REPORT

BEAR (Sustainable energy from soils)

LIFE CYCLE ANALYSIS (LCA) AND COSTS FOR ENERGY STORAGE IN PILES

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Summary

This report is a part of the research project *Sustainable energy from soils* (**BEAR**). The BEAR project is a collaboration project between the industry, municipality and research institutions in mid Norway, funded by the regional research fund of Trøndelag (grant number 32116). The BEAR project involves designing and testing an energy concept that utilize the soil as a stable source of thermal energy for buildings, meanwhile also working as an integrated part of the building foundation, so called "*energy piles*". The hypothesis is that integrating heat exchangers within the building foundations will enable and reduce the investment cost for the establishment of ground source heating systems in buildings that are situated on soils. The BEAR consortium consists of Malvik Municipality (project owner), NGI (project lead), Winns AS, Fundamentering AS, Noranergy AS and NTNU. BEAR comprises of four working packages, where this report summarizes the results and findings of work package 3 (WP3 - Evaluation).

A set of fictional case-studies are here presented where the goal of the studies is to enable us to evaluate how the two differently sized energy piles of the BEAR concept might perform in Norway, with Norwegian soil conditions, foundation traditions and climate conditions. The energy pile cases are then compared, via a simplified Life Cycle Analysis (LCA), to two conventional energy systems that might otherwise have been employed in said building case, namely a district heating system or a water-air heat pump system. It is shown that there are relatively small differences in over-all energy performances between the two sizes of energy piles tested in the BEAR project. Given the specific geological case, with the same pile depth and building thermal loads and mechanical loads, the dimensioning of the building foundation, either with RD-140/10 piles or with RD-320/10 piles, will result in very similar energy systems in view of environmental impact, investment cost, energy coverage and efficiency. However, the studies show that energy piles must be operated as a thermal energy storage if they are to function in Norway at all. This fact that should be given due consideration in the design and utilization of energy pile foundations in new projects in the future.

It is therefore important to emphasise that the case-study presented here might favour the piles to some degree, because the building thermal energy demand turned out to be relatively equal to the size and capacity of the thermal storage in the pile foundation (Figure 12). If the building demand would have been larger, or the storage volume smaller, the energy foundation would have been too small to cover the whole heating demand. This indicates that tall and heavy buildings, with a relatively smaller building footprint and especially with short pile lengths, results in a foundation design that do not favour the energy pile concept compared to other conventional solutions.

The LCA indicate that the energy pile concept can compete with a conventional air-water heat pump system common for Norway. However, as one might perceive from the LCA data, the major reason of the improved environmental impact originates from a lower seasonal consumption of electrical energy by the pile solution in this study. This entails that the energy piles concept relies on higher energy efficiency than competing solutions to triumph in the rivalry in the energy market.

Contents

Review and reference page

1 Introduction

The research project *Sustainable energy from soils* (**BEAR**) is a collaboration project between the industry, municipality and research institutions in mid Norway. The BEAR project involves designing and testing an energy concept that utilize the soil as a stable source of thermal energy for buildings, meanwhile also working as an integrated part of the building foundation, so called "*energy piles*". The hypothesis is that integrating heat exchangers within the building foundations will enable and reduce the investment cost for the establishment of ground source heating systems in buildings that are situated on soils. The BEAR project aims to verify this hypothesis via pilot testing. The BEAR consortium consists of Malvik Municipality, NGI, Winns AS, Fundamentering AS, Noranergy AS and NTNU. The project is owned by the municipality of Malvik, with NGI as acting project leader for the project group. The project is in part financed by the regional research fund of Trøndelag (RFF Trøndelag project number: 321116).

The BEAR-project consists of four work packages, this report summarizes the work and results of work package 3 (WP3 in Table 1).

Table 1: Work package description of the BEAR project

Work packages (WP) in BEAR			
WP1: pre- and site-investigations Investigate and characterize the soil of a given site to allow for design of energy piles, adapted to the local soil, climate and user needs in the pilot project.	**WP2: Pilot project** Testing a new and innovative energy solution in soils in a local construction project in Malvik by means of energy piles.	**WP3: Evaluation** Conduct a cost/benefit analysis and evaluate the energy potential of the pilot project piles.	**WP4: Dissemination** Dissemination and communication of the results to the industry in Trøndelag, Norway and abroad

2 Background

The application of energy piles is a new concept in Norway at present-day. There is ongoing research activity on the topic within the scientific community, particularly by NGI, NTNU and SINTEF, but there are currently no full-scale projects in Norway that offer a direct method of comparison with the BEAR-project. The potential for energy savings and cost analysis is therefore limited to theoretical scenarios that aim to upscale smaller tests to large systems, aiming to predict the performance of the energy system as a whole. Similar approaches are indeed common in the design of heating and cooling applications in general, but it is well documented that such theoretical analysis can be quite misleading compared to the actual performance of energy systems in real world applications (Spitler & Gehlin; 2022). The work presented in the following is thus intended as a preliminary analysis for the energy pile concept in Norway.

The BEAR-project has conducted field tests on two different sizes of drilled steel energy piles in the pilot project at Saksvik in Malvik municipality. The data from the pilot project are presented in detail in the project report (ID 20210083-01-R). This data is here used as input data for the life cycle analysis (LCA) and cost analysis for a relevant case-study. The case-study aim to demonstrate how these energy piles can function in a full-scale application in Norway, with relevant Norwegian climate, energy demand and under suitable soil conditions. However, in practice the use of energy piles will obviously be an application which is limited to the areas in Norway where pile foundations are needed. The areas that might be suitable for energy piles might in fact not be suitable for other geoenergy solutions, such as borehole energy heat pump systems or aquifer heat pump systems. The analysis is thus selected based on a relevant geological setting for piles.

This case-study involves analysing the energy potential for the BEAR piles in a fictional building situated on thick soil deposits, meaning that these piles are the main foundation method for the whole building layout. The system is given operational limitations, e.g. temperature limitations and strain limitations in order to ensure that the foundation requirements are maintained. The LCA and the potential of these piles is then compared to other relevant traditional energy sources that are common for heating and cooling applications in general.

In Norway it is common to utilize electricity for heating, particularly in small residential buildings (via electric boilers, resistance panel heaters, etc.), but current trends show that a relatively larger share of the energy mix is increasingly being provided by district heating (via waste incineration or bio-combustion) and heat pump systems (various sources; air, sea-water, waste-water, geo-energy systems, etc.). The BEAR-pile system must thus compete with these conventional energy systems in order to win market shares. The LCA of the case-study aim to demonstrate how the energy pile concept differ from the more conventional energy systems used in buildings today.

3 Case study – An Office building in OSLO-climate

The pilot project in WP 2, presented in detail in the BEAR project report 20210083-01-R, has provided relevant field scale data for energy pile performances over short time intervals. This data is here used as the base line input data for the life cycle analysis (LCA) and cost analysis for a relevant case-study. The energy saving potential of the two different pile sizes are evaluated theoretically using a case-study with a simplified model approach. The case-study is developed to fit the energy demand of a fictional building, with OSLO-climate. The building is situated on a thick deposit of soft clay and silty soils. The model development involves categorising the size and type of the building, which in turn determine how many piles are needed in the foundation and the extent of heating and cooling needed by the building annually.

The building type was selected to be an office building for a medium sized company in Norway. The specifications of the building are provided in Table 2 and Table 3. Office buildings in OSLO-climate will typically have both a demand for heating and a demand for cooling, which is beneficial for the energy pile concept. The relevant input data for the office buildings energy requirement were based on data provided by the Enova report "*Hensiktsmessige varme og kjøleløsninger i bygninger*" (ENOVA, 2013).

The size of the building determines the weight of the building, and consequently the load requirements for the foundation. The number of piles must then be designed according to the load requirements, local soil conditions and to the requirements given in the EuroCodes. The selected piles meet the piling class II (PTL2) according to the definition to the consequence class I-III and geotechnical classes in Eurocode 1990 National Annex and is described in chapter 3.1. The energy analysis is presented for two different scenarios on two different pile dimensions and are described in chapter 3.2 – 3.4.

Table 2: Building specifications for the case-study evaluation.

Building type	Office building
Ground floor area	1 500 m^2
Number of floors	3
Total floor area	4 500 m^2
Building gross weight	90 000 kN (20 kN/m^2 of floor space)

Table 3: Technical specifications for the building (ENOVA, 2013)

Climate zone	Oslo
Building standard	TEK10
Indoor air temperature	21°C
Peak power demand, space heating at DUT	57 W/m^2
Energy demand space heating	60 kWh/m^2 per year (270 MWh/year)
Tap water demand	1.14 W/m^2 (5,1 MWh/year)
Peak power demand cooling	30 W/m^2
Energy demand cooling	9 kWh/m^2 per year (40,5 MWh/year)

3.1 Energy pile design and operational limitations

The soil beneath the office building consists of a 25-meter-thick deposit of soft marine clay sediments above bedrock, similar to the soil conditions at the BEAR pilot pile site in Saksvik. For such conditions it is most often required that the foundation piles transmit the building weight to the bedrock, which implies that the piles must be so called "end bearing" piles. This is typically done via drilled steel-tube piles (RD-piles) in Norway (Figure 1). The full structural load of 90 000 kN is to be carried by the steel wall of the RD-piles. The RD-piles in this case study are similar to the BEAR-piles installed in Saksvik, although with additional load bearing capacity and higher steel quality. In terms of the Eurocode 1990 piling class II this results in RD-piles with increased wall thickness compared to the BEAR-piles. The number of the piles required for supporting the building is determined by the pile diameter and wall thickness of the piles and the steel quality.

