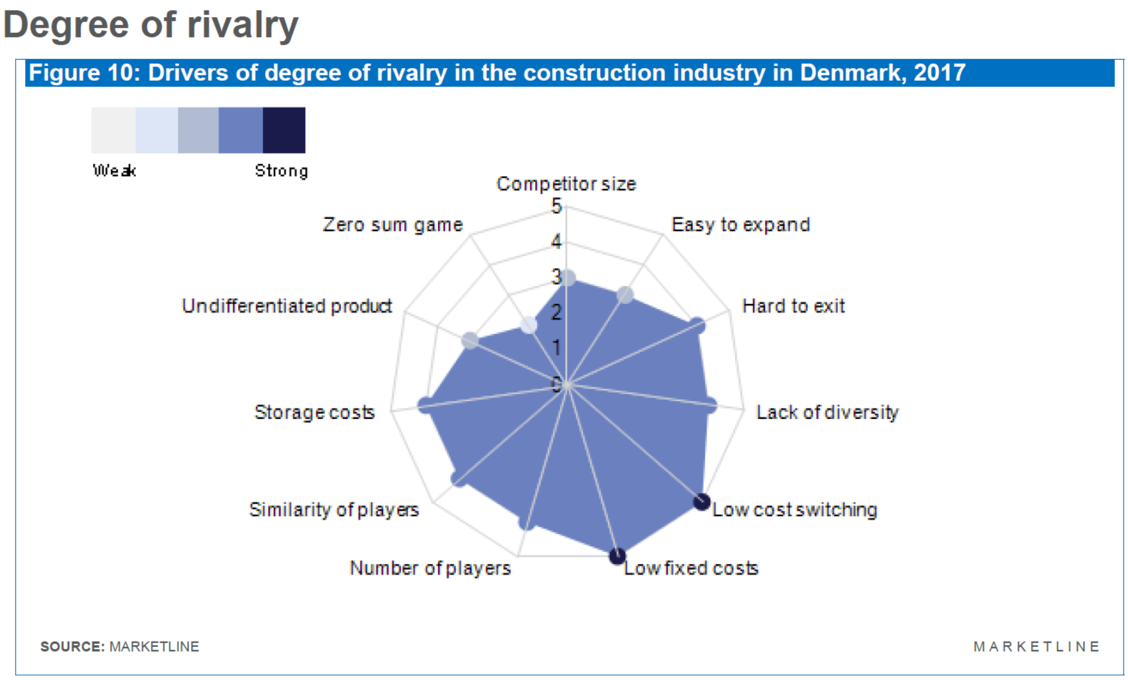


Figure 45: Degree of Rivalry analysis for the construction industry.

Since the solution is more expensive initially, it is very important to communicate the total running cost and the payback time. There is also a tendency in the construction industry to focus more on green solutions but the main driver is still hardcore economics. The energy pile solution is therefore very strongly positioned in relation to that.

Additional supporting material has been prepared by Centrum Pæle at their own expense to support the sales of the solution. These materials are included in Appendix D.

The overall the conclusion on the business model is that it is very attainable. With the current partner set up, the possibilities that the dimensioning and business model tools provide and with the technology at hand, it is possible to make a very strong green product to the construction market with a low running cost and a very little footprint.

9. Utilization of project results

9.1 Centrum Pæle

- How do the project participants expect to utilize the results obtained in the project?

Centrum Pæle expects to use the results mainly to provide the baseline for the future potential of energy piles in a larger grid. Primarily, Centrum can utilize the findings from the project to convince district heating providers, municipalities, advisors, entrepreneurs, investors and the public of the potential of the system as a decentral solution to replace the burning of fossil fuels and biomass.

- Do any of the project participants expect to utilize the project results - commercially or otherwise?

Centrum Pæle will utilize the project results commercially in their marketing efforts as stated in the previous point. See appendix D created and paid by Centrum Pæle as a consequence of the project.

- Which commercial activities and marketing results do you plan for?

Using the EUDP project findings as a “proof of concept” to convince the above-mentioned stakeholders to first and foremost invest in carrying out the first project which can be used as a reference for the future.

The commercial activities will mainly be carried out through social media and direct marketing (presentations, networking, canvassing).

- Has your business plan been updated?

A new business model has evolved during the process resulting in the business model canvas shown previously in Figure 40.

Through collaboration with the key partners the value proposition will be realized.

A new value proposition has been worked out during the work process regarding the business model supporting the solution. The value proposition is *”Energy piles are a vital source to effective and efficient climate solutions in building sustainably by the use of the earths inherited resources”.* The value proposition canvas is shown in Figure 41.

We have also identified the strength and weaknesses of the set-up we wish to pursue (Figure 42).

- Or a new business plan produced?

Yes – a concrete business plan for energy piles at Centrum Pæle has been developed alongside the EUDP project. The business has resulted in a new business unit with a separate budget that realizes the potential of the technological setup. We believe it will address the barriers that need to be overcome during the manifestation of the solution in the market.

- What future context is the end results expected to be part of, e.g. as part of another product, as the main product or as part of further development and demonstration?

The results are expected to be a vital part of highlighting the possibility of establishing a decentral grid of buildings which are all founded on energy piles in Ny Rosborg. The solution is an integral part of the energy pile which the company has many years of experience in producing.

- What is the market potential?

Centrum Pæle estimates that the maximum potential is equivalent to a scenario where all buildings in areas with beneficial thermal conductivities are founded on energy piles.

This would amount to roughly 400,000 meters of energy piles per year. However, realistically, Centrum Pæle has an expectation that this number would be closer to 200.000 meters – or 10.000 piles in total in the Danish market alone.

Then there is potential in technology transfers and licencing solutions. Both as an export item since energy piles does not transport very far. The size of that part of the business can have a very high potential and dialogue is already established with several companies.

Lastly it is our hope that the knowledge from this solution will disseminate out to the universities around the world and from there into the market as a very legit and stable green solution.

- Competition?

There is limited competition from homogenous products, but huge competition in the shape of other methods of providing energy. In relation to traditional district heating systems, using energy piles is a more expensive solution to establish in terms of capital costs. However, as shown in the financial calculations, energy piles have a relatively low payback period in most cases (4.14 years for Rosborg Ø), which will justify the expense.

- Do project participants expect to take out patents?

