Large energy storage for urban area

- *Potential for thermal energy storage based on solar assisted clean-up plant for contaminated soil*

Funded by Bjarne Saxhof Foundation

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Preface

This report has been prepared for the project ‘Large energy storage for Urban area.’
Large energy storages are often not feasible in urban communities due to insufficient areas or high land prices. This project has investigated and analysed the feasibility of the reuse of soil cleanup plants with borehole storage. It is also investigated if solar thermal energy can be used in connection with the treatment of contaminated soil and, after that, provide local heat storage close to the demand.

We would like to acknowledge the Barne Saxhof Foundation, which funded this investigation and made it possible to try and connect two technologies in an attempt to provide decision-makers with a feasible solution for cleaning up contaminations from the past.

Kgs. Lyngby, February 2025

Content

1. Introduction

At the end of 2020, there were approx. 38,500 contaminated or potentially contaminated cases registered in Denmark. 19,774 cases have been fully or partially mapped at knowledge level 2 (V2), which means that contamination has been detected at the site. 18,659 cases have been mapped at knowledge level 1 (V1), which means that there is knowledge of activities at the site that may have caused soil contamination.

Contaminated soil can be removed with different methods, where one of them is with thermal energy, where holes are drilled into the ground and pipes are inserted where fluid can heat the ground slowly to 100°C. Depending on the contamination and the method of heating, the duration of the cleaning can be between 5-24 months. After the cleaning process, the boreholes no longer serve a purpose, and they can now be utilized as a borehole thermal energy storage.

In Danish households, 40% of the energy is used for heating, and this heat is delivered by district heating in 64 % of the cases. In rural areas, district heating is supported by renewable energies such as large solar collector fields, with large pit thermal energy storage. Large energy storage is often not possible in urban areas, simply because there is no land available within an acceptable distance from the district heating network. What sometimes is found, unfortunately, in urban areas is contaminated soil, which needs to be cleaned. These areas can potentially be cleaned and turned into borehole thermal energy storages.

2. Borehole Thermal Energy Storages

2.1 Borehole storage

Borehole Thermal Energy Storage (BTES) is used for seasonal thermal energy storage, especially in connection with large scale heating plants or industrial waste heat recovery systems. BTES is storing thermal energy in boreholes, charging the ground during the summer and discharging during winter. The principle behind BTES is to use the natural thermal capacity of underground materials, such as soil or rock, to store heat over time. BTES can also be used to increase the efficiency of district heating networks by reducing peak energy loads.

Design

BTES consist of multiple boreholes, typically ranging from 20 to 200 meters in depth. The ground water will often determine the dept of the boreholes, unless additional measures are set in place to avoid the storage being cooled by the flowing ground water. It is recommended that the boreholes are not drilled closer than 5 meters to the ground water level [1].

The boreholes are arranged in patterns, where several boreholes are connected in series to form strings, which are then linked in parallel. Figure 1 shows two different patterns of boreholes, where the one in the middle and to the left are both square patterns and where the distance between the boreholes determines whether they will overlap in covered area or have 'dead area' between them. The pattern to the right is the triangular pattern and the most often used pattern.

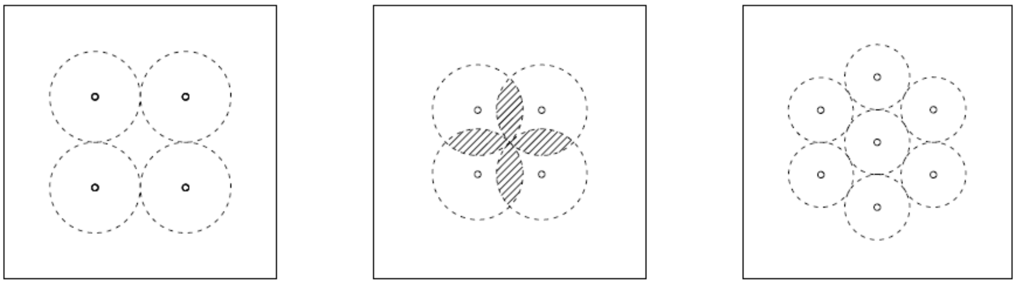

Figure 1 Typical patterns for borehole thermal energy storage

In Figure 2 the arrangement of the boreholes in the storage located in Brædstrup is given. The pattern used here is the triangular pattern. The different colours indicate which boreholes are connected to form a string. Each string contains in this case 6 boreholes.

It is unfavourable to have an uneven number of boreholes in the different strings, because it will be necessary to run with different volume flows in order to have optimal operation conditions for the storage.

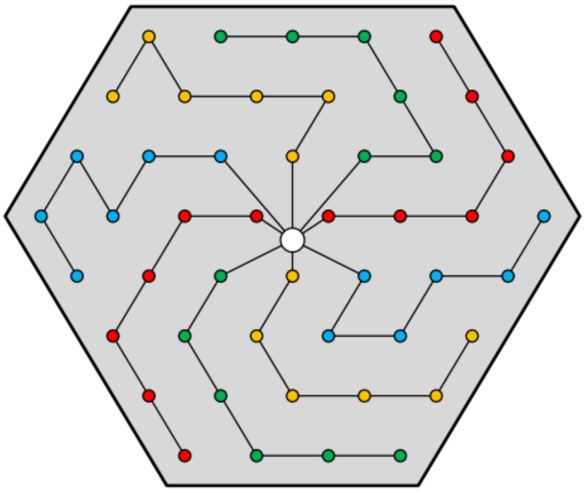

Figure 2 The arrangement of boreholes the storage location in Brædstrup [1].

Each borehole contains tubes embedded in grout material, to secure a good thermal contact with the surrounding soil. The tubes are either configured as single U-tube or Dobbel U-tube, se Figure 3.