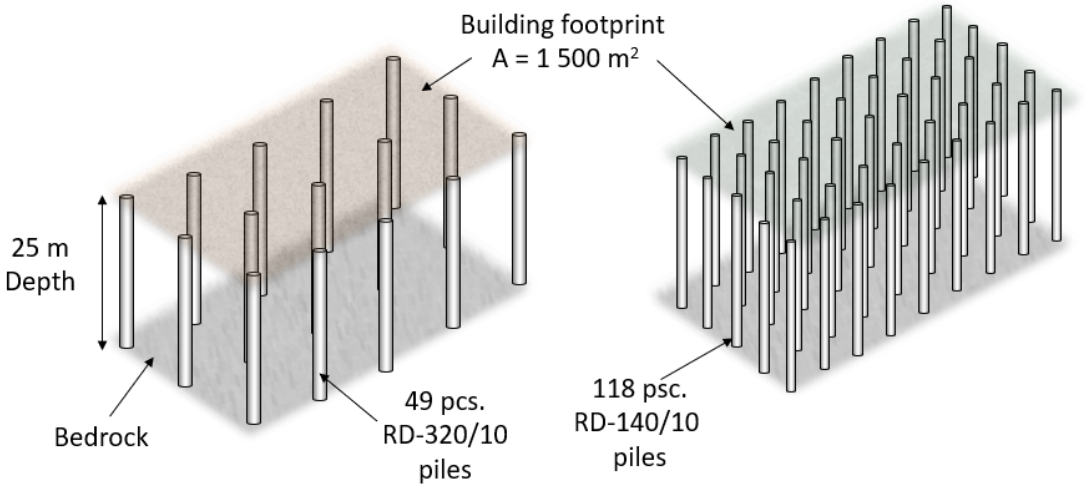

Figure 1: Conceptual sketch for the two foundation solutions assessed in the case study. The number of piles is determined by distributing the total building load of 90 000 kN evenly on all piles in accordance with the axial load capacity of each RD-pile.

Table 4 shows the pile specifications corresponding to each of the selected pile sizes used in the BEAR-project. For simplicity it is here assumed that the RD-piles are pure end-bearing piles with no additional frictional load bearing capacity along the shaft. All the building load is thus carried by the endpoint of the piles in contact with the bedrock at >25 meters depth. The pile sizes of choice are the same as regular RD-pile types available on the global market. One relevant example is the RD-piles provided by SSAB, with the RR/RD140/10 class for the small pile size and RR/RD320/10 class for the large piles. Steel quality is then equal to the S460MH quality (SSAB, 2022). Table 4 shows that the small pile size requires 118 RR/RD140/10 piles to carry the 90 000 kN building load, while the large pile size requires 49 RR/RD320/10 piles. Note however that the total amount of steel utilized in the pile foundation is equal for both pile diameters.

Table 4: Energy pile specifications for the two foundation solutions. The number of piles are determined by distributing the total building load of 90 000 kN evenly on all piles in accordance with the load capacity of each RR/RD140/10 or RR/RD320/10 pile (SSAB, 2022).

	Outer diameter OD [m]	Inner diameter ID [m]	Wall thickness [mm]	Depth [m]	Axial load capacity per pile [kN]	# of piles	Total steel volume [m^3]	Total water volume [m^3]
Large RD-piles	0.323	0.303	10.0	25	1852	49	12.05	86.2
Small RD-piles	0.140	0.120	10.0	25	765	118	12.05	31.0

The energy system must be given operational limitations on temperature variation in the piles to ensure that no damage occur to the building foundation. The limitations are governed by the thermo-mechanical reactions in the soil and in the load bearing construction segments in the building foundation. Both the soil and the pile will react to temperature alterations, by volume expansion if the temperature increases, or by volume contraction if the temperature decreases. These changes in volume induce stress and strain in the foundation (Figure 2).

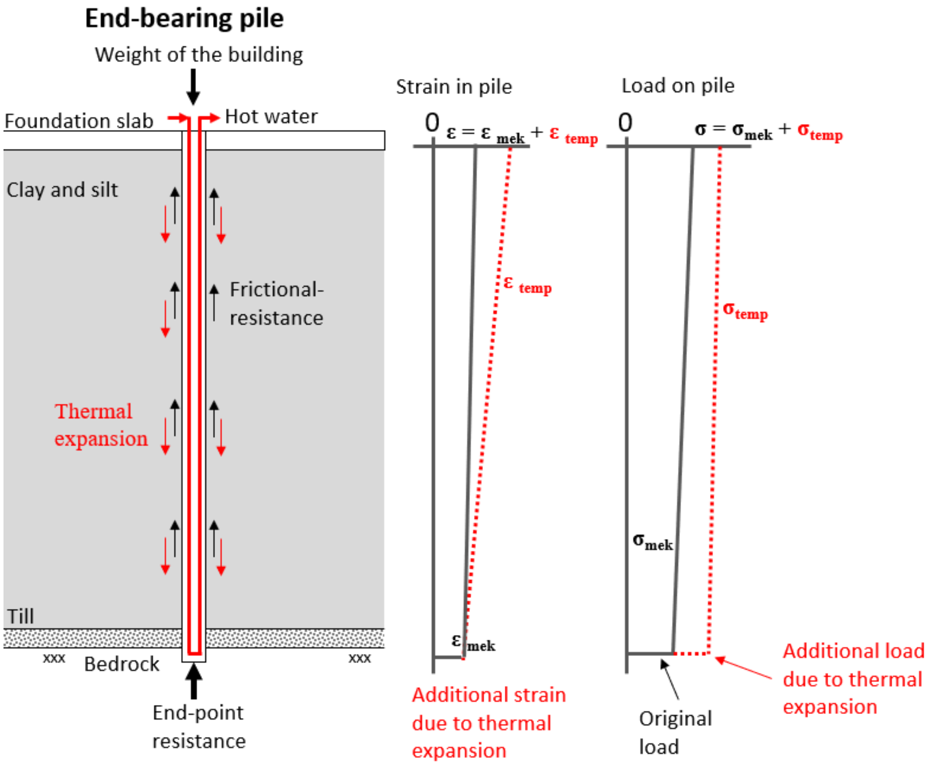

Figure 2: Schematic sketch of the thermal response in an end-bearing pile due to thermal activation.

The limitations in allowable strain induced in each pile or pile group is the typical design criterion for the piles. The thermally induced strain is proportional to the change in temperature with respect to the initial temperature in the ground during installations. It is conservative and reasonable to assume that the bedrock does not allow for downwards movement of the piles, so all the expansion must occur in the upwards vertical direction. For an end-bearing pile the friction along the shaft is negligible and does not reduce the strain. It is therefore possible to assume that the whole expansion and contraction of the pile will result in a vertical shift of the pile head. The most severe case for such a shift is the unconfined expansion criterion which, for simplicity, corresponds to the linear thermal expansion coefficient of the steel walls of the RD-piles. The linear thermal expansion coefficient of the steel ($1.2\cdot10^{-2}$ [$\mathrm{mm\cdot m^{-1}\cdot{}^{\circ}C^{-1}}$]) is thus assumed to represent the maximum potential of displacement of the piles under these conditions.

With 25-meter-deep piles this imply that each pile will expand or contract by 0.36 mm per °Celsius (C) change in pile temperature. Due to the RD-pile design in the BEAR-project, with a water filled centre, the pile walls will quite rapidly adopt to the water temperature entering the pile. The temperature limitations that apply to each pile along the pile wall soil interface therefore essentially also apply to the entry water temperature from the energy system. The undisturbed initial temperature of the ground at the BEAR-pilot site in Saksvik is ca. 7.2 °C and is selected as the baseline for the model analysis. The limitations for the model are selected to be:

- The lower limit for the temperature is set 2 °C due to freezing risks in the soil
- Upper limit for the temperature is set 25 °C due to strain and stress in the foundation (due to the steel expansion)

With these temperature limitations, the RD-piles will be able to expand and contract by 6.4 mm and -1.8 mm, in the upwards vertical direction in response to heating and cooling, respectively.

Conventional RD-piles are hollow during installation but are typically filled with concrete afterwards. The RD-piles in this case-study are filled with water (Figure 3). The purpose of the water within the pile is to function as the heat carrier fluid for the energy system of the building. The total amount of water in the system depends on the pile dimensions. The two different pile sizes in this case study have a relatively large difference in total water volume, where the 49 large piles contain a total of 86.2 $\mathrm{m^3}$ of water and the 118 small piles contain a total of 31.0 $\mathrm{m^3}$ of water. This render the large pile design to have more heat carrier fluid to work with in the operation of the energy system.

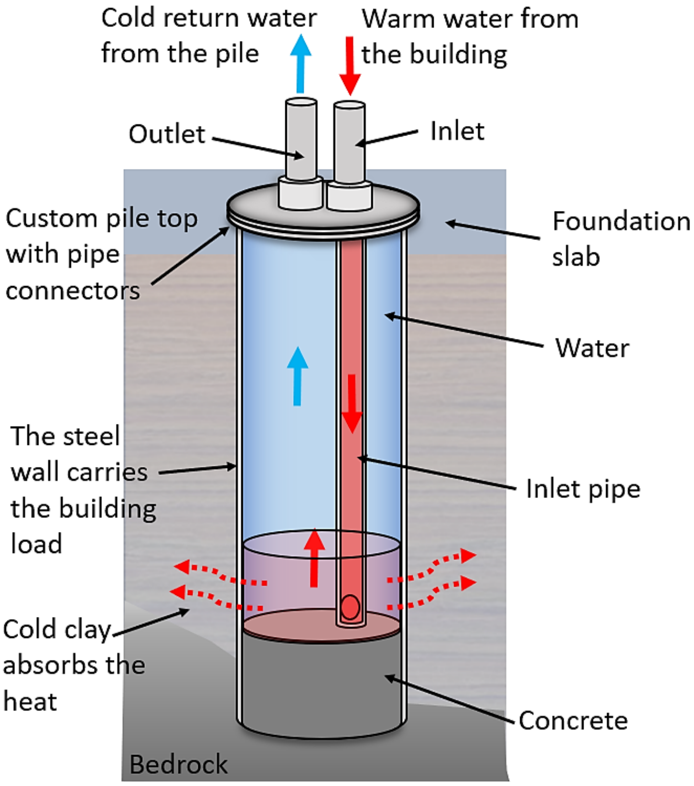

Figure 3: Conceptual sketch of the BEAR-project end-bearing RD-pile.