Not at the current moment. The calculation possibilities from the Ph.D. has resulted in a configurations tool that will be very hard to imitate.

- How do project results contribute to realize energy policy objectives?

They contribute positively, as the results clearly prove that there is a sustainable solution which can provide sufficient energy for heating and at the same time replace burning fossil fuels.

As an additional benefit, this solution provides one of the absolute most cost-effective ways of using a cooling system to provide a comfortable living temperature inside the building.

The overall global goals that the solution addresses are:

- Have results been transferred to other institutions after project completion?

Through the collaboration with the partners in the project there will be significant knowledge transfer. VIA will use it in education of students and future consultants in the building industry. Hopefully energy piles will evolve into a “natural” solution in all future energy systems.

If Ph.D.s have been part of the project, it must be described how the results from the project are used in teaching and other dissemination activities

There are no Ph.D.s associated with the project. However, this project draws significantly on Maria Alberdi-Pagolas Ph.D.-project that was initiated in 2015 by VIA UC with CP and Aalborg University as partners. Thus, the current project is basically a spin-off from her Ph.D-project which again was initiated by VIA UC. The results from the Ph.D. is used in courses in supply engineering at VIA and further spin off-projects are planned with additional emphasis on CDH.

9.2 Vølund Varmeteknik

- How do the project participants expect to utilize the results obtained in the project?

The market for heat pumps in commercial projects is increasing in Denmark. Vølund is experiencing increased demand for heat pumps for larger buildings (schools, offices, etc.), especially in and around the larger Danish cities. In urban buildings, it is usually a challenge to make room for the heat pump's heat absorber and here energy piles are an obvious solution. As the technology is now verified and thoroughly analyzed, we will now try to spread the knowledge of heat pumps combined with energy piles to market stakeholders.

- Do any of the project participants expect to utilize the project results - commercially or otherwise?

At present, we have shared the results of Maria Alberdi-Pagolas Ph.D. project with colleagues in the heat pump business from Norway, Finland and Sweden. In addition, we have referred to the results of the project to potential customers in Denmark.

- Which commercial activities and marketing results do you plan for?

As the technology is now verified and thoroughly analyzed, we will now try to spread the knowledge of heat pumps combined with energy piles to market stakeholders.

- Has your business plan been updated?

No

- Or a new business plan produced?

No

- What future context is the end results expected to be part of, e.g. as part of another product, as the main product or as part of further development and demonstration?

We expect energy piles to be included in the future as a natural heat absorber for heat pumps on a par with other sources (horizontal geothermal heat, air / water heat pumps, etc.)

- What is the market potential?

We have not analysed this.

- Competition?

In the larger cities, district heating is usually an alternative / competitor to the heat pump. With energy piles combined with heat pumps, we can, like district heating, supply heat and hot water, but in addition to cooling the buildings during the summer months. Passive cooling with energy piles has proven extremely effective (high EER) due to the ability of the pile to absorb / deliver heat to the surrounding soil.

- Do project participants expect to take out patents?

No

- How do project results contribute to realize energy policy objectives?

Larger shares of the Danish energy sector is being transformed into electricity produced by wind wills. This conversion makes it more advantageous to use heat pumps combined with different types of heat absorbers such as energy piles.

- Have results been transferred to other institutions after project completion?

Not by us.

- If Ph.D.s have been part of the project, it must be described how the results from the project are used in teaching and other dissemination activities?

Not relevant for us.

9.3 VIA

The present project has allowed VIA UC to take an increasingly dominant position in the research area of shallow geothermal energy in Denmark. The promising results obtained in this project motivates additional research proposals where the concepts of CDH are implemented at either demonstration- or full scale with detailed monitoring of operational data.

VIA UC and additional commercial and public partners applied for the project “Combined energy-efficient sustainable district heating and cooling and surface water drainage system (Thermo-road)” in the autumn of 2019 at the second application round in the EUDP program. The project aims to combine CDH with surface water drainage in which the sand and gravel roadbed is simultaneously used for rainwater retardation and as a heat source and sink for a ground source heat pump. VIA expects the combined system to be economically competitive with individual energy supply systems and rainwater management at the end of the project. In that case, a validated and economically competitive collective heating and cooling supply is made available for dissemination in areas without traditional district heating, thereby greatly aiding the green transition here. The current project has shown that energy pile based CDH is able to potentially compete directly with traditional district heating and cooling due to the short payback period in the Rosborg Ø case. The new EUDP project therefore also aims to quantify whether the Thermo-road is able to compete directly with traditional DH in terms of user economy.

VIA UC discourages the use of patents and IPR as we believe that it will only serve as a barrier for the implementation of CDH on a larger scale.

10. Project conclusion and perspective

Denmark is destined to become free of fossil fuels in 2050. The current transition into CO_2 neutral heat production in Denmark is largely based on biomass, but in time, heat pumps are projected to gradually replace both fossil and biomass fuels. As such, there is a need for further technological development of renewable, economically competitive, collective building heating and cooling systems to support the transition away from biomass in the future.

This project has fully developed a concept for collective, renewable, energy efficient ground source heat pump based heating and cooling for the future energy supply in Denmark. Moreover, the developed technology is economically competitive when compared to traditional DH and cooling. The current project builds upon and extends the results and conclusions from an industrial Ph.D.-project on energy piles that finished in 2018.

The project consists of six work packages (WP 1 is assigned to project management) that outline the steps for screening Ny Rosborg for the possibilities of establishing collective energy pile based heating and cooling supply. Work package 2 develops a methodology for mapping the thermal properties and energy potential of the shallow soil layers, situated between the surface and 15 m depth, where heat is abstracted and dissipated. The method draws upon well-established field investigations that combine borehole information and geophysical surveys with laboratory measurements of the thermal and geotechnical properties of soil samples from Ny Rosborg. A series of planning maps of soil thermal conductivity, heat capacity, depth to the foundation layer and geotechnical properties can be constructed on basis of the field investigations in Ny Rosborg. The screening method is easy to adopt for engineering companies that carry out geological and geotechnical investigations.