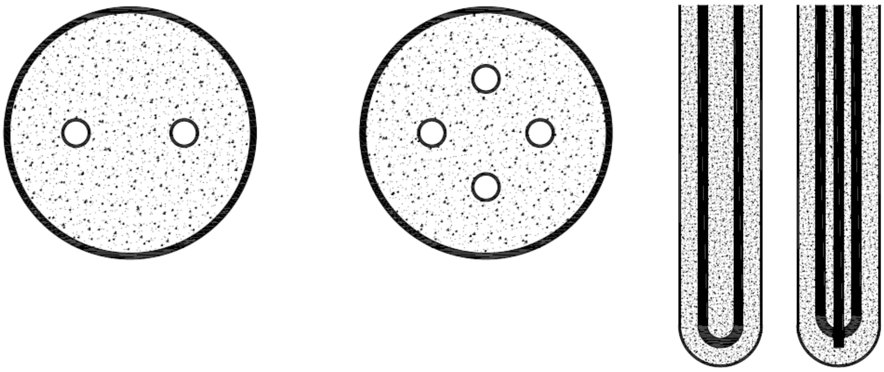

Figure 3 Single and double U-tubes for borehole storages.

The performance of the storages depends on the thermal properties of the soil. In

Table 1 the thermal properties are given for rock and soil at different saturations. The specific heat ranges from 0.84 to 1.05 and increases when the water content increases. This means that the ability to store heat decreases when the soil is dried out.

Table 1 Thermal properties of soil [1].

Soil	Density	Thermal con-ductivity	Specific heat	Thermal dif-fusivity	Density · Specific heat
	[kg/m³]	[kJ/h·rm·K]	[kJ/kg·K]	[m²/day]	[kJ/m³·K]
Dense rock	3200	12.46	0.84	0.11	2683
Average rock	2800	8.72	0.84	0.09	2347
Heavy saturated soil	3200	8.72	0.84	0.08	2683
Heavy damp soil	2100	4.67	0.96	0.06	2012
Heavy dry soil	200	3.12	0.84	0.04	1677
Light damp soil	1600	3.12	1.05	0.04	1677
Light dry soil	1500	1.25	0.84	0.02	1238

The boreholes and tubes are covered with roughly 500 mm of graded sand to protect the connections. On top of this is ridged insulation, that can withstand moisture and pressure. This is again covered with a layer of sand and on top of this approx. 1000 mm of topsoil, see Figure 4.

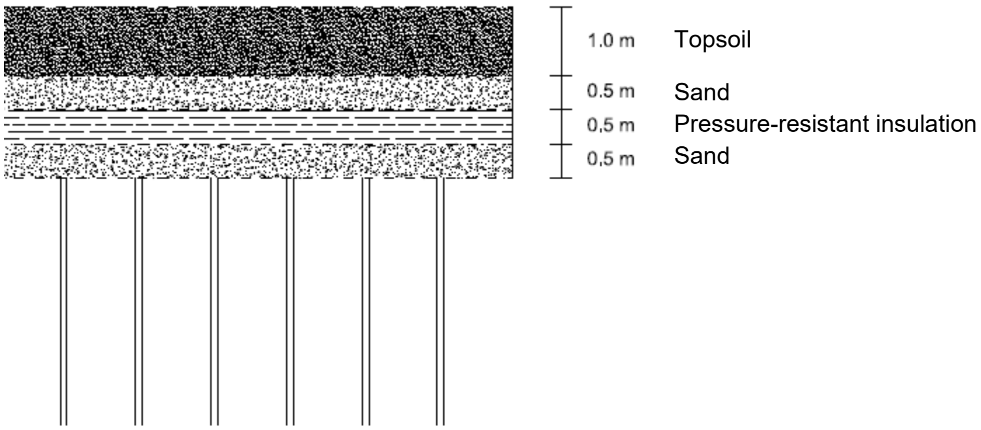

Figure 4 Example of top insulation.

The area above the borehole storage can be utilised for many purposes. If the top insulation is dimensions for higher pressure smaller structures can be placed on top.

2.2 Capacity of borehole storage

The capacity of the storage depends on the type of soil, accurate prediction of the ground water level, design pattern and distances of the boreholes, and on the lid construction. In the project HEATSTORE [2] efficiency of 4 boreholes storages were investigated and found to be much lower than expected, see Table 2 This was attributed to heat losses being higher than expected and discrepancies between modeled soil conditions and actual conditions.

Table 2 Selection of BTES system presented in the HEATSTORE project [2].

Country	Start of operation	No. of boreholes	Borehole depth (m)	Max. Temp (°C)	Tubes	Storage volume (1000 m^3)	Esti-mated capacity (MWh)	Storage efficiency
Canada	2006	144	35	80	U-tubes	34	780	0.5
Sweden	1983	120	65	65	Open	115	2000	0.45-0.55
	2002	99	65	45	n/a	59	1467	0.46
Denmark	2013	48	45	70	U-tubes	19	616	0.61

3. Soil contamination

Denmark's Environmental Portal [4] is a joint public partnership owned by the state, municipalities, and regions. The purpose of the environmental portal is to support digital environmental management. The basic idea is that the state, municipalities, and regions report, update, and retrieve data from the same databases and that data is freely available to companies and citizens in Denmark.

In Denmark's Area Information [5], which is part of Denmark's Environmental Portal, contamination-mapped land registers can be viewed. This is done by adding different map layers, e.g., soil contamination, V1 and V2 surfaces.

V1 surfaces (knowledge level 1) are blue, Figure 5 and used when the land register may be contaminated. V1 surface data is based on knowledge of activity on the land register that has most likely resulted in pollution, but this has not been proven with soil samples.

V2 surfaces (knowledge level 2) are red, see Figure 5, and here, the contamination has been documented, and soil contamination certificates can also be found here.