1.1 Energy demand and operation of the system

In the following section two alternative energy storage applications, in combination with a heat pump, are described to demonstrate how the energy piles can be used in practice. Generally, the heating and cooling load for an office building will be unbalanced. In Norway the heating demand is typically larger than the cooling demand. For such cases a thermal storage is beneficial. During periods of surplus (heat or cold) energy will be stored in the thermal storage, which in this case is underground in the water filled RD-piles. Storage of heat will typically take place e.g., during daytime in the summer season when there is a need for cooling of the building mass and air conditioning of the office workspace. When there is a need for heating, the energy will be retrieved from the storage and supplied to the heat pump system. This will e.g. take place during the night or during all hours during the winter season.

In the first alternative, Case 1, only the total water volume of the piles is considered as the thermal storage. This alternative will demonstrate how the water volume can function as a thermal storage and will show how this can impact the power demand of the energy system during short time periods (daily fluctuations). Only the water volume stored piles and its effect on peak cooling load is considered, not the heat transfer of the piles with the surrounding clay.

In the second alternative, Case 2, the energy piles and the surrounding clay represent a seasonal thermal energy storage that cover the whole annual heating demand (270 000 kWh/year) of the office building. The thermal storage will cover annual fluctuations in thermal demand, charging the storage with heat during the summer and extracting this heat during the winter. The heat charging during the summer will in part come from the cooling energy needed during the summer but must also be accompanied with supplementary external thermal energy to provide the full heating load coverage during the winter. In this case the supplementary thermal energy is acquired from the outside air with an additional air source heat exchanger.

These two alternatives represent different uses of the energy piles in the energy system. Both alternatives will be evaluated with the two different foundation scenarios mentioned above. In the first scenario, the energy storage consists of the small diameter piles of the 140-size class, while in the second scenarios, the larger diameter piles of the 320-size class piles are used. The difference in number of piles in the foundation and in total water volume in the storage signify the major differences between the two scenarios (Table 4). The BEAR energy pile TRT-tests are used as the baseline for the thermal performance of each energy pile in the case study evaluation. In these TRT-tests the data does not represent a steady-state-condition, especially for the large pile test. However, the trend of the data show that the quasi-steady thermal response of both the large pile and the small pile have a similar thermal conductivity towards the clay. The quasi-steady data is represented by the thermal response after the initial exchange of water volume in the piles, and these data show that the piles have approximately daily performance of 13.6 Wm^{-1}°C^{-1} and 5.7 Wm^{-1}°C^{-1} for the large and the small pile, respectively (Figure 4).

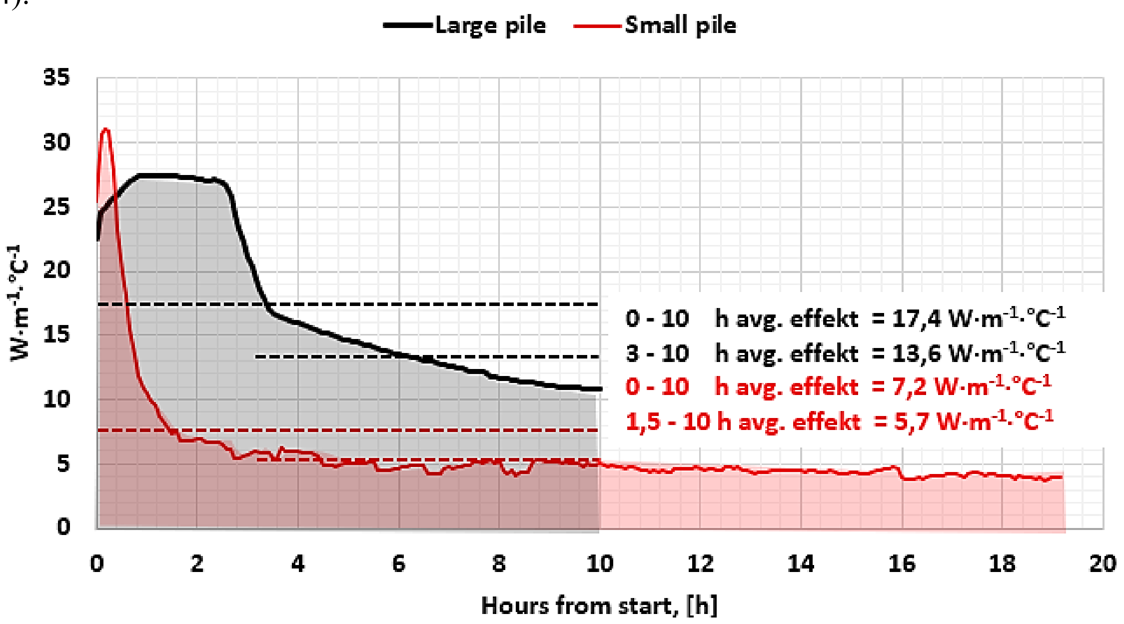

Figure 4: Normalized energy performance data for the BEAR energy piles. The thermal effectthat is delivered to the piles during the TRT-test is divided equally over the entire length (m) of the pile and divided by the temperature difference of the injected water versus the initial temperature of the pile (BEAR-project report ID 20210083-01-R).

Upscaling the performance from a single pile to the entire foundation in this case study entails a set of simplifications. First and foremost, the piles are assumed to not interfere with each other's performance in the analysis. The performance described above is thus implemented for each pile, even though this will not necessarily be the case in an actual full-scale application. This simplification might therefore overestimate the performance compared to actual cases. In the following we provide a simplified analysis for the models.

1.2 Case 1 – the "cold" thermal energy storage in the piles

A typical feature for modern office buildings in Norway, as well as many other building types, is that the cooling demand during the summer is characterized by very high peak power loads over a short period of time. One practical consequence of this phenomenon is that the building's cooling system is designed with large chiller/heat pump units that operate over very short periods of time. This leads to cooling systems that do not utilize the cooling machines very well, resulting in relatively large investment costs and operational cost per hour of operation. The same phenomenon can also occur in heating systems. However, a major difference is that in the heating system it is normal to use a peak load source, like an electric boiler, to cover these short periods of peak load, which consequently allow the energy system to employ a smaller heat pump, at lower costs.

The purpose of the Case 1 study is to look at how an energy system with energy piles will affect the peak load of the heat pump, particularly in the cooling mode. The large volume of water stored in the energy piles will enable the cooling system to distribute the thermal load, which should allow the heat pump/chiller to operate more evenly. The following constraints and assumptions are made for the chosen system configuration shown in Figure 5:

- Assumed adiabatic system (adiabatic piles with no heat loss to the environment)
- Assumed closed loop with water
- Operating temperatures cooling loop: 12°C supply – 17°C return
- Loading with cold water: 6°C
- Good stratification in piles, with a stratification factor of 90%.

The main feature of the system configuration is that the cooling loop of the building is directly coupled to the building’s cooling system. Excess heat is either rejected to the outdoor air or delivered to the building if there is a need for it. The heat pump control strategy in this “cooling mode” (dominating cooling demand) is to deliver the cooling needed, and if the storage is not “fully depleted”, i.e. the water in the piles are at 6°C, the control system diverts the flow and will start to load the thermal storage. If the heat pump is not able to deliver enough cooling power, it will be taken from the storage directly.

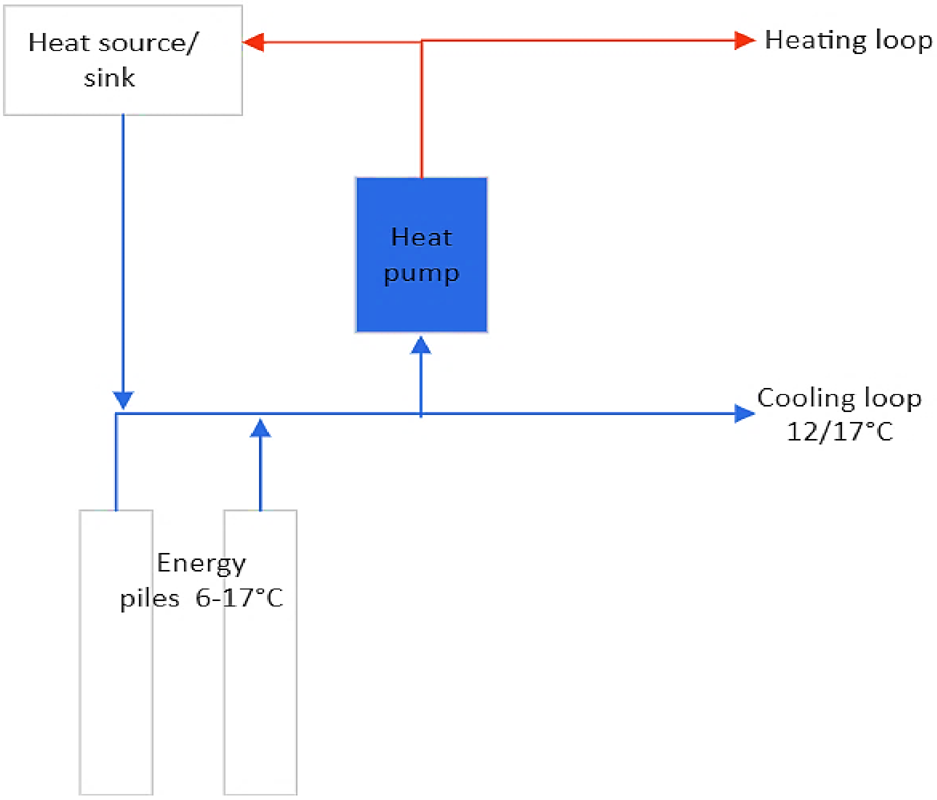

Figure 5: Energy piles and heat pump system configuration in Case 1.