The energy potential scales directly with soil thermal conductivity which is the single most important performance parameter for GSHP systems. The geothermal screening has therefore proved vital to the case study of Rosborg Ø (a small residential subarea of Ny Rosborg) as it indicates a relatively high thermal conductivity in the southern part of the Ny Rosborg area where Rosborg Ø is located (1.7-2.2 W/m/K). In the northern part of Ny Rosborg, soil thermal conductivity is around 1.5-1.7 W/m/ which implies that the energy potential here is ca. 15% lower, relative to Rosborg Ø.

The pile testing in WP 3 has been aimed at testing a novel design of the HE embedded in the energy pile in order to explore whether piles can be put in series without significantly reducing the heat exchange with the ground. This potentially reduces the complexity and costs of connecting the piles to the heat pump. The new design is cheaper to produce and utilizes a larger diameter single-U geothermal pipe that reduces the pressure loss and the associated pumping costs during operation. The results of the investigations imply that at least two energy piles can be connected in series. The single-U HE increases the thermal resistance between the geothermal fluid and the ground by 58% relative to the original design. However, it is currently believed that the increased pile thermal resistance does not negate the benefits of the production cost reductions associated with the single-U HE.

Work package 4 aims to quantify the heating and cooling demand on Rosborg Ø by using state-of-the-art building energy modelling. Building energy simulations estimate the heating and cooling needs to 45 and 11 kWh/m^2, respectively, indicating that the planned buildings are likely to violate the BR20 building regulation, given that standard building materials are used. The fluid temperature on the CDH is highly sensitive to the thermal load from the buildings. Accurate building energy simulations are therefore vital for making reliable predictions of the thermal load on the CDH network.

The energy demand profile serve as input for calculating the fluid temperatures to the heat pumps, which allows for an assessment of the COP (coefficient of performance) of the heat pumps connected to the CDH and thereby the costs of operation. To calculate the fluid temperatures to the heat pump, a prototype computational model of temperatures in CDH has been developed in the project. The model allows engineers and planners to dimension CDH networks in real applications, provided that reliable information on the heating and cooling demand of the planned buildings and the thermal properties of the subsurface are available.

Applying the CDH temperature model to the Rosborg Ø case shows that CDH can fully supply the heating and cooling demand so long the ratio between the building footprint and liveable area is greater than 11%. Thus, Ny Rosborg is well-suited for CDH based on energy piles, however, recalculation of the scenario is necessary once additional information on the planned buildings become available.

Work package 5 has established a business model for collective heating and cooling supply with energy piles. The total costs has been quantified for all elements in deploying energy pile foundations, heat pump installations and the CDH network. The model is applied to the case of Rosborg Ø for estimating the construction costs and variable costs of operation for an energy pile based CDH network. We find a payback period of 4.24 years for the energy pile based CDH heating and cooling supply using traditional district heating and cooling as the reference scenario. The contributing factors to the short payback period are the relatively low costs of electricity, the high COP of the Ground Source Heat Pump (GSHP), the relatively high power tariff (effektbidrag) from traditional DH and finally the exceptionally low costs of passive cooling/seasonal heat storage.

Given the findings in the project, there are many interesting perspectives of utilizing shallow geothermal resources in the future energy supply in Denmark. The concept of CDH or Termonet (the latter being the Danish term for CDH) is in its infancy with only a few small operational systems in Denmark. Silkeborg District Heating owns and operates a small Termonet that supplies 15 houses on Balle Bygade with heating by means of a CDH network supplied by 6 BHEs as traditional DH is not possible in that area. Cooling is not possible as the required technical installations in the houses are missing. The business case for the Termonet in Silkeborg shows that the Termonet is cheaper than individual supply systems (e.g. air-water heat pumps) but more expensive than traditional DH, primarily due to the costly Termonet BHEs. On that basis, the Termonet is a viable and economically attractive solution to the green transition in the areas without the possibility of traditional district heating (dansk: område 4). The district heating companies in Denmark are in need of new heat pump technologies for collective heating and cooling to replace biomass in the future. Therefore, it is worth exploring whether is possible to reduce the number of Termonet BHEs and replacing them by cheaper heating and cooling sources, to improve the economic viability to an extent where it can compete directly with traditional DH.

In March 2018 VIA UC opened its 50 m of Climate Road (Klimavej) that serves simultaneously as energy collector for a ground source heat pump and as a rainwater retardation basin. The Climate road is able to retain large amounts of rainwater in the roadbed and in addition heat can be extracted from it by means of 800 m of geothermal piping embedded 0.5 m and 1 m below the road surface. The Climate Road has supplied 30 MWh of domestic hot water and space heating to a nearby child care centre in the period 1st of April - 19th of December, 2019. Installing the geothermal piping in the Climate Road is relatively cheap, as the roadbed is to be constructed in any case and therefore serves as a cheap source of heating and cooling. The Climate Road can therefore alleviate the thermal load on the BHEs in the Termonet, potentially reducing the required number of expensive BHEs. Consequently, combining the concepts of the Climate Road and Termonet in the Thermo-road concept is proposed in a new, approved EUDP project scheduled to start the 1st of January 2020 with VIA UC as project owner and leader. The main idea is to combine two different climate adaption methods (rainwater management and renewable energy supply) in a single system - but it is also a means to reduce the number of expensive geothermal drillings (i.e. BHEs) by instead abstracting and dissipating heat in the roadbed. The expectation is that the business case for the Thermo-road is better than for the Termonet, where the latter relies exclusively on expensive BHEs as the primary heat source and sink. Moreover, the project seeks to explore the business case, where passive cooling is procured by the consumer, thus improving the revenue stream and the performance of the heat pump, for the heating company that owns and operates the Thermo-road.

The future for CDH based on energy piles is promising as both the technical and economic feasibility has been demonstrated quite clearly. Nevertheless, more research is necessary to support this conclusion. Additional development of the CDH model tool is required and detailed operational data must be compiled from operational CDH networks to support and validate the computational model.

Cold District Heating is a somewhat complex technological product as it involves several professional disciplines from geothermal investigations, energy consulting, pile driving and geotechnics, plumbing, heat pump installation/operation/service and indoor climate and thermal comfort. To deliver CDH to customers successfully, an ensemble of companies specializing in said disciplines must corporate. The companies that chose to do so potentially enters a huge worldwide market for collective, renewable heating and cooling where very little competition exists.

Acknowledgements

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Appendices

Appendix A. Soil descriptions Ny Rosborg

In the following, tables provide the soil description for each drilling.