Figure 5 Map showing V1 and V2 surfaces (https://danmarksarealinformation.miljoeportal.dk/)

It is also possible to add other map layers, e.g., of drinking water interests and thereby assess how great a social benefit there will be by cleaning up a particular pollution.
Searching for specific pollution-mapped land registers at Denmark’s Area Information can be cumbersome. Therefore, other sources may be worth looking at, such as the Ministry of the Environment or the Municipalities' Action Plans, where it is often mapped in which areas there are significant water-threatening contaminants.
On the homepage of The Ministry of the Environment [6], there is an overview of generational pollution in Denmark. These typically have a significant vertical distribution, and several of them contain light pollution components that are cleaned up at a temperature level that solar heat can deliver. Generational contamination covers soil contamination cases from before 2001, estimated to cost more than DKK 50 million to investigate and clean. Another common denominator is that they will pose a problem for many generations if nothing is done. In 2020, the regions designated ten of Denmark's largest soil contaminations as generational contamination. These contaminations pose a significant threat to targeted surface water areas such as lakes, streams, and the sea or to groundwater where there is water abstraction or special drinking water interests. As the name “generational contamination” indicates, the pollution has happened in the past, and there is no longer anyone to hold accountable, or the perpetrator cannot be held responsible for other reasons. Generational contamination is the most extensive and expensive to clean soil contamination, which is often also very complex pollution with many different contamination components. It is the responsibility of the regions to clean up the generational pollution and apply to the Danish Environmental Protection Agency for subsidies for the various investigations and clean-ups. DKK 630 million has been allocated in the Finance Act for the investigation and clean-up of ten of the largest generational pollutions between 2021 and 2025.

3.1 Types of pollution

There are many different pollution components, and they can all, in principle, be cleaned up with heat, but there is a significant difference between whether it requires 100°C or 1000°C. Since the focus here is to investigate the possibility of soil remediation by the use of solar thermal energy, the focus is on the light pollution components that are cleaned up at a temperature level that solar heat can deliver.
In general, the lighter a contaminant component is, and the lower the boiling point, the more susceptible it is to purification with heat.
The following relevant light contamination components are very often seen in connection with pollution cases:

- Chlorinated solvents and degradation components, including, in particular, Tetrachloroethylene, Trichloroethylene, Dichloroethylene (Trans or Cis), Vinyl chloride, and others.
- Petroleum products (hydrocarbons), especially light oils such as benzene (C6-C12), turpentine (C9-C12), and perhaps diesel (C9-C21)
- BTEX (short for Benzene, Toluene, Ethylbenzene and Xylenes). These are generally also seen in connection with fuel contamination

The lightest contaminants are the most volatile, and thus there is a great risk that they penetrate the groundwater and contaminate drinking water resources. In the same way, if the contaminants are located under buildings, there is a risk that they evaporate into buildings where they affect the indoor climate and pose a health risk to people.
Heavy contaminants, such as heavy metals, tend to largely remain where they are and only leach very slowly, and they are thus not as critical as light contaminants. Less mobile pollutants will, therefore, rarely be seen in larger depts. Heavy contamination is, therefore, often dug up and cleaned off-site.
From the ten generational pollutions, at least four cases are contaminated with chlorinated solvents and could potentially be cleaned by a solar heating system:

- Grindstedværket, 7200 Billund: Large generational pollution with many different substances, several of which could potentially be purified at low temperatures, such as benzene, cyanide, and chlorinated solvents.
- Lundtoftevej 150-160, 2800 Kgs. Lyngby: Industrial site with production of white goods, including metal processing. Large generational pollution with chlorinated solvents and large dispersion in the groundwater.
- Naverland 26A-B, 2600 Glostrup: Industrial site with large generational contamination with chlorinated solvents and an approx. 2-kilometer-long pollution plume in the groundwater.
- Vestergade 5 v/Skudelev, 4050 Skibby: Former metal products factory site with generational contamination with chlorinated solvents. The site is partially cleaned up in the worst areas in several rounds, but the contamination is still present in soil and groundwater.

3.2 Sources and contamination area

In general, pollution originates from surface spills, e.g., industrial emissions and agricultural production, or leaks in sewers, etc. The source area will thus often be relatively close to the ground (about 0-6 meters), and then the pollution will decrease with depth. Depending on how volatile the contaminants are, they will have a different vertical distribution. The vertical distribution will

also depend largely on the geology, hydrological conditions, and whether the substance is water-soluble. Low-permeable clay soil layers, combined with a high groundwater table contaminated with low water-soluble oil, will, for example, result in a smaller vertical distribution.
“Soil pollution cases to more than 25-30 meters are rarely seen, but they may exist. In most cases, the prevalence is less than 10 meters” says Sebastian Andersen, Environmental Engineer at Norconsult Denmark A/S.
The following is an example of contamination investigated down to about 20 meters below the terrain. The terrain is around elevation +8.5 meters above sea level. The upper 8-10 meters of soil is moraine clay, after which the soil type is sand. The mass distribution down through the soil layers for the chlorinated solvent Trichloroethylene (TCE) is shown in Table 3 and in Table 4 the distribution of diesel oil (THC) is shown. The pollution source is most likely a sewer located about 2.5 meters below the soil surface. The volatile and highly water-soluble TCE is present in almost evenly large quantities many meters below the source, whereas >90% of the less volatile and hydrophobic THC is detained in the clay layer and hence remains close to the location of the spill.

Table 3: Mass distribution of Trichloroethylene (TCE) in different depth ranges [7].

Elevation [m DRV90[1]]	Mass TCE [kg]	Share of total mass TCE [%]
+8.4 to +3.5	13.9	8.4
+3.5 to +2.5	35.9	21.7
+2.5 to +1.5	43.1	26.0
+1.5 to -0.5	35.7	21.5
-0.5 to -2.5	15.2	9.2
-2.5 to -4.5	12.0	7.2
-4.5 to -6.5	3.6	2.2
-6.5 to -8.5	3.5	2.1
Deeper than -8.5	2.9	1.8
Sum	165.8	100

Table 4: Mass distribution of diesel oil (THC) in different depth ranges [7].