In the model analysis the characteristics of the building shown in Table 3 was combined with OSLO-climate data on an hourly basis from 01.05.21 to 01.09.2021. This serves as a model of the realistic heating and cooling demand of the building during the period where there is a cooling demand in our fictional office building. The specific thermal demand over this period is shown in Figure 6, distributed for heating demand and cooling demand, which dominates at different time periods. In the start and end of the period, there are days where you have cooling demand during the day, and heating demand during the night. Peak cooling demand during the summer is 30 W/m^2, corresponding to 135 kW for the building as a whole. None of the curves reaches zero, due to assumed constant cooling loads (server room), and heating loads (tap water). Based on this data and the aforementioned control strategy, an hour-to-hour calculation of the energy level is performed, optimizing for the lowest necessary cooling duty. Two such calculations are performed, one for the large energy pile foundation and the other with the small energy pile foundation.

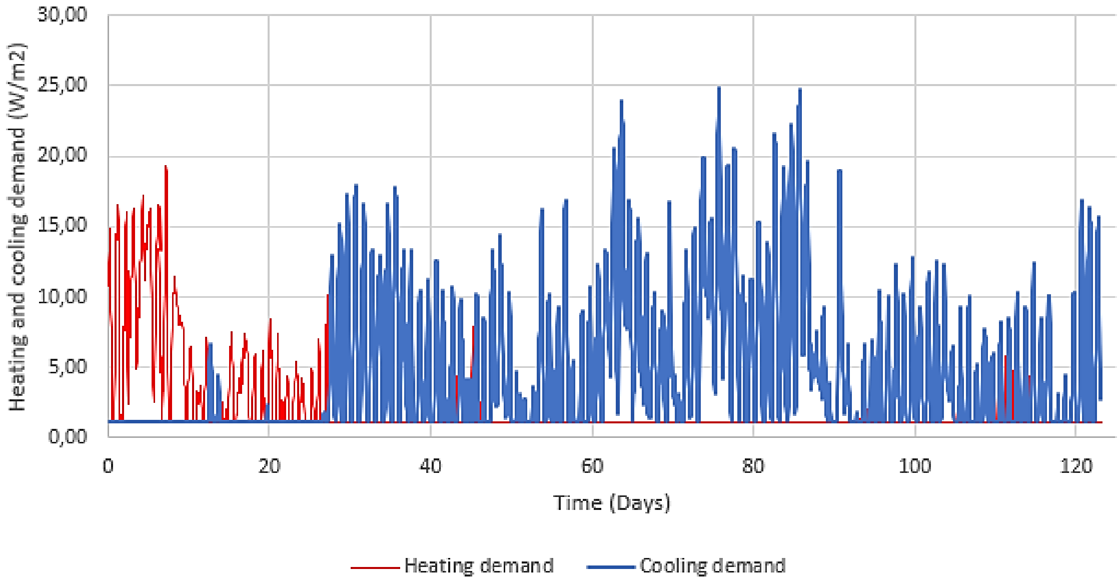

Figure 6: Heating and cooling demand during summer months in Case 1.

Figure 7 shows the results of the hour-to-hour calculations for the case where large piles were used in the foundation during the three weeks with the highest average cooling load in Figure 6. The blue curve is the building cooling demand. The green line is the cooling produced by heat pump, and the black line represents the cooling energy stored in the piles. Under the given temperatures', from the initial 7.2°C to the upper bound of 25.0°C, the cooling storage capacity in the water volume is approximately 1 000 kWh in total for the building, corresponding to 230 Wh/m^2. In this case, the necessary peak load power for cooling is reduced from 30 W/m^2 to 10.7 W/m^2, a reduction of 65 %, due to the more evenly distribution of the cooling load.

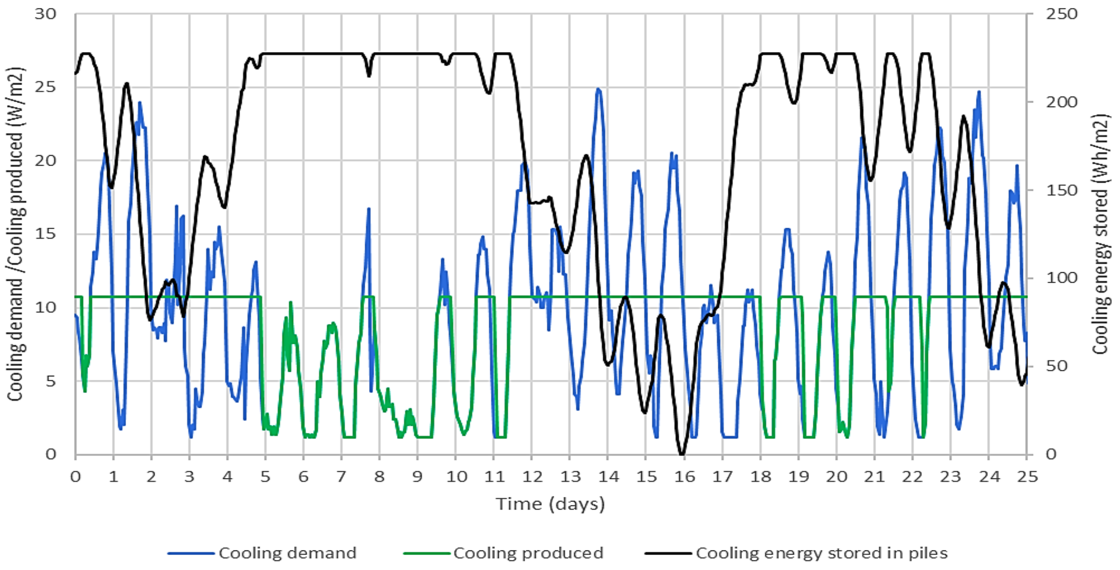

Figure 7: Cooling energy demand, production, and storage for a 3-week summer period in Case 1 with large energy piles working as the thermal energy storage.

The corresponding values for the small piles are shown in Figure 8. The storage cooling capacity in the water volume is here approximately 380 kWh in total for the building, corresponding to 155 Wh/m^2. In this case, the necessary peak load power for cooling is reduced from 30 W/m^2 to 14.2 W/m^2, a reduction of 51 %, due to the more evenly distribution of the cooling load.

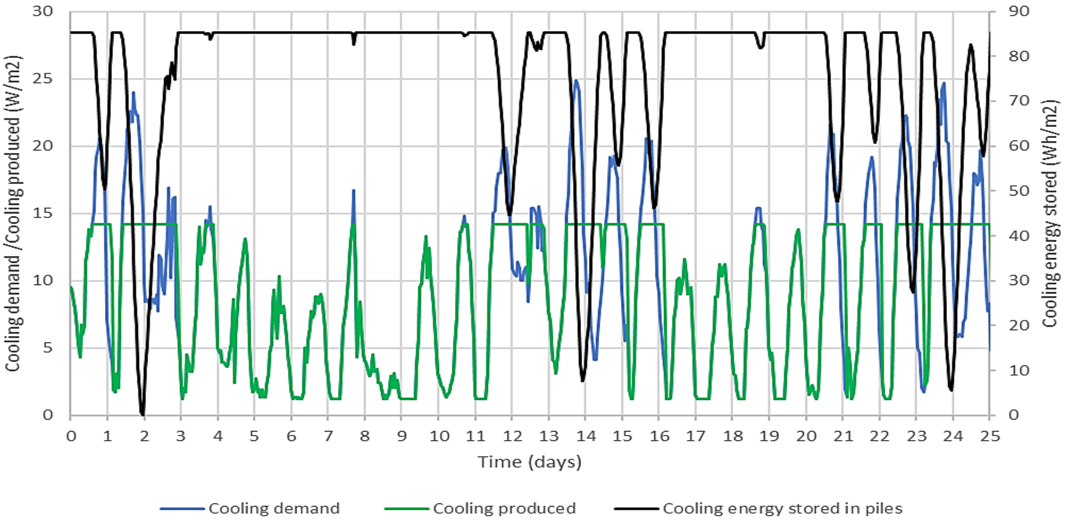

Figure 8: Cooling energy demand, production, and storage for a 3-week summer period in Case 1 with small energy piles functioning as the thermal energy storage.

With the storage volumes provided by these pile sizes (86.2 m^3 and 31.0 m^3 of water, respectively), the analysis in Figure 7 and Figure 8 show that it is no longer the hourly peak cooling load that determine the system layout. It is now the average load over several days that will determine the peak load cooling power. This enable the cooling system to employ a smaller cooling unit, at lower capital costs and the operation of the smaller cooling unit will be much better and can essentially be much more even, with less starts and stops through the day, as it is able to run both day and night. An additional beneficial consequence of the storage is the better average temperature conditions for the cooling unit, which enable the cooling unit to operate at a better coefficient of performance (COP).

The presented analysis thus shows that the building cooling system will benefit from the thermal storage provided by the energy piles. However, the presented analysis assumes an adiabatic system, which is considered very conservative. Given the test results of the piles shown in Figure 4, it can be observed that the energy pile system is not adiabatic but will interact with the surrounding clay. It is therefore expected that the energy piles will function even better as a day-to-day cold energy storage than the presented analysis show. Further analysis is therefore recommended, with more advanced calculations of the storage interaction, that should include the heat transfer to the clay surrounding the piles. This is performed in the Case 2 analysis.

1.3 Case 2 – Seasonal thermal storage in the piles and the clay

The purpose of the Case 2 study is to look at how energy piles and the surrounding clay can function as a seasonal thermal energy storage for the office building, where enough heat is stored during the summer to be extracted during the winter, and thus cover the entire yearly thermal energy load. This concept depends on a sufficient storage size to function.