Table A-1: Drillings B1, B2 and B3.

Depth [m]	Soil classification B1	Soil classification B2	Soil classification B3
0.0	-	-	-
-0.5	FILLINGS, sand, gravels, organic content	FILLINGS, sand, clay, organic content	FILLINGS, sand, clay, gravel, organic material
-1.0	FILLINGS, sand, gravels, organic content	FILLINGS, sand, clay, organic content	FILLINGS, sand, clay, gravel, organic material
-1.5	FILLINGS, sand, clay, gravels, organic content	FILLINGS, sand, clay, organic content	FILLINGS, sand, clay, gravel, organic material
-2.0	FILLINGS, sand, clay, gravels, organic content	FILLINGS, sand, clay, organic content	FILLINGS, sand, clay, gravel, organic material
-2.5	FILLINGS, sand, clay, gravels, organic content	FILLINGS, sand, clay, organic content	FILLINGS, sand, clay, gravel, organic material
-3.0	FILLINGS, sand, clay, gravels, organic content	FILLINGS, sand, clay, organic content	FILLINGS, sand, clay, gravel, organic material
-3.5	FILLINGS, sand, clay, gyttja, organic content	PEAT, minor clay lenses	FILLINGS, sand, lenses of peat
-4.0	GYTTJA, peat with plant remains	SAND, medium grain size, lenses of peat	FILLINGS, sand, lenses of peat
-4.5	SAND with a high content of gyttja	SAND, medium grain size	FILLINGS, sand, lenses of peat
-5.0	GYTTJA	SAND, medium grain size	SAND, fine to medium grained size, organic content
-5.5	GYTTJA	SAND, medium grain size	GYTTJA
-6.0	GYTTJA	GYTTJA	GYTTJA
-6.5	GYTTJA, sand lenses	GYTTJA	GYTTJA
-7.0	GYTTJA	GYTTJA	GYTTJA
-7.5	GYTTJA	GYTTJA	GYTTJA
-8.0	GYTTJA	GYTTJA	GYTTJA
-8.5	GYTTJA, sand lenses	GYTTJA	GYTTJA
-9.0	GYTTJA, sand lenses	GYTTJA	GYTTJA
-9.5	GYTTJA, sand lenses	GYTTJA	SAND, medium grained, sorted, gyttja lenses
-10.0	GYTTJA, sand lenses	GYTTJA	SAND, medium grained, sorted

Table A-2: Drillings B1, B2 and B3.

Depth [m]	**Soil classification B4**	**Soil classification B5**	**Soil classification B6**
0.0	-	FILLINGS, sand, clay, organic content	-
-0.5	FILLINGS, clay, silt, sand, gravel, organic content	FILLINGS, sand, clay, organic content	FILLINGS, sand, clay, bricks, organic content,
-1.0	FILLINGS, clay, silt, sand, gravel, organic content	FILLINGS, sand, clay, organic content	FILLINGS, sand, clay, bricks, organic content,
-1.5	FILLINGS, clay, silt, sand, gravel, organic content	FILLINGS, sand, clay, organic content	FILLINGS, sand, clay, bricks, organic content,
-2.0	FILLINGS, clay, silt, sand, gravel, organic content	FILLINGS, sand, clay, organic content	FILLINGS, sand, clay, bricks, organic content,
-2.5	FILLINGS, clay, silt, sand, gravel, organic content	FILLINGS, sand, clay, organic content	FILLINGS, sand, clay, bricks, organic content,
-3.0	FILLINGS, clay, silt, sand, gravel, organic content	FILLINGS, sand, clay, organic content	FILLINGS, sand, clay, bricks, organic content,
-3.5	CLAY, gyttja, sand, organic content	FILLINGS, sand, clay, organic content	FILLINGS, sand, clay, bricks, organic content,
-4.0	GYTTJA	FILLINGS, sand, clay, organic content	FILLINGS, sand, clay, bricks, organic content,
-4.5	GYTTJA	FILLINGS, clay, sand, organic content	FILLINGS, very sandy, clay, bricks, organic content,
-5.0	GYTTJA	FILLINGS, clay, sand, organic content	FILLINGS, very sandy, clay, bricks, organic content,
-5.5	PEAT	FILLINGS, clay, sand, organic content	FILLINGS, very sandy, clay, bricks, organic content,
-6.0	PEAT, gyttja	FILLINGS, clay, sand, organic content	FILLINGS, very sandy, clay, bricks, organic content,
-6.5	GYTTJA, sand lenses, few rocks	FILLINGS, clay, sand, organic content	FILLINGS, very sandy, clay, bricks, organic content,
-7.0	GYTTJA, sand lenses, few rocks	PEAT	GYTTJA, clay
-7.5	SAND, medium size, gravels, gyttja	SAND, medium size, sorted, organic content	PEAT
-8.0	SAND, medium size, gravels, gyttja, clay	SAND, medium size, sorted, organic content	PEAT
-8.5	SAND, medium size, sorted, gravels	SAND, fine size, sorted, silt	PEAT
-9.0	SAND, medium size, sorted, gravels	SAND, fine size, sorted, silt	PEAT
-9.5	SAND, medium size, sorted, gravels	SAND, fine size, sorted, silt	PEAT
-10.0	SAND, medium size, sorted, gravels	SAND, fine size, sorted, silt	PEAT

Table A-3: Drillings B7, B9 and B11.