Elevation [m DRV90[1]]	Mass THC [kg]	Share of total mass THC [%]
+8.4 to +3.5	5250.6	90.1
+3.5 to +2.5	281.7	4.8
+2.5 to +1.5	49.5	0.8
+1.5 to -0.5	55.2	0.9
-0.5 to -2.5	54.4	0.9
-2.5 to -4.5	57.7	1.0
-4.5 to -6.5	35.9	0.6
-6.5 to -8.5	11.7	0.2
Deeper than -8.5	29.8	0.5
Sum	5826.5	100

[1]DRV90=Danish Vertical Reference 1990 (Denmark's new height level, which was introduced on 1 January 2005 and replaced the old Danish Normal Zero, DNN)

3.3 Cleaning options

There are many different cleaning options, depending on the nature of the contamination. The different remediation methods can be divided into the following four categories [8]:

- Physical remediation (incl. thermal desorption, TD)
- Chemical Remediation
- Bioremediation
- Joint remediation

Excavation is by far the most common redemption method and the one that everything else is compared to when looking at costs. However, excavation will be too expensive at great depths, especially if there is no room for digging and the groundwater table is high. Further, excavation is only an option where residual contamination can be accepted. In general, at depths greater than 5-7 meters, in-situ solutions are considered [9].

The most common method of thermal in-situ purification is In-Situ Thermal Desorption, ISTD. With ISTD, a network of thermal heat wells is made, which are equipped with electrically powered heaters at the depths from where the contamination is to be cleaned. The wells are set at a distance so that the average temperature between the wells is higher than the boiling point of the pollution, typically 100 °C so that an even clean-up over the entire area is achieved. How close the boreholes are located depends on the geology and the thermal properties of the soil (thermal conductivity, density, heat capacity, etc.). Typically, the heat wells are placed at a distance of 1-3 meters. On top of the contaminated soil volume, a barrier is laid, e.g., a layer of concrete, to prevent the evaporated contamination from escaping, and possibly a layer of insulation to reduce heat losses.

With the boreholes, the contaminated soil volume is heated until the contamination evaporates up through the soil layers. Between the heat wells, some extraction wells are placed. These are connected to a vacuum ventilation system, which then sucks the evaporated contamination out of the ground.

The polluted air is led to a water separator and then to a filter, e.g. carbon, and finally, it is discharged into the ambient air. Likewise, the water separator is equipped with a filter, e.g. carbon, after which the water is led to the sewer or re-filtered to the ground, depending on the project.

“A traditional ISTD typically takes about 9 months from installing the plant and boreholes until the plant is dismantled again,” says Sebastian Andersen, Environmental Engineer at Norconsult Denmark A/S.

The time frame for the cleaning process could look something like this:

- Establishment of heat wells and installation of plants. (approx. 1.5 months)
- Heating to the operational temperature. (approx. 3-4 months)
- Once the operational temperature is reached, the plant keeps running for a few months. (approx. 2-3 months)
- Continuously in the process and when the soil is considered clean, a number of wells are made from which soil and water samples are taken to document the remediation effect. The final measurements are taken after the operation has been stopped to assess whether there is a rebound effect (approx. 1 month).
- The plant is taken down. (approx. 0.5 months)

Groundwater is not an obstacle to ISTD remediation, but energy consumption will increase as the water has a cooling effect.

4. Solar assisted soil cleaning

It is here investigated how solar collectors can be utilized to produce heat for a clean-up of contaminated soil. It will, therefore, typically be remediation projects that are made to protect the groundwater resource, typically the older pollutions that fall into this category, for example, generational pollution.
The heavier the contaminant components, the less they will react to a temperature change of the magnitude experienced by solar heating systems.
Solar heating will be suitable for highly volatile contaminant components, such as cyanide, chlorinated solvents and degradation products, MTBE, BTEXs, and the lightest oil fractions, such as gasoline or turpentine (C5-C12).
Solar heating will be less effective for cleaning up the medium-heavy contaminant components, such as medium and heavy hydrocarbons, such as diesel, heating, and hydraulic oil, as well as tar substances (PAHs). For the purification of these substances, solar heat may act as an assistant to another remediation method, e.g., bioremediation.
Solar heat will eventually be very little useful for very heavy polluting components, such as heavy metals.
In general, it must be assumed that the closer the boiling point of the substances is to the operational temperature of a solar heat storage, the better the method will be suitable for purification.
Since solar heat is an alternating energy source, the purification period using only solar heat must be expected to be long because it takes a long time to reach the final temperature. This is less true if solar heating is used in combination with, for example, In-situ thermal desorption, ISTD, where the solar heat is intended to preheat the soil so that energy consumption can be saved by ISTD.
A low-temperature solution will thus be less suitable for remediation projects where the contamination poses an acute risk to human safety and health and thus requires a short remediation time.
In the case of very light contaminant components, it will be possible to achieve the boiling point of the contaminant component with solar heat, whereby the substance will transition to gaseous form and evaporate up through the soil layers, after which it can be sucked out of the soil.
Although for some pollutants it is not possible to achieve a temperature that provides complete evaporation of the pollutants by solar heating, a temperature change will cause a change in the phase distribution of the substances. For example, the water solubility of tetrachloroethylene will increase by >100% with a temperature increase from 10 to 90°C [10]. The same applies to the vapor pressure of the substances and thus their tendency to transition to gaseous form.
In this way, solar heating can act as a contributing factor in combination with other remedial measures, such as a remedial pumping/forced leaching of a soil-bound contaminant in a water-saturated zone or a vacuum venting of a soil-bound contaminant in the unsaturated zone.

4.1 Theoretical investigation of solar remediation

Figure 6 shows an initial conceptual model of the site, Lundtoftevej 150-160 [11]. The site is polluted with volatile organic components, which evaporate at a temperature of 100 °C [12]. The source of pollution is located at or just below the soil surface. Above the groundwater table in the secondary aquifer, the soil is unsaturated. The dark green areas indicate the pollution source areas and the highest pollution concentration, and the light green areas indicate the vertical spread of the pollution and a lower pollution concentration. In the same way, the darker blue colour in the groundwater indicates where the pollution concentration is the highest. Pollution first seeps down through the unsaturated soil, after which it seeps into the aquifers. The spread in the unsaturated zone is mainly vertical, while it is both vertical and horizontal in the aquifers, where it flows with the groundwater and threatens surrounding streams and drinking water wells.

The aim of the investigation is to theoretically investigate if solar heating can be used to heat the unsaturated zone to at least 100 °C This approach will stop the pollution from continuing to be leached into the groundwater which it will for many years if it remains in the ground. During the ISTD remediation with solar energy, measures to stop the pollution plume in the groundwater should also be taken. After remediation of the unsaturated zone, the remediation of the pollution plume in the groundwater can also be completed.