The size of the thermal storage relies on the 1 500 m^2 floor area of the building and the 25-meter deep piles, corresponding to 37 500 m^3 of storage volume (ignoring peripheral soil volumes). The clay at Saksvik has between 30-35% water content (weight percentage), which entail that the volumetric heat capacity of the clay is approximately 0.9 $kWhm^{-3}°C^{-1}$. In view of the annual heat demand for the building (270 000 kWh/year) it is evident that the initial thermal energy available in the clay (if the clay is cooled down from 7,2°C to 2°C = 5,2 °C) is only 175 000 kWh, not even enough to cover the heat demand for on single year.

The thermal storage must be "charged" with heat before the start of the winter season to be able to cover the annual heating demand of the building. The temperature of the storage volume must be altered by 8.0°C on average, from 7.2°C to 15.2°C, to enable full coverage each year. However, the heat pump compressor will produce between 25%-33% (COP of 3-4) of the heat during operation, which mean that the storage temperature can be correspondingly less for full coverage (5.2 – 6.0°C temperature alteration in the whole storage).

Another important aspect for the thermal storage is the rate with which heat can be stored in the clay. This rely on the heat conducting properties of the clay and the piles. The TRT-results in Figure 4 show that the heat rate is different for the piles. Also, fever piles means that the heat is injected more concentrated in some areas. For example, if the piles are evenly distributed over the 1 500 m^2 floor area, each of the 49 large piles cover approximately 30.6 m^2 of the ground floor area and correspondingly 765 m^3 of the soil volume beneath the building, whereas for the 118 small piles each pile cover 12.75 m^2 and 318 m^3, respectively. The large piles are thus separated approximately 6 meters apart, whereas the small piles are 4 meters apart. This makes the heat more evenly distributed in the storage with the small piles.

In the following analysis the heat transfer rate between the clay and the different piles are considered in accordance with the TRT-results shown in Figure 4. These quasi-steady state tests show that the heat transfer rate of the large piles (13.6 $Wm^{-1}°C^{-1}$) are approximately 2.4 times larger than for the small piles (5.7 $Wm^{-1}°C^{-1}$). However, in the analysis this is compensated due to the larger number of foundation piles required by the small pile size. The number of 118 small piles is 2.4 times the 49 large piles used in the two different foundation designs. Consequently, the heat transfer rate for the whole group of small energy piles (16.5 $kW°C^{-1}$) will become virtually equal to the large energy pile group (16.6 $kW°C^{-1}$). This is not a coincidence, as it is the steel quantity that determine both the load bearing capacity of the foundation and the heat transfer area in contact with the clay. The total volume of steel is equal in both pile foundation designs, and this evidently leads to the same over-all heat transfer rate in both cases (Table 4).

The conceptual sketch of the system is shown in Figure 9. In heating mode, heat is extracted from the storage, and serves as heat source for the heat pump. The temperature is lifted trough the heat pump and delivered to the building. This is represented in the whole red lines in Figure 9. In cooling mode, the heat pump removes heat from the cooling system. Heat at higher temperatures is supplied into the storage and charging the storage. This is represented by the whole blue line. The office building has a significant heat imbalance over the year (Table 3), where the yearly demand for heat of 60 kWh/m^2 is more than six times larger than the cooling demand of 9 kWh/m^2. Additional heat is therefore extracted from the outdoor air during the summer and supplied to the storage. This is represented by the dotted red line in Figure 9.

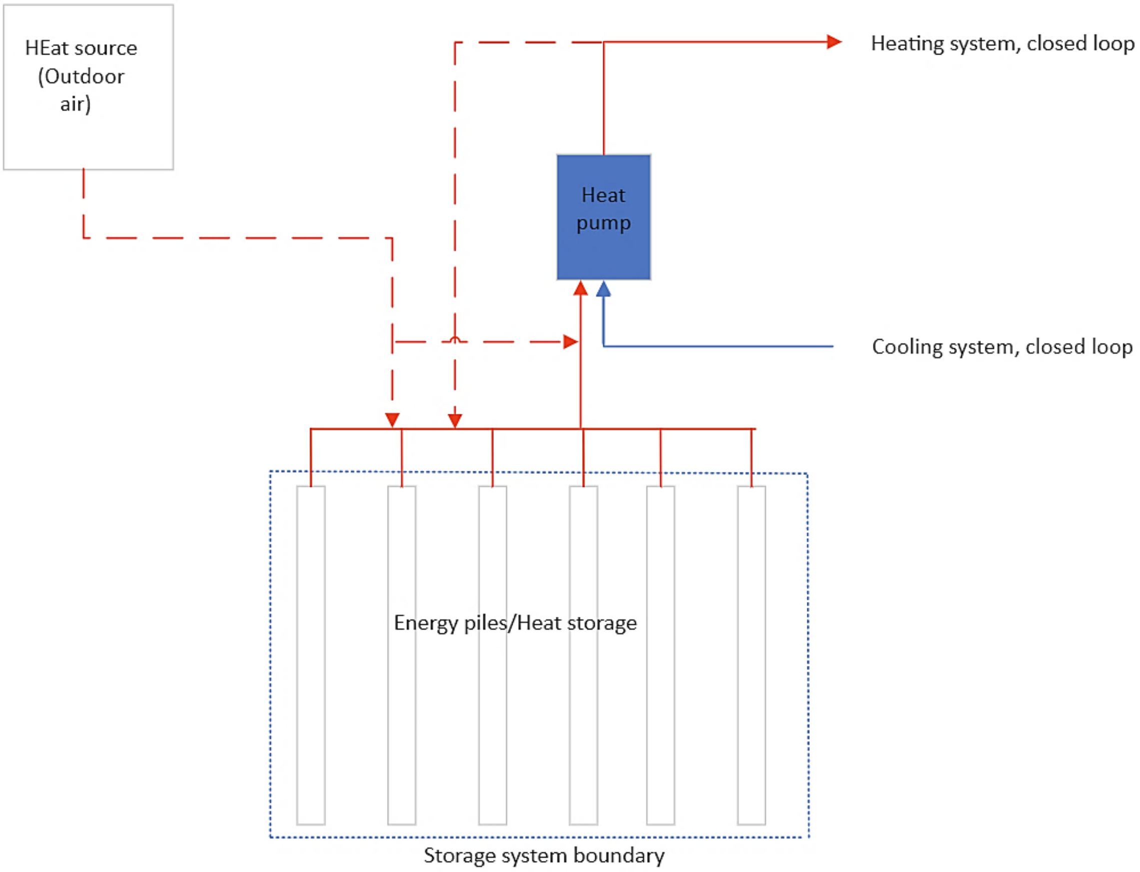

Figure 9: Energy piles and heat pump system configuration in Case 2.

The office building's overall thermal energy balance per year is presented in Table 5. The yearly heating demand for building is 60 kWh/m^2-year, where 6 kWh/m^2-year is covered by a peak load electric boiler unit (10 %). The efficiency of the heat pump determines the load requirement for the thermal storage. The heat pump is dimensioned to cover the peak cooling demand, i.e., 30 W/m^2 of refrigeration capacity. The heating

COP is assumed constant at 3.5, resulting in a specific heating capacity of 38.5 W/m^2 of the same heat pump (173 kW). This is corresponding to about 65% of the peak heat demand (60 W/m^2 or 270 kW). The resulting heat extraction from the storage is 38.6 kWh/m^2-year, i.e., this is the total amount of heat to be extracted. It is assumed that the storage must be in balance over one year, and the heat loss out of storage volume is neglected. The storage capacity needed corresponds to seasonal temperature difference (average) in the storage volume of approximately 5.5°C, assuming a specific heat capacity of 0,9 kWh/m^3°C^{-1} for the clay.

Table 5: Energy storage balance per year for Case 2.

Storage Energy Balance, per year	***Specific energy (kWh/m^2-year)***	***Total energy (kWh/year)***
Heat surplus from the cooling system	9.0	40 500
Heat from heat pump (cooling mode)	12.6	56 700
Heat delivered by heat pump for heat demand	54.0	243 000
Heat input to heat pump (heating mode)	38.6	173 571
Heat deficiency (need to be added to storage)	26.0	116 871

Table 6 shows heat transfer rates from and to the thermal storage under peak load conditions. As seen in Case 1, the cooling power demand is reduced by 50-65%. This means it is the heating mode that is decisive for the heat pump unit size. The size is chosen so that maximum allowed heat extraction is set to match a heat output of 30 W/m^2, still enough power to cover approximately 90% of the heating energy demand. This results in a necessary average temperature difference of water to clay of approximately 4.9 °C. This is the average temperature difference between average clay temperature, and average water temperature in the piles.

Table 6: Storage peak load specifications for Case 2.

Peak power demand case, cooling mode	***Specific values***	***Unit***	***Total values***	***Unit***
Peak cooling demand of building	30.0	W/m^2	135	kW
Heating demand supplied to storage	38.6	W/m^2	174	kW
Required average ΔT between pile and clay	10.5	K	10.5	K
Peak power demand case, heating mode				
Heat demand to HP, extracted from storage	17.9	W/m^2	80	kW
Required average ΔT between pile and clay	4.9	K	4.9	K

In charging mode of the storage (cooling mode of the heat pump), the corresponding values is 10.5°C, due to higher power requirement in cooling mode. This peak load is only present in short periods of time and are not very relevant as the water volume will buffer and distribute this load over time, as shown in Case 1. The actual steady state thermal flow will be significantly lower (10.7 W/m^2 for large piles), hence the heat transfer rates in heating mode will have higher numerical values. In the heating mode, there will be heat extraction at the given rate over prolonged time periods. The steady state heat delivery of 17.9 W/m^2 to the building is used for the heat transfer calculations, as there will be no load distribution. Given the temperature operating limits chosen of 25°C maximum and 2°C minimum, this means that the average clay temperature must be minimum around 10°C, considering that the average water temperature must be 4-5°C in the piles to ensure enough heat transfer rate. This average water temperature means approximately 2°C inlet and 7°C outlet.