Depth [m]	**Soil classification B7**	**Soil classification B9**	**Soil classification B11**
0.0	-	-	-
-0.5	FILLINGS, sand, clay, bricks, organic content	FILLINGS, clay, minor amounts of sand, organic content	FILLINGS, sand, organic content
-1.0	FILLINGS, sand, clay, bricks, organic content	FILLINGS, clay, minor amounts of sand, organic content	FILLINGS, sand, clay, organic content
-1.5	FILLINGS, clay, sand, bricks, organic content	FILLINGS, sand, organic content	SAND, fine to medium size, sorted
-2.0	FILLINGS, clay, sand, bricks, organic content	FILLINGS, sand, organic content	SAND, fine to medium size, sorted
-2.5	FILLINGS, clay, sand, silt, bricks, organic content	FILLINGS, sand, organic content	SAND, fine to medium size, sorted, lenses of gyttja
-3.0	FILLINGS, clay, sand, silt, bricks, organic content	FILLINGS, sand, organic content	GYTTJA
-3.5	FILLINGS, clay, sand, silt, bricks, organic content	FILLINGS, clay, sand, silt	GYTTJA
-4.0	FILLINGS, clay, sand, silt, bricks, organic content	FILLINGS, clay, sand, silt	GYTTJA
-4.5	FILLINGS, clay, sand, silt, bricks, organic content	FILLINGS, clay, sand, silt	GYTTJA
-5.0	FILLINGS, clay, sand, silt, bricks, organic content	FILLINGS, clay, sand, silt	GYTTJA
-5.5	FILLINGS, clay, sand, silt, bricks, organic content	FILLINGS, clay, sand, silt	SAND, fine to medium size, sorted, lenses of gyttja
-6.0	FILLINGS, clay, sand, silt, bricks, organic content	PEAT	SAND, medium size, sorted, lenses of gyttja
-6.5	SAND, medium size, sorted, clay and gyttja lenses	PEAT	SAND, fine to medium size, sorted
-7.0	SAND, medium size, sorted, clay and gyttja lenses	PEAT	SAND, fine to medium size, sorted
-7.5	GYTTJA	SAND, medium size, sorted, organic content	SAND, fine to medium size, sorted
-8.0	GYTTJA	SAND, medium size, sorted, organic content	SAND, medium size, sorted
-8.5	GYTTJA	SAND, medium size, sorted, organic content	SAND, medium size, sorted
-9.0	GYTTJA	SAND, medium size, sorted, organic content	SAND, medium size, sorted
-9.5	GYTTJA	SAND, medium size, sorted, organic content	SAND, medium size, sorted
-10.0	GYTTJA	SAND, medium size, sorted, organic content	SAND, medium size, sorted

Table A-4: Drillings B12, B14 and B15.

Depth [m]	**Soil classification B12**	**Soil classification B14**	**Soil classification B15**
0.0	-	-	-
-0.5	FILLINGS, sand, gravel, bricks	FILLINGS, clay, sand, bricks, organic content	FILLINGS, clay, sand, bricks, organic content
-1.0	FILLINGS, sand, gravel, bricks	FILLINGS, clay, sand, bricks, organic content	FILLINGS, clay, sand, bricks, organic content
-1.5	FILLINGS, sand, gravel, bricks	FILLINGS, clay, sand, bricks, organic content	FILLINGS, clay, sand, bricks, organic content
-2.0	FILLINGS, clay, silt, sand, gravel, organic content	FILLINGS, clay, sand, bricks, organic content	FILLINGS, clay, sand, bricks, organic content
-2.5	FILLINGS, clay, silt, sand, gravel, organic content	FILLINGS, clay, sand, bricks, organic content	FILLINGS, clay, sand, bricks, organic content
-3.0	FILLINGS, clay, silt, sand, gravel, organic content	FILLINGS, clay, sand, bricks, organic content	FILLINGS, clay, sand, bricks, organic content
-3.5	FILLINGS, clay, silt, sand, gravel, organic content	FILLINGS, clay, sand, bricks, organic content	PEAT
-4.0	FILLINGS, clay, silt, sand, gravel, organic content	PEAT	PEAT
-4.5	FILLINGS, clay, silt, sand, gravel, organic content	GYTTJA	PEAT
-5.0	FILLINGS, clay, silt, sand, gravel, organic content	GYTTJA	GYTTJA
-5.5	FILLINGS, clay, silt, sand, gravel, organic content	GYTTJA	GYTTJA
-6.0	FILLINGS, clay, silt, sand, gravel, organic content	GYTTJA	GYTTJA
-6.5	GYTTJA	GYTTJA	SAND, medium size, sorted, lenses of gyttja
-7.0	GYTTJA	GYTTJA	SAND, medium size, sorted, lenses of gyttja
-7.5	GYTTJA	GYTTJA	SAND, medium size, sorted
-8.0	SAND, medium size, sorted, lenses of gyttja	GYTTJA	SAND, medium size, sorted
-8.5	SAND, medium to large size, gravels, poorly sorted	SAND, medium size, sorted	
-9.0		SAND, medium size, sorted	
-9.5		SAND, medium size, sorted	
-10.0		SAND, medium size, sorted	

Appendix B. Soil description Pavilion

In the following, tables provide the soil description for each drilling in the pavilion area.

Table B-1: Soil description by Pavilion area, Drillings 1 and 2.

Depth	Drilling 1	Drilling 2
[m]		
0.0	-	-
-0.2	FILLINGS, bricks	FILLINGS, sand, stones, bricks
-0.5	FILLINGS, sand, bricks, stones	FILLINGS, sand, stones, bricks
-1.0	FILLINGS, sand, bricks, stones	FILLINGS, sand, stones, bricks
-1.5	CLAY, greyish	CLAY, sandy, greyish
-2.0	SAND, small clay stripes, grey	SAND, stones, grey – brownish (water)
-2.5	SAND, stones, brown (water)	SAND, stones, brown
-3.0	SAND, stones, brown	SAND, stones, brown
-3.5	SAND, stones, brown	SAND, stones, brown
-4.0	SAND, stones, brown	SAND, stones, brown
-4.5	SAND, peat, lenses of gyttja, greyish	SAND, root and wooden residues, greyish
-5.0	GYTTJA, wooden small sand strips	SAND, root and wooden residues, peat, gyttja strips, greyish
-5.2	SAND, gyttja lenses, grey	-
-5.5	GYTTJA, shells, wood residues	GYTTJA, shells, peat residues
-6.0	GYTTJA, shells, wood residues	GYTTJA, shells, peat residues
-6.5	GYTTJA, shells, wood residues	GYTTJA, shells, peat residues
-7.0	GYTTJA, shells, wood residues	GYTTJA, shells, peat residues
-7.5	GYTTJA, shells, wood residues, peat	GYTTJA, shells, peat residues
-8.0	GYTTJA, shells, wood residues, peat, sand strips	PEAT, gyttja, sand
-8.5	GYTTJA, wood residues, shells	GRAVEL, stones, sand, grey-brown
-9.0	SAND, greyish - brown	GRAVEL, stones, sand, grey-brown
-9.5	SAND, greyish - brown	GRAVEL, more stones, sand, grey-brown
-10.0	SAND, greyish - brown	GRAVEL, more stones, sand, grey-brown
-10.5	SAND, gravely stones, grey	GRAVEL, more stones, sand, grey
-11.0	SAND, gravely stones, grey	GRAVEL, more stones, sand, grey
-11.5	SAND, stones slightly gravely, grey	GRAVEL, more stones, sand, grey
-12.0	SAND, stones, grey	GRAVEL, more stones, sand, grey
-12.5	SAND, gravely, grey	GRAVEL, more stones, sand, grey
-13.0	SAND, gravely, grey	GRAVEL, more stones, sand, clay strips, grey
-13.5	SAND, gravely, lumps of clay, silted, grey	GRAVEL, more stones, sand, clay strips, grey
-14.0	SAND, lumps of clay, grey	SAND, clay strips, grey
-14.5	SAND, lumps of clay, grey	SAND, clay strips, grey
-15.0	SAND, more clayey, grey	SAND, clay strips, grey
-15.5	SAND, grey	SAND, clay strips, grey
-16.0	SAND, grey	SAND, clay strips, grey
-16.5	SAND, grey	SAND, clay strips, grey
-17.0	SAND, grey	SAND, clay strips, grey
-17.5	SAND, grey	SAND, clay strips, grey
-18.0	SAND, grey	SAND, clay strips, grey