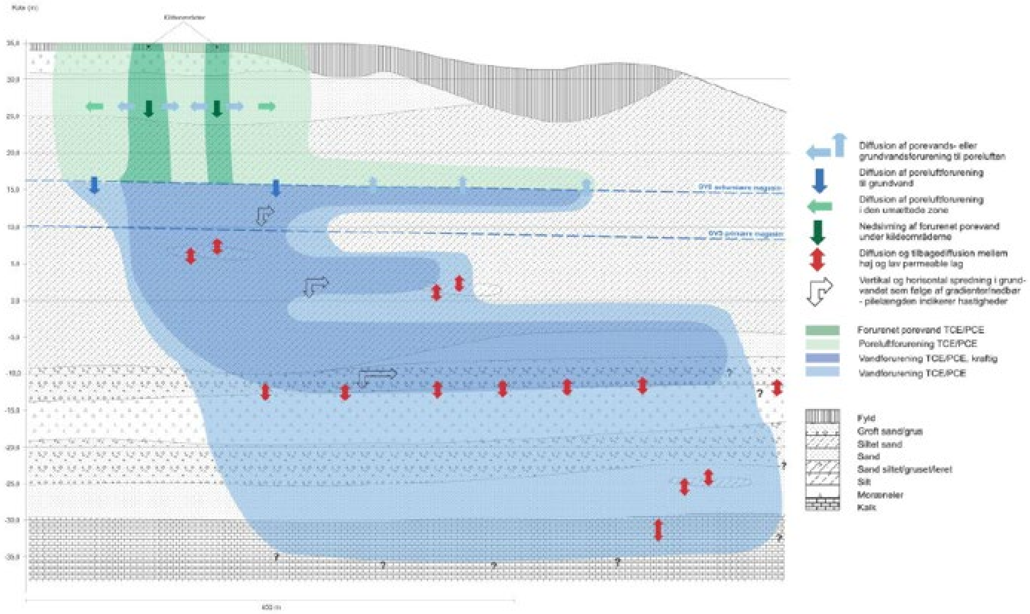

Figure 6: Initial conceptual model of the site, Lundtoftevej 150-160 (Hovedrapport Lundtoftevej)

To simulate the temperature in the unsaturated ground during heating with solar energy, the Trnsys model shown in Figure 7 is used. The parameter settings for the model are listed in Table 5 and Table 6.

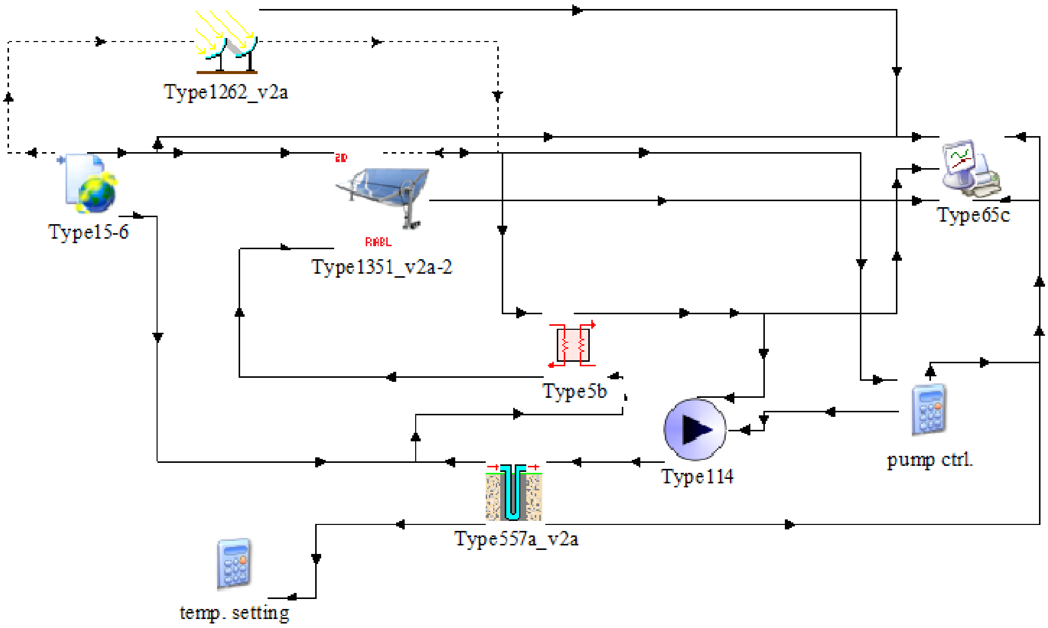

Figure 7: TRNSYS model

The two-axis tracking parabolic trough solar collector rows are oriented North-South. The multiple series of three solar collectors are connected in parallel to form the solar collector field. The distance between the solar collector rows is 9 meters, and shading between the collector rows is considered. The heat transfer fluid is a synthetic blend of dibenzyl-toluene isomers with an operating temperature of up to 350 °C. The volume flow rate is varied between a maximum and a minimum to meet a collector outlet set point of the solar collector fluid of 150 °C. The pump in the ground loop is only started when the outlet temperature from the solar collector exceeds 110 °C. Meteonorm weather data for Copenhagen is used. The solar collector utilizes beam solar irradiance and a minimal fraction of the diffuse irradiance.