Evaluating the peak load considerations and heat balance together demonstrate that it is possible to operate a 173 571 kWh/year thermal energy pile storage in clay by alternating the average clay temperature by approximately 4.1°C. The peak energy demands require a peak temperature difference between the piles and the clay to be ca. 10.5°C during cooling mode and 4.9°C during heating mode (average temperatures). This means that the seasonal temperature variations of the storage must fluctuate around 10-14°C throughout the season, with the storage having a temperature of 10°C on average in the end of the spring and must be increased to 14°C on average in the autumn.

One major uncertainty of this consideration is that the heat distribution within the clay varies during the season. The TRT (Figure 4) show that the driving temperature difference would have to rise with time to enable heat to travel further into the surrounding clay. Therefore, it is expected that the actual temperature difference between pile and clay must be higher at the end of each season. This should be further examined with numerical simulations.

1.3.1 Annual performance of the thermal energy storage

The calculated total electrical energy consumption of the thermal system in Case 2 is presented in Table 7. Assumptions on the COP of the heat pump is given for different operating conditions, which was assumed to be 3.5 for both the heating and the cooling operations, while the charging operation with the summer air was assumed with a COP of 4.0. The seasonal coefficient of performance (SCOP) of the whole system then becomes SCOP = 2.2 if the entire electric energy consumption (141 846 kWh/year) is distributed over the total thermal energy demand of the building (both heating and cooling – 310 500 kWh/year). The SCOP drops slightly to 2.1 if the electric energy consumption (125 646 kWh/year) is distributed over the total heating energy demand of the building only (heating demand – 270 000 kWh/year).

Table 7: System energy consumption per year for Case 2.

System electric energy consumption	***Specific values (kWh/m²-year)***	***Total values (kWh/year)***
Electric energy for Peak load boiler, 10% of the heat load (COP = 1.0)	6.0	27 000
Electric energy for HP Cooling operation (COP = 3.5)	3.6	16 200
Electric energy for HP Heating operation (COP = 3.5)	15.4	69 429
Electric energy for charging thermal storage during summer (COP = 4.0)	6.5	29 218
Total electric energy consumption per year	25.0	141 846

These SCOPs are lower than the expected performance of conventional ground source heat pump systems with borehole energy wells (Spitler & Gehlin, 2022). One reason for this is due to the active use of the heat pump both for heating and for cooling. In practice one could improve the system by utilizing more direct exchange, particularly for cooling but also for heat recharging purpose. There is a theoretical possibility of supplying some portions of the heat directly to the heat storage, in cooling mode, at least in the spring when the storage is cold, and cooling demand is limited (with a high temperature cooling loop – 12°C /17°C). It is also the possibility of charging the storage with direct heat exchange to air (without heat pumping). If we assume that this could be done when the outside air temperature is above 18°C, there is approximately 1000 hours available to do this. If a temperature difference between pile to clay of 2-3°C is achieved during the charging period, the resulting charging power would be 6-9W/m^2, and the potential amount of heat charged will be about 30% of the total demand.

These results of Case 1 and Case 2 show two ways to use energy piles and clay as a seasonal thermal energy storage, for a generic building with dominating heating demand. This building energy demand is frequent in the Norwegian climate. The concept of Case 2 would probably be more beneficial if the heating and cooling demands were more balanced, as it would reduce the need for supplementary charging. However, as demonstrated in Case 1, the system can also be designed according to the cooling demand, with the peak load shaving, chiller size reduction and intermediate storage capacity as the main beneficial features. In summary, there are several possible system solutions and control strategies for the use of piles as thermal energy storage. The choice will have an impact for the overall system efficiency. This should be further examined and simulated.

4 LCA – An environmental impact assessment

To evaluate the possible effects of the RD-energy-piles on the environmental impact from the operational phase, a life cycle analysis (LCA) was performed for the two different foundation designs in Case 2 described above. Both the small and the large piles are included to assess if the material usage would result in significant differences between the two, in view of the environmental impact perspective. The LCA of the piles are also compared to two other energy system that might otherwise be employed in our fictional office building. Four different alternatives (1–4) are therefore presented in the LCA in following subchapters.

The four alternatives are shown in Table 8. Alternative 1 and 2 represent the seasonal warm storage of Case 2 with the small and the large piles, respectively. Alternative 3 and 4 represent traditional heating and cooling scenarios commonly used in the Oslo-area today. Alternative 3 is heating supplied from district heating and cooling supplied by air-to-water heat pumps. District heating was chosen as it is often mandatory to connect to the district heating grid in some areas. In alternative 4 both the heating and the cooling is supplied by air-to-water heat pumps. This was chosen to show how the energy piles might perform as a supplement to one of the most common heat-pump types in Norway.

Table 8: Description of alternatives 1 – 4 for the LCA.

Alternative	**Description**
Alternative 1	Case 2, seasonal warm storage, small piles (140 RD-piles)
Alternative 2	Case 2, seasonal warm storage, large piles (320 RD-piles)
Alternative 3	Heating is supplied from district heating Cooling is supplied by air-to-water heat pump
Alternative 4	Heating and cooling are supplied by air-to-water heat pump.

The goal of this study is to compare the total environmental impact from four different alternatives for heating and cooling of the office building. The aim is to quantify the overall impact to assess how the increased material usage for the energy piles compares to the reduced total quantity of electricity needed when utilizing the foundation structures to facilitate for storage of thermal energy in the ground. The carbon footprint of all four alternatives of the building are then calculated.

4.1 LCA – Methodology, system boundaries & functional unit

The LCA study follows the methodology and requirements described in ISO 1404 and ISO 14044 (Norsk standard, 2006) using the software SimaPro Analyst v. 9.4.0.2. The impact assessment method used is ReCiPe 2016 V1.07 midpoint method, Hierarchist version (Huijbregts et al., 2017). The background processes were from the ecoinvent database v. 3.8. Impact to all environmental categories available from SimaPro are presented.

The system boundaries are illustrated in Figure 9. All four alternatives are dependent on water for energy distribution within the building. As these systems will be identical for all four of the alternatives this is not included in the system boundaries. Furthermore, the foundation piles are regarded as a part of the building itself. Buildings that require foundation piles will always construct these piles regardless of their use as energy piles or not. Foundations for buildings are thus included in the LCA for the building and not for the energy system (Direkteratet for byggkvalitet, 2017). The environmental footprint of the piles is therefore not allocated to the energy system in this LCA.

For conventional RD-piles the interior of the piles is typically backfilled with concrete, but this is not the case for the BEAR energy piles. Theoretically the energy piles can therefore be said to improve the environmental impact by limiting the use of concrete in the foundation design. However, this is not highlighted in the analysis and the only pile components that are included in the LCA are the additional pile components that would not otherwise be installed in the foundation, if they were not to be used as a thermal storage. The following input is included in the analysis:

- Alternative 1 & 2: the heat collector system with HDPE pipes, a polyurethane (PUR) liner on the inside of the piles, the heat pumps and energy necessary to run the heat pumps.
- Alternative 3: the district heating, heat pumps and energy needed to run the heat pumps.
- Alternative 4: heat pumps and energy needed to run the heat pumps.

The life cycle inventory (LCI) processes included for each of the alternatives, quantities and qualities for each of the processes, for each alternative is shown in Table 9 . The energy demand of the building is equal in all four cases, but the air-to-water heat pump is given a slightly lower SCOP due to the colder winter temperatures, resulting in a slightly larger electricity use in Alternative 4. The electricity-mix that is used in the program is Norwegian quality valid for the year 2016.

Table 9: Life cycle inventory (LCI) for the analysis of environmental impact.

Process inventory	**Unit**	**Alt 1.**	**Alt 2.**	**Alt 3.**	**Alt 4.**
HDPE pipes for the pile heat collector	kg	640	266	-	-
PUR liner heat collector	kg	3 600	3 704	-	-
Heat pump (130 kW size)	p	3	3	4	4
Electricity for heat pump/heating system	kWh	141 846	141 846	18 900	159 300
District heating	kWh	-	-	270 000	-
Transport impact for heat pump, rubber lining and HDPE pipes	tkm	227	214	15	15

A literature review of Röck et al. (2020) on the carbon footprints of energy solutions for buildings were calculated from 52 peer-review studies across the world and show corresponding functional unit values of 1.4, 0.5 and 0.2 kg CO^2-eq./m^2/year for existing building standard, new building standard, and new advanced building standards for office buildings. The functional unit values were recalculated to emissions per year with a 60 years reference study period. The results from this LCA are therefore presented for the same total lifetime of the building, which is set with a reference study period of 60 years. The carbon footprint for this period was calculated for all four alternatives. The results are presented as the functional unit CO2-eq./m^2/year to enable comparison between the four alternatives and the literature.

4.2 Life cycle analysis - Results

Results from the LCA are summarized in Figure 10 for all 18 relevant LCA parameters. For each of the categories the impact is presented relative to the largest impact within the category. For example, in view of the global warming potential this means that alternative 4 with only air-to-water heat pumps has the highest impact, the impact for the three other alternatives are therefore presented relative to this impact. The carbon footprints (functional unit: CO2-eq./m^2/year) calculated for each of the four alternatives are shown in Table 10.