Table B-2: Soil description by Energy Pile 3, drilling B5.

Depth	B5
[m]	
0.0	FILLINGS, sand, clay, organic content
-0.5	FILLINGS, sand, clay, organic content
-1.0	FILLINGS, sand, clay, organic content
-1.5	FILLINGS, sand, clay, organic content
-2.0	FILLINGS, sand, clay, organic content
-2.5	FILLINGS, sand, clay, organic content
-3.0	FILLINGS, sand, clay, organic content
-3.5	FILLINGS, sand, clay, organic content
-4.0	FILLINGS, sand, clay, organic content
-4.5	FILLINGS, clay, sand, organic content
-5.0	FILLINGS, clay, sand, organic content
-5.5	FILLINGS, clay, sand, organic content
-6.0	FILLINGS, clay, sand, organic content
-6.5	FILLINGS, clay, sand, organic content
-7.0	PEAT
-7.5	SAND, medium size, sorted, organic content
-8.0	SAND, medium size, sorted, organic content
-8.5	SAND, fine size, sorted, silt
-9.0	SAND, fine size, sorted, silt
-9.5	SAND, fine size, sorted, silt
-10.0	SAND, fine size, sorted, silt

Appendix C. Full-scale ground source heat pump setup: as-built.

This is a working document that should be updated as information is collected. It describes the setup existing at the pavilion area in Ny Rosborg, also mentioned in Chapter 7 - WP3: Installation and testing of energy piles, where 2 energy piles have been connected to a heat pump.

Situation plan

Vejle Kommune’s Pavilion at Vestre Engvej 66, 7100 Vejle.

Figure C-1: Pavilion area.

Installation diagram and measured parameters

One energy pile serves as a heat source (EP2) and the other as a heat sink (EP1).

Parameters to measure and installed devices, ready to be used. Only the loggers need to be configured.

- Energy extracted from ground: Energy meter Kamstrup 6M2.
- Energy injected to ground (i.e., produced by the heat pump): Energy meter Kamstrup 6M2.
- Electricity consumption of the heat pump and circulation pump together: Electricity meter Kamstrup OMNIPOWER ® + Module to electricity meter.
- Soil temperatures (from drilling D2 nearby EP1). The cables are already in place. Use Testo 174H Datalogger.
- Optic eye with USB stick to download data to computer.
- The heat transfer fluid is ethanol (30-40%), and so the energy meters have been calibrated. Please contact Vølund to confirm.
- The heat pump is a NIBE F1255 (https://www.nibe.by/nibedocuments/24313/331296-5.pdf) and it can be remotely operated. Please, contact Maria Alberdi-Pagola or Vølund Varmeteknik.