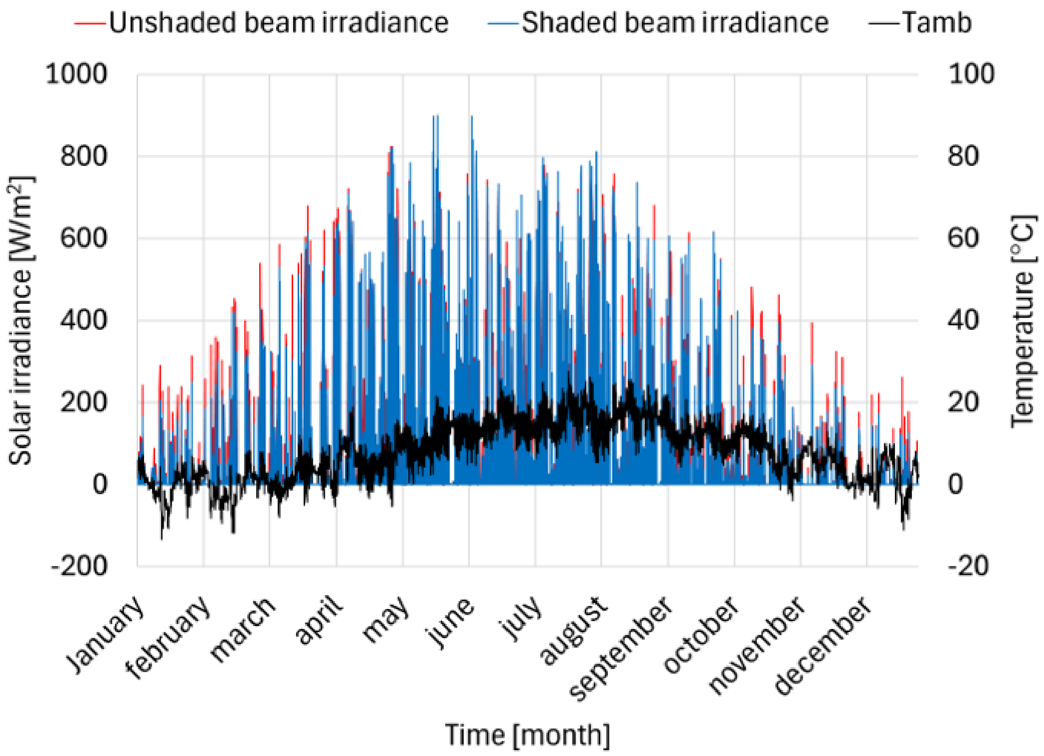

Figure 8: Solar irradiance on the solar collector and ambient temperature

Figure 8 shows the unshaded and shaded beam solar irradiance and the ambient temperature during the year. It is clear to see that there is more shading during the winter months, where the solar elevation is low, compared to the summer months, where the solar elevation is high.

For all the simulations, the soil volume and soil parameters are kept constant as well as the solar collector type and distance between the solar collector rows. The parameter variations include the solar collector area, number of boreholes, and with and without insulation on top of the soil volume with the boreholes.

In the simulation model, with insulation on the top of the ground storage, the temperature just below the insulation is modelled as the average ground storage temperature, while the temperature on the top of the insulation is the ambient temperature. In the simulation model without insulation on the top of the ground storage, the temperature on the top of the ground storage is the ambient temperature.

Table 5: Parameters used for modelling the borehole storage with TRNSYS Type 557

Parameter	Value	Unit
Storage volume	45000	m^3
Borehole depth	18	m
Borehole diameter	0.3	m
Number of radial soil subregions	4	-
Number of vertical soil subregions	10	-
Fill thermal conductivity (dry sand)	0.972	kJ/(h·m·K)
Outer/inner diameter of U-tube pipe	0.032/0.025	m
Center-to-center distance of U-tube pipe	0.075	m
Pipe thermal conductivity	1.8	kJ/(h·m·K)
Storage thermal conductivity (moist sand)	2.88	kJ/(h·m·K)
Storage heat capacity (moist sand)	1400	kJ/(m^3·K)
Number of serial boreholes	10	-
Volume flow rate per serial of boreholes	20	l/min
Borehole distance - 500 boreholes	2.4	m
Borehole distance - 400 boreholes	2.7	m
Borehole distance - 300 boreholes	3.1	m

Table 6: Parameters used for modelling of the North-South axis tracking parabolic trough solar collector with TRNSYS Types 1351 and 1262

Parameter	Value	Unit
Collector length	6.8	m
Collector width	4.5	m
Collector area	30.6	m^2
Row distance	9	m
Optical efficiency	0.8	-
1st order loss coefficient	0.36	kJ/(hr·m^2·K)
2nd order loss coefficient	0.00072	kJ/(hr·m^2·K^2)
Concentration ratio	67	-
Collector thermal capacity	0.7	kJ/(m^2·K)
Fluid specific heat	1.8	kJ/(m^2·K)
Fluid density	987	kg/m^3
Number of serial collectors	3	-
Maximum volume flow rate per collector row	2.8	l/(min·m^2)
Minimum volume flow rate per collector row	0.2	l/(min·m^2)
Set point collector outlet temperature	150	°C
Inner diameter of absorber tube	0.057	m

Figure 9 to Figure 14 show the outlet temperature from the solar collector field and the average soil temperature as a function of the simulation months. The results are shown for different combinations of numbers of solar collectors and boreholes. Further, the results are shown with and without insulation on the top of the borehole storage volume. The time it takes the average soil temperature to reach 100 °C depends strongly on the solar collector area and whether there is insulation on the top of the borehole. The outlet temperature from the solar collector field depends strongly on the number of boreholes. The more boreholes, the lower the outlet temperature. The heat loss from the parabolic trough solar collector is very low, and therefore, the temperature level of the solar collector does not significantly influence the amount of produced energy. With fewer boreholes also the temperature level in the boreholes increases compared to a system with a larger number of boreholes. However, the energy transferred from the solar collector to the boreholes is the same for the same solar collector area regardless of the number of boreholes. The simulations show that it is possible to heat the soil volume to 100 °C with solar energy in about 2 years and maintain the high temperature for 2-3 months with 78 solar collectors corresponding to a solar collector area of 2386.8 m^2, and insulation on top of the borehole storage volume. With 60 solar collectors corresponding to a solar collector area of 1836 m^2, and insulation on top of the borehole storage volume, the soil volume is heated to 100 °C in about 3 years. With 39 solar collectors corresponding to a solar collector area of 1193.4 m^2 and insulation on top of the borehole storage volume, the heating period is about 4 years. The number of boreholes determines the temperature level in the solar collector and the temperature should stay below the maximum fluid temperature of 350 °C. Consequently, for fast heating of the soil volume, 78 solar collectors combined with 400 boreholes, and insulation on top of the borehole storage volume should be used while 39 solar collectors combined with 300 boreholes, and insulation on top of the borehole storage volume can be used if the remediation time can be long. Without insulation on the top of the borehole storage volume, the heating time is much longer.