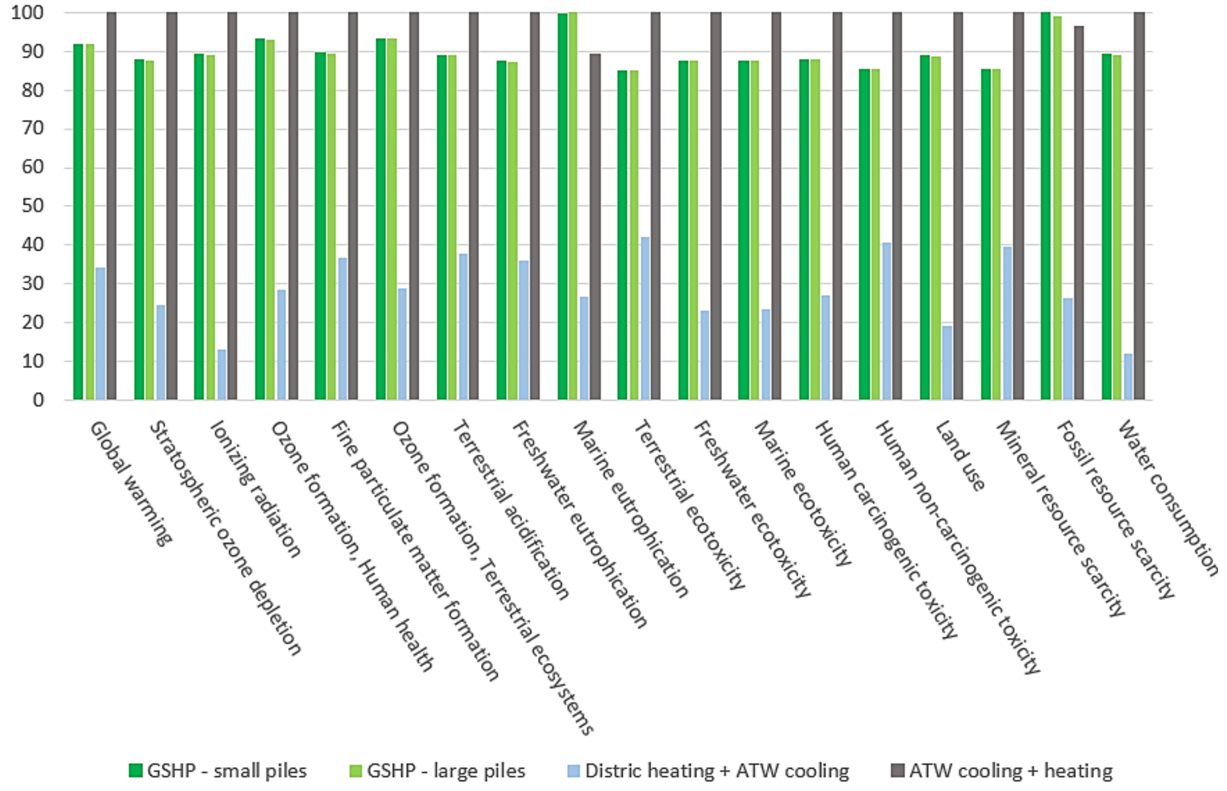

Figure 10: LCA of the four alternative energy systems for the case-study office building. For each impact category, the impact is presented relative to the highest impact amongst the four alternatives.

Table 10: Carbon footprint of the Alternatives 1 – 4.

	CO2-eq/m^2/year
Alternative 1 – small energy piles	1.14
Alternative 2 – large energy piles	1.14
Alternative 3 – District +ATW cooling	0.43
Alternative 4 – ATW cooling/heating	1.25

The results show that the differences between Alternative 1 and 2 are limited, with the larger piles (Alt. 2) obtaining marginally better results than the small piles (Alt.1). Table 10 show that there are no significant differences in environmental impact between the small piles and the large piles. Compared to Alterative 4, with the heating and cooling set-up with air-to-water heat pumps, the Alternatives 1 & 2 with energy piles obtain between 7 and 15% reduced impact for all categories, except marine eutrophication and fossil resource scarcity. For these two impact categories, the impact from Alternative 2 with large piles is 10% and 4% higher, respectively. Alternative 3 with district heating obtain the best results for all impact categories due to the additional benefit given to waste burning in the LCA model. The carbon footprint is therefore substantially lower for the district heating alternative (Table 10). Alternative 4 with the air-to-water (ATW) heat pump has a higher carbon footprint, but only higher 9%-points higher impact compared to the energy pile alternatives.

Figure 11 shows a hotspot analysis for Alternative 1. The figure demonstrates that the largest contributor (over 60 years) of the input variables in Table 9, to all impact categories for the energy piles, is the electricity used for running the heat pumps. The use of additional materials for the inside tube in the piles (the PUR liner and the HDPE pipes) only contribute slightly to the environmental impact. This is mainly due to the main bulk of the pile material is installed as a part of the substructure of the building, and their emissions are allocated to the building LCA. Utilizing these energy piles for additional energy storage functions is thus beneficial from an LCA point of view. Previous studies have also shown significant reduction in environmental impact. The study reported by Sutman et al. (2020) showed substantial differences between conventional systems and use of energy piles, with a 65% and 55% reduction for CO2-eq. emissions for Seville and Rome, respectively. Sutman et al. (2020) showed that for Berlin, the difference between conventional system and energy piles was lower, and this was due to the higher need for energy during the winter season for heating in Berlin.

The Norwegian electricity mix has a low environmental impact compared to other countries, since most of the electric energy production in Norway is provided by hydropower. The European electricity mix is produced from sources with a higher environmental impact, which would affect the LCA results. The Norwegian electricity grid has gradually opened towards Europe through several export/import cables. To allow for comparisons with other European publications, the LCA was re-run to compare the results of Alternative 1 with the European electricity mix (Table 11). The results are presented in relative terms where Alternative 4 represent the base-line for the data.

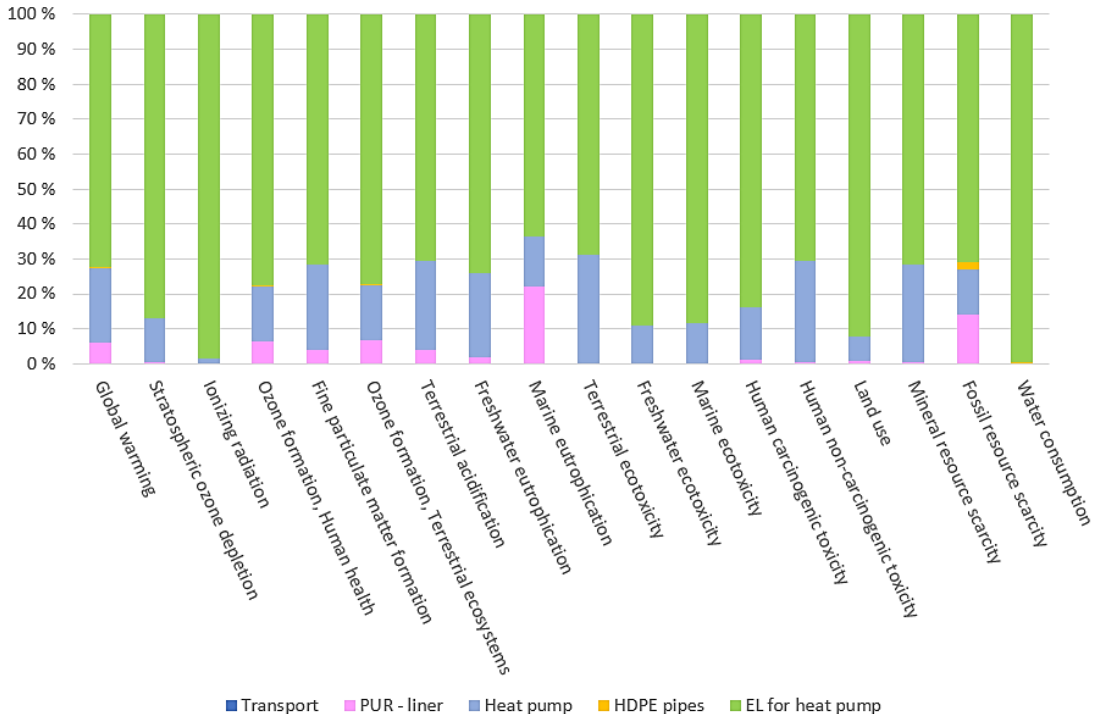

Figure 11: Hotspot analysis for Alternative 1 – small energy piles

Table 11: Difference between Alternative 1 and Alternative 4 for each impact category with European (RER) or Norwegian (NOR) electricity mix.

Impact category	RER [%]	NOR [%]
Global warming	10	8
Stratospheric ozone depletion	13	12
Ionizing radiation	8	11
Ozone formation, Human health	9	7
Fine particulate matter formation	10	11
Ozone formation, Terrestrial ecosystems	9	7
Terrestrial acidification	11	11
Freshwater eutrophication	10	13
Marine eutrophication	8	-10
Terrestrial ecotoxicity	27	15
Freshwater ecotoxicity	15	12
Marine ecotoxicity	16	12
Human carcinogenic toxicity	12	12
Human non-carcinogenic toxicity	16	15
Land use	9	11
Mineral resource scarcity	25	15
Fossil resource scarcity	8	-4
Water consumption	8	11

The analysis with the European electricity mix shows larger differences, in favour of the piles, than compared to the Norwegian energy mix. This is mainly due to the slightly better SCOP of the energy pile scenarios compared to Alternative 4. In future scenarios where the electricity usage in Norway might have a larger negative impact from import of electricity from Europe, the utilization of the underground for storing cooling and heating energy shows a promising potential for reducing environmental impact. However, this does require the piles to achieve a favourable SCOP to reduce the need for external energy for the operation phase of buildings.

5 Cost-analysis for the energy piles

The foundation cost and the cost of the pile installation is principally allocated to the cost of the building, and not allocated to the cost of the energy system. However, the activation of the piles for energy purposes do have implications for the foundation costs. The main drivers for increased costs are associated to situation with poor installation efficiency, where the installation of pipes and couplings in the piles cause the building project to spend more over-all time for their construction. These costs are deemed highly site specific and might be significant or insignificant depending on the project in question. The over-all costs might eventually become a tipping point for the selection of foundation design and the choice of activating the piles or not. The BEAR pilot project has not been able to investigate such cost dynamics.