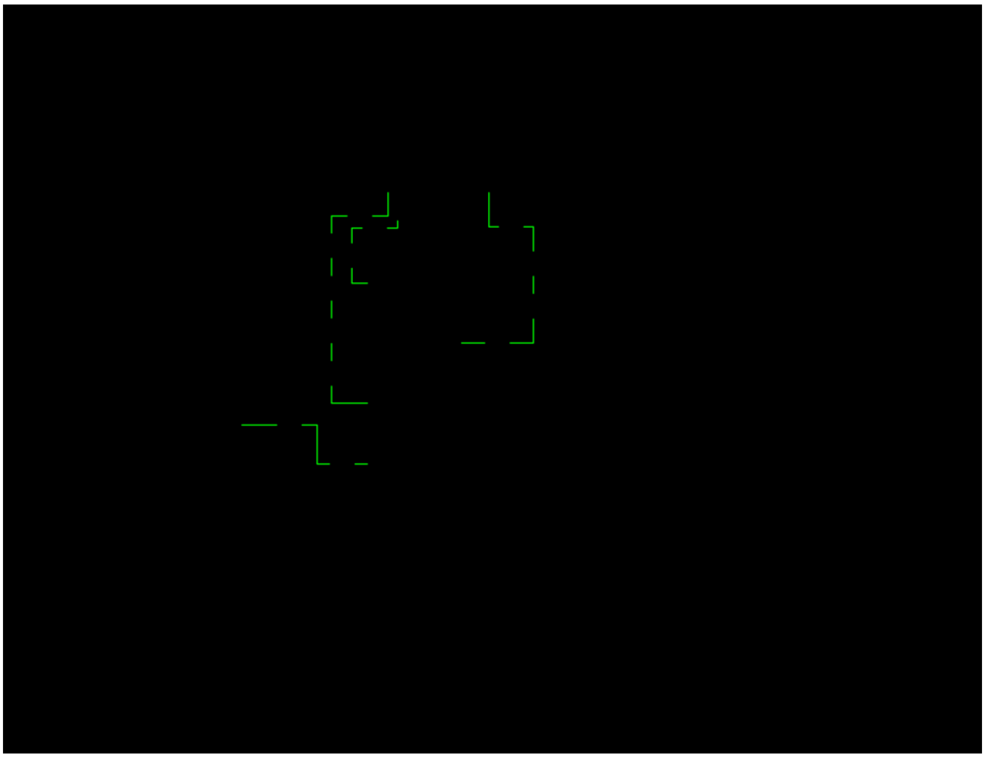
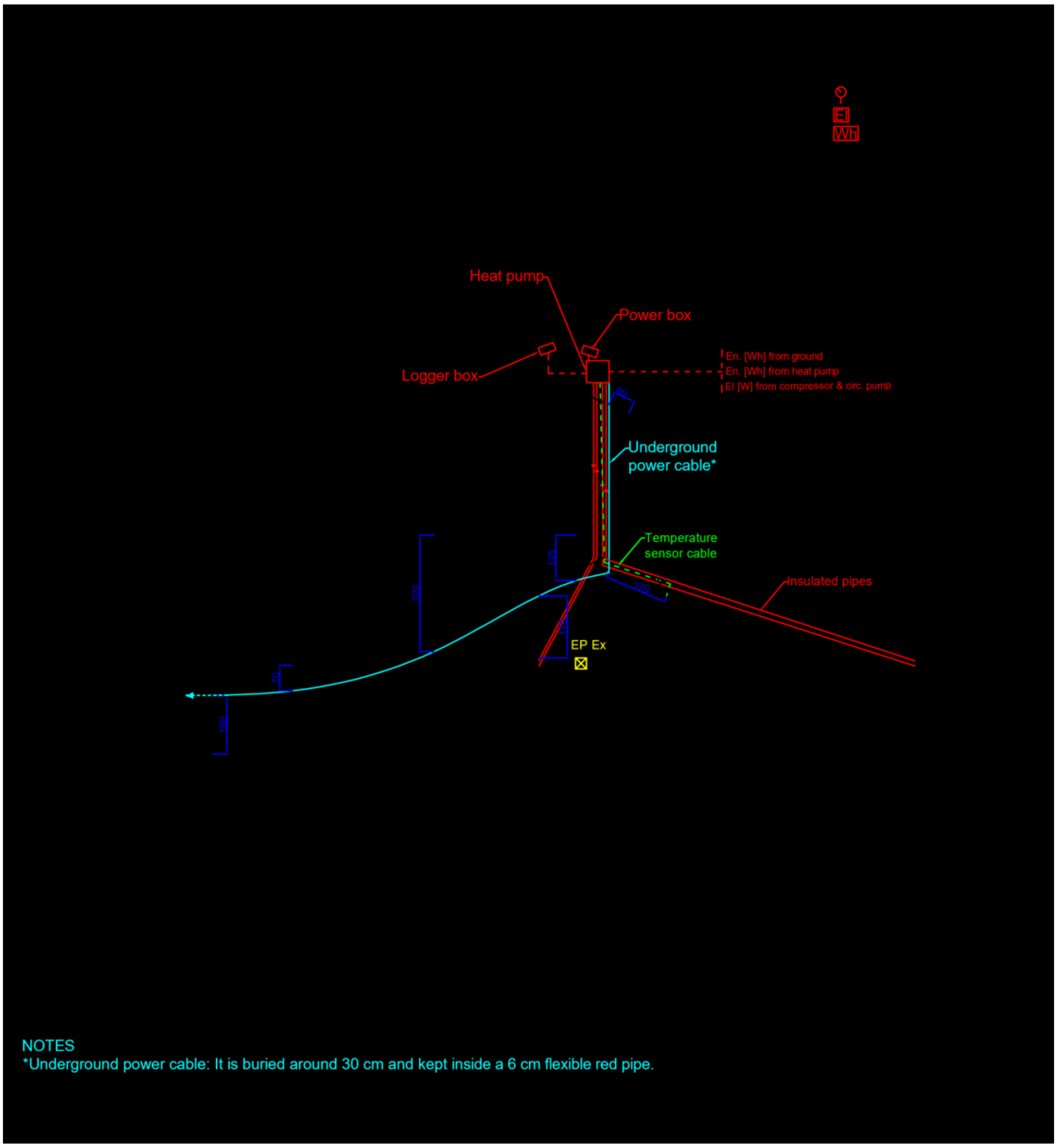


Figure C-2: Installation diagram. The electricity meter needs to check the consumption of both circulation pumps and the heat pump.

Setup drawings



NOTES
*Underground power cable: It is buried around 30 cm and kept inside a 6 cm flexible red pipe.

Figure C-3: Top view setup proposal. The temperature loggers need to be in a box nearby the heat pump.