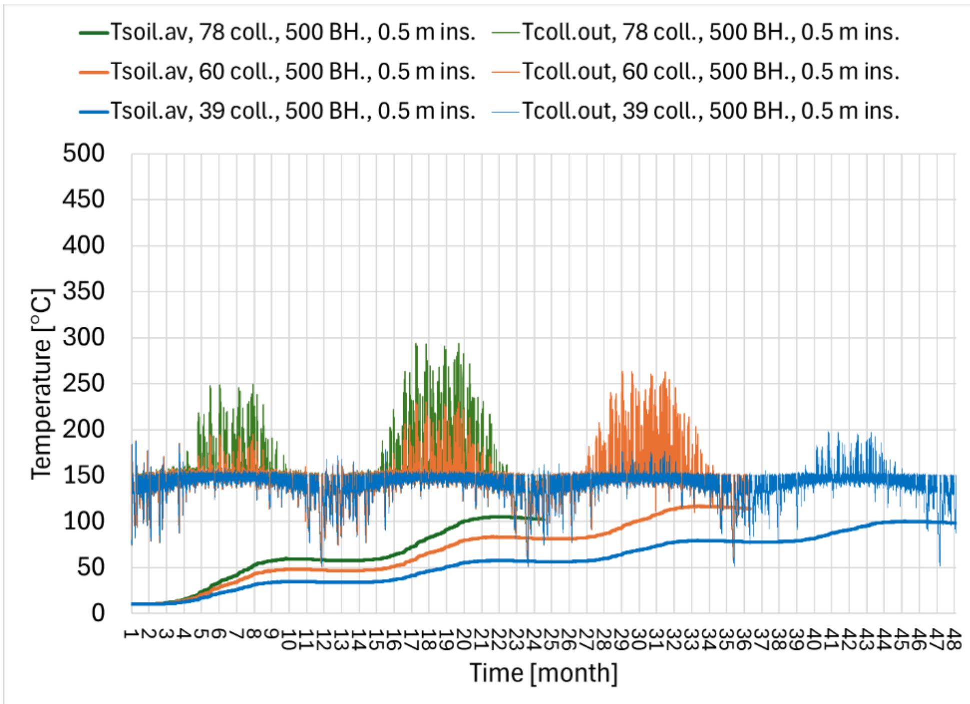

Figure 9: Solar collector outlet and soil temperatures with different solar collector areas and 500 boreholes with insulation on the top

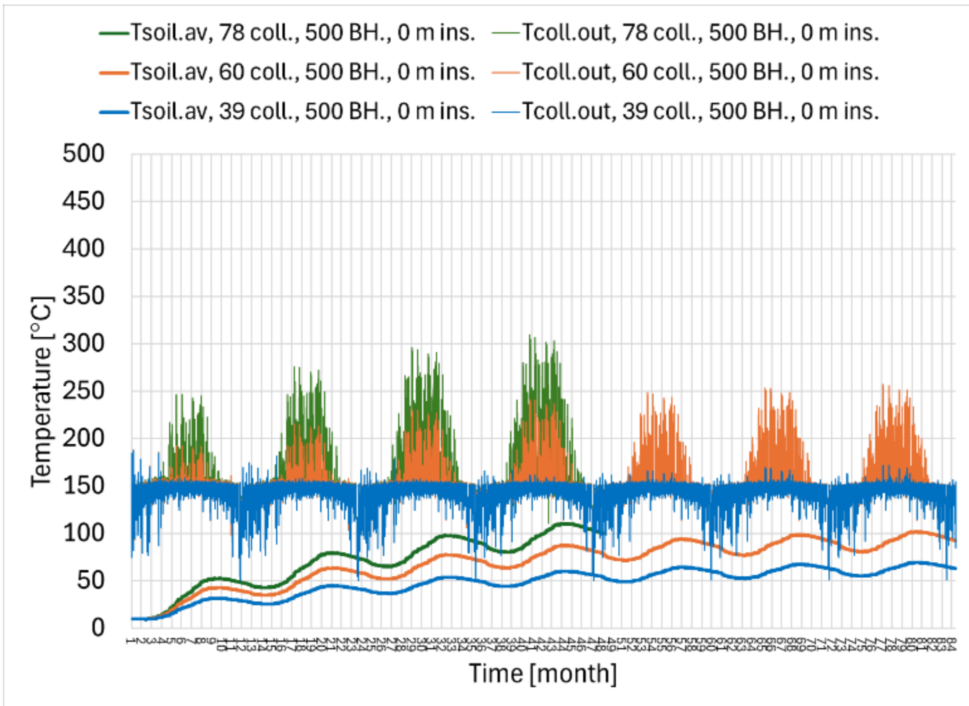

Figure 10: Solar collector outlet and soil temperatures with different solar collector areas and 500 boreholes without insulation on the top