Some key cost numbers (valid for 2022) from the BEAR pilot are provided in the following, in an effort to exemplify the costs for the two different BEAR-piles (RD-140/10 and RD-320/10 with S460MH steel quality) and the potential costs for the energy activation of the whole building foundation in the case-study described in Chapter 3. The cost of the BEAR RD-piles is largely involved with the cost of the steel for the piles, the mobilisation costs for the equipment & crew and the costs for the construction time of the pile installation. These costs are evenly distributed per meter pile in Table 12, for the RD-140/10 and RD-320/10 alternative. The costs of the single BEAR pilot energy piles are here scaled up to the total number of piles required by the foundation, respectively.

For the 25-meter deep RD-140/10 pile the total cost amount to 1 526,- NOK per meter pile. The corresponding cost for the RD-320/10 pile is 3 678,- NOK per meter pile, approximately 240 % higher costs per pile. However, the total costs for both cases become very similar, where the cost of the foundation with the small piles amount to a total of 4 501,- kNOK and the cost for the large pile foundation amount to 4 449,- kNOK. This is largely due to the fact that both pile designs utilize the same amount and quality of steel in their design (Table 4) and both the RD-140/10 and the RD-320/10 pile classes utilize the same installation equipment, yielding equal mobilization costs and over-all installation costs.

For conventional RD-piles the interior of the piles is typically backfilled with concrete. In this case the total cost for the conventional RD-piles become slightly different due to the higher concrete volume needed in the RD-320/10 pile alternative. The RD-140/10 pile foundation then cost 275,- kNOK less than the RD-320/10 pile foundation (* price in Table 12).

*Table 12: Installation cost for the conventional RD-piles, per scenario in Table 4. The total amount of pile length is based on 25-meter-long individual pile lengths. * This price include concrete backfill in conventional RD-piles.*

	Outer Diameter OD (m)	Inner Diameter ID (m)	Wall thickness (mm)	Length (m)	Number of piles	Total pile internal volume [m^3]	Cost per meter pile [NOK/m]	Total cost [kNOK]
Large pile RD-320	0.323	0.303	10,0	25	49	88,3	3 673,-	**4 499,-** **(4 940*)**
Small pile RD-140	0.140	0.120	10,0	25	118	32,8	1 526,-	**4 501,-** **(4 665*)**

For the BEAR RD-piles the backfill with concrete is not required, so the BEAR-pile design essentially represent at potential saving for the over-all costs. However, additional cost for the installation of pipe components within the energy piles must be included in the investment cost for the energy system. This mainly involve the cost for the heat exchanger within the piles, which in this case involve the installation time costs and the material cost for the PUR-liner pipe hose, internal HDPE supply pipe and the top pipe coupling unit at the pile lid. These costs are estimated in Table 13. In total the activation of the small RD-140/10 piles costs 917,- kNOK and the activation of the large RD-320/10 piles cost 587,- kNOK. In this case the higher number of small piles results in a significant larger investment cost for the activation of the pile foundation.

*Table 13: Energy pile heat exchanger pipe materials and cost per scenario in Table 12 . *This price subtracts the costs for the concrete backfill in conventional RD-piles shown in Table 12.*

	Coaxial hose of PUR liner [NOK/m]	Coaxial hose of PUR liner [NOK]	Stand pipe 25 mm PE [NOK/m]	Stand pipe 25 mm PE [NOK/m]	Pipe coupling and lid [NOK/ps.]	Pipe coupling and lid [NOK/ps.]	Total [kNOK]	*Total [kNOK
Large piles	450,-	551 250,-	23,-	1127,-	700	34 300,-	587,-	**146,-**
Small piles	300,-	885 000,-	23,-	2714,-	250	29 500,-	917,-	**753,-**

The additional cost for activating the BEAR RD-piles, subtracting the unnecessary concrete backfill, show that the large RD-320/10 pile design is most favourable among the two, costing an estimate of 146,- kNOK more than compared to conventional piles (* costs in Table 13). The costs of 753,- kNOK for the smaller RD-140/10 pile design is significantly higher because of the larger number of couplings and components needed in the system design. It is also relevant to assess the possibility that there will be increased complexity in coupling the 118 small piles to the energy system compared to the 49 large piles. The cost differential would therefor probably increase if the entire cost situation is taken into account. The presented cost evaluation therefor favours an energy pile design with fewer and larger piles in the foundation.

Operational & maintenance costs are associated with the cost of operating the heat pump system in a building that employ energy piles. As the piles are embedded into the foundation floor, they are not readily available for maintenance and the costs associated with maintenance is therefore not deemed relevant in the BEAR study. Further work on this topic is recommended, particularly for full scale testing in real buildings.

6 Discussion & conclusions

It is shown in the presented case-study that energy piles must be operated as a thermal energy storage if they are to function in Norway. This is not often emphasised or debated in the literature and this fact should be given due consideration in the design and utilization of energy pile foundations in new projects in the future.

It is shown in the case study of Chapter 3 and in the LCA in Chapter 4 that there are relatively small differences between the two sizes of RD-energy piles tested in the BEAR project. Given a specific geological case, with the same pile depth and building thermal and mechanical loads, the dimensioning of the building foundation, either with small RD-140/10 piles or with larger RD-320/10 piles, will result in very similar energy systems in view of environmental impact, cost, energy coverage and energy efficiency. For a given case the general trend for the RD-piles are:

- Smaller pile diameter tends to result in foundations with:
    - More piles, which would result in slightly more costly installation.
    - Smaller storage volume of water in the piles, resulting in lower peak energy demand coverage.
    - More evenly distribution of the heat in the clay storage volume, which might enable the piles to operate at better ΔT over the season.
    - More over-all complexity of pipe connections, which would result in more costly installation for the energy system.
- Larger pile diameter tends to result in foundations with:
    - Less piles, which would result in slightly less costly installation.
    - Larger storage volume of water in the piles, resulting in higher peak energy demand coverage.
    - Larger distance between piles, with less evenly distribution of the heat in the clay storage volume, which might give the piles a less favourable ΔT over the season.
    - Less over-all complexity of pipe connections, which would result in more affordable installation for the energy system.

The LCA indicate that the energy pile concept can compete with a conventional air-water heat pump system common for Norway. However, as one might perceive from the LCA data, the major reason of the improved environmental impact originates from a lower seasonal consumption of electrical energy by the pile solution in this study. This entails that the energy piles concept relies on higher SCOP than competing solutions to triumph in the rivalry.

It is therefore important to emphasise that the case-study presented here might favour the piles to some degree. The building energy demand (173 kWh) for the storage in this case-study turned out to be relatively equal to the size (37 500 m^3) and capacity (average $\Delta T = 4°C$) of the thermal storage in the pile foundation (Figure 12). If the building demand would have been larger, e.g. due to an additional fourth floor with 1 500 m^2 more office space, the storage volume would have been too small to cover the whole heating demand. The same would occur if the depth to bedrock was shorter than the 25-meter-deep clay in this case, because the storage volume would be smaller.

This indicates that tall and heavy buildings, with a relatively smaller building footprint and especially with short pile lengths, results in a foundation design that do not favour the energy pile concept compared to other conventional solutions. Indeed, this would most likely result in relatively small storage volumes with many piles of limited energy coverage and capacity compared to the building requirement (Figure 12). On the other hand, under ideal conditions, much like in our case, the energy pile concept might very well out-compete other solutions due to the low capital cost for installation.

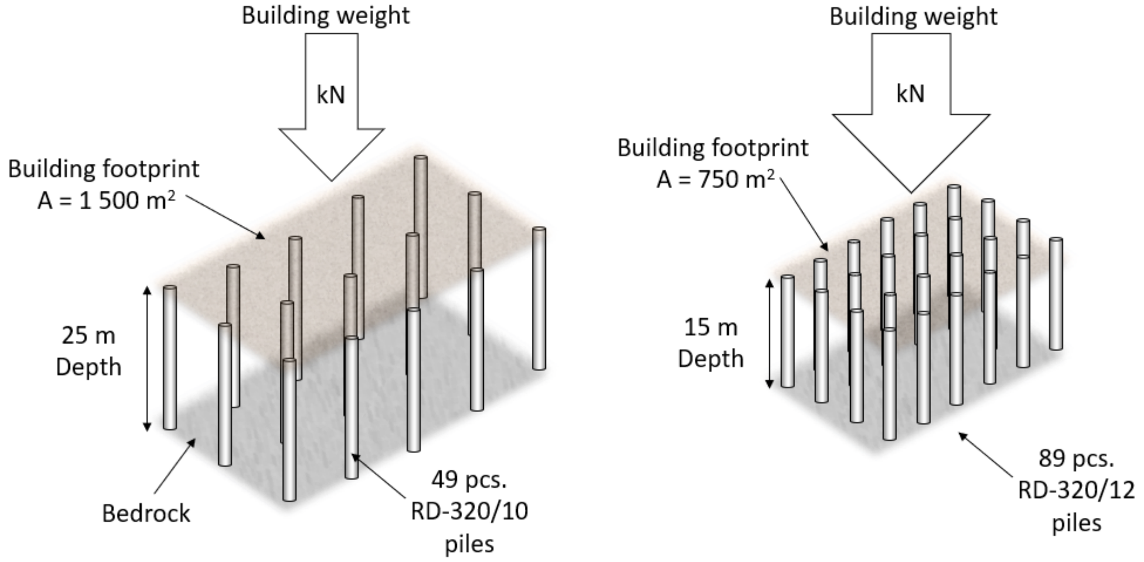

Figure 12: The energy demand for the thermal storage should be relatively equal to the volume size and heat capacity of the thermal storage in the pile foundation. The size of the building, the building footprint and the geological conditions will determine if this is the case.

The presented analysis demonstrates that the potential for use of energy piles in Norway, where the annual demand for heating and cooling is different than in most other southern European countries, is subjected to different dimensioning constraints and have other economical bounds than we see in the established literature (e.g. Laloui & Loria, 2020 and the references therein). Further research is therefore deemed necessary to demonstrate the full potential benefit of this technology in various locations across the country.

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