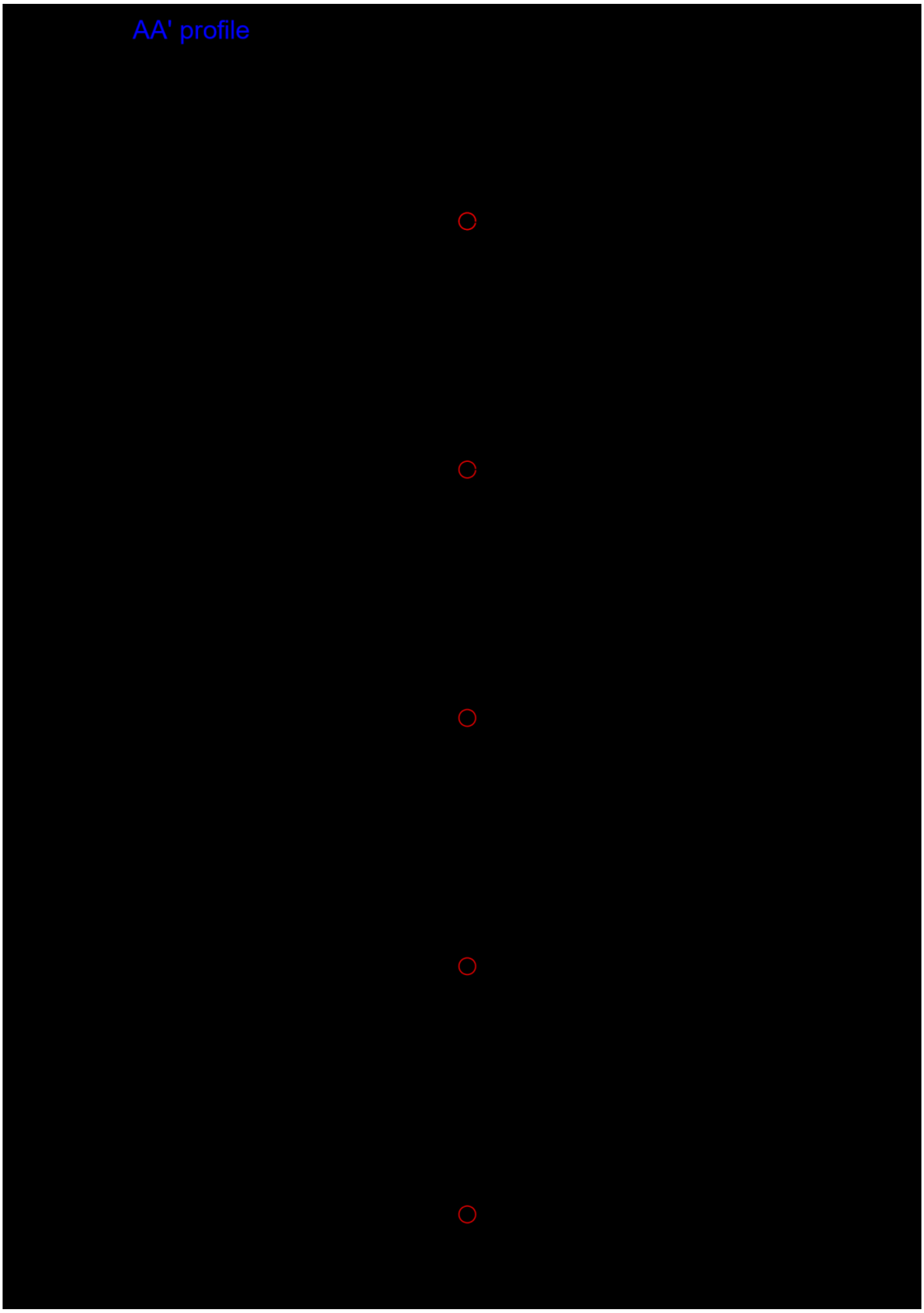


Figure C-4: AA’ vertical profile.

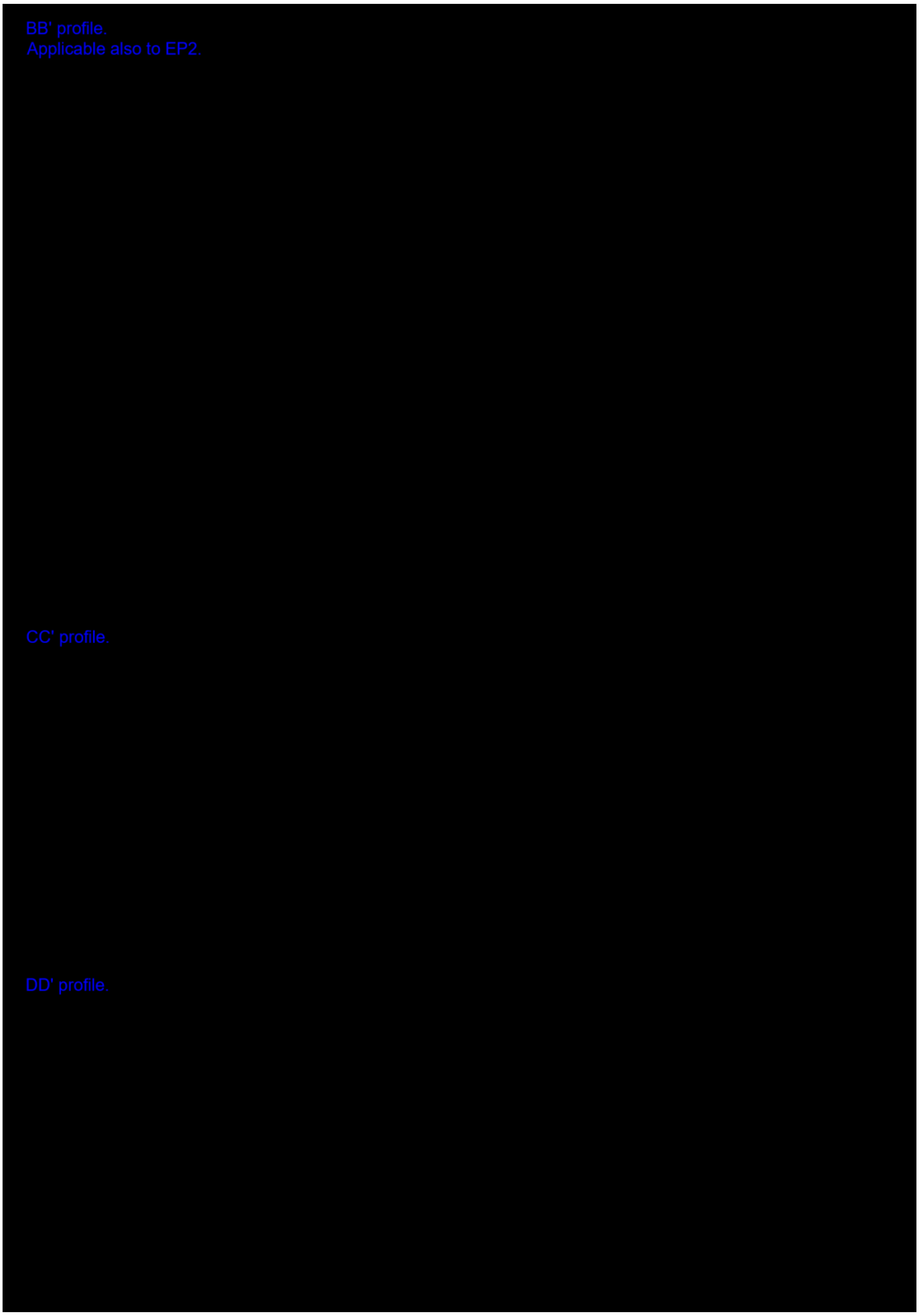


Figure C-5: BB' and CC' details.

Appendix D. Business model and marketing material

Tool for calculating payback period (Excel file)

beregningsmodel.xlsx

Marketing plan (PowerPoint)

Markedsføringsplan Energipæle.pptx

Energy pile teaser (pdf)

Teaser - Energy piles.pdf