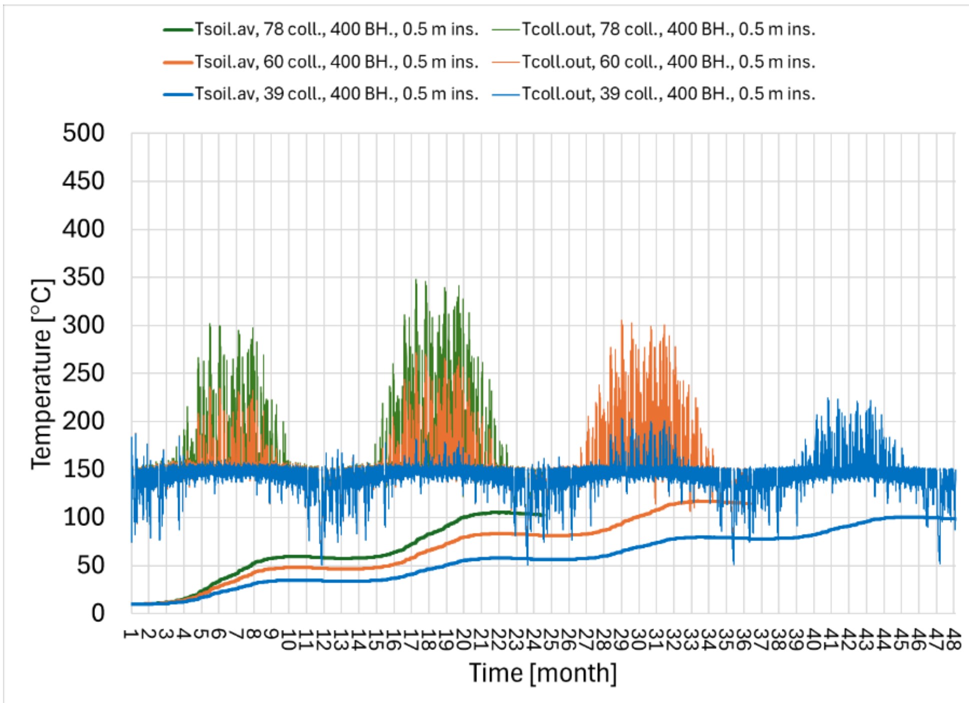

Figure 11: Solar collector outlet and soil temperatures with different solar collector areas and 400 boreholes with insulation on the top

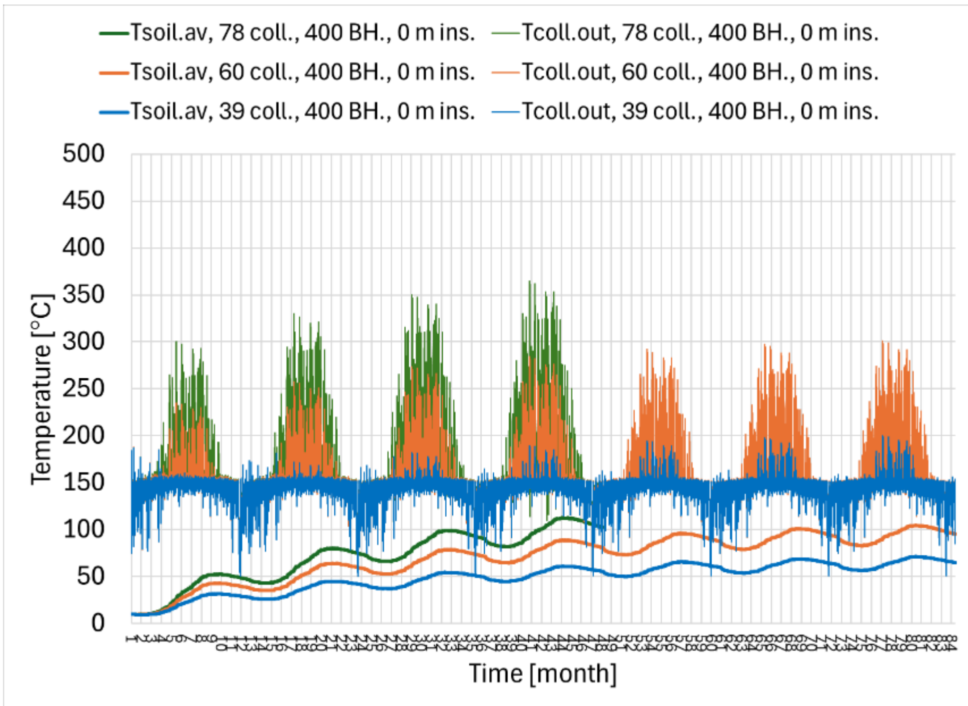

Figure 12: Solar collector outlet and soil temperatures with different solar collector areas and 400 boreholes without insulation on the top

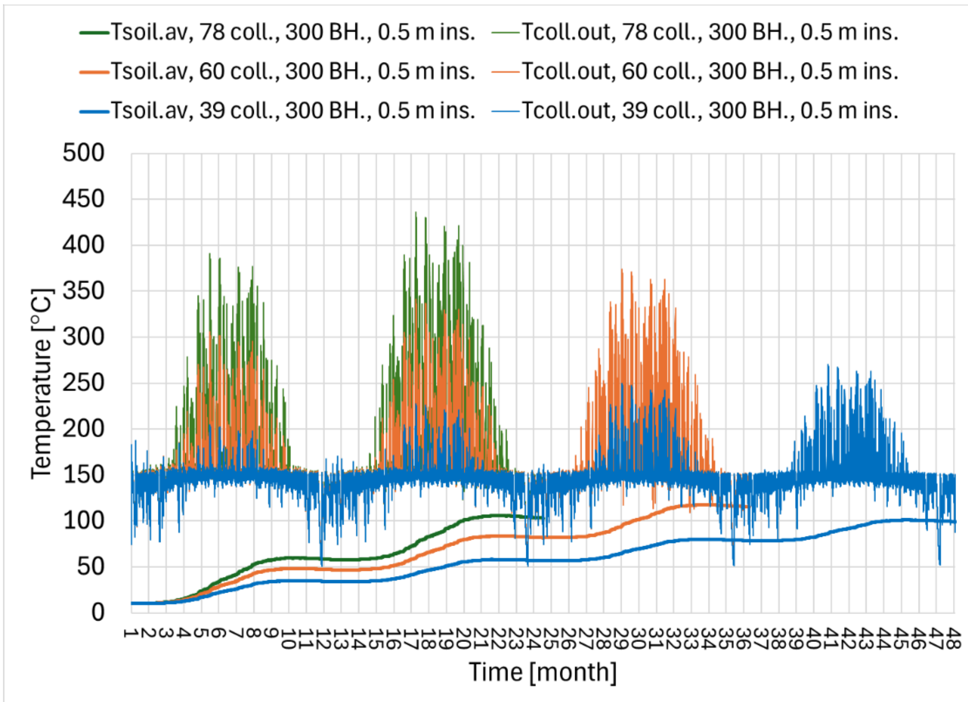

Figure 13: Solar collector outlet and soil temperatures with different solar collector areas and 300 boreholes with insulation on the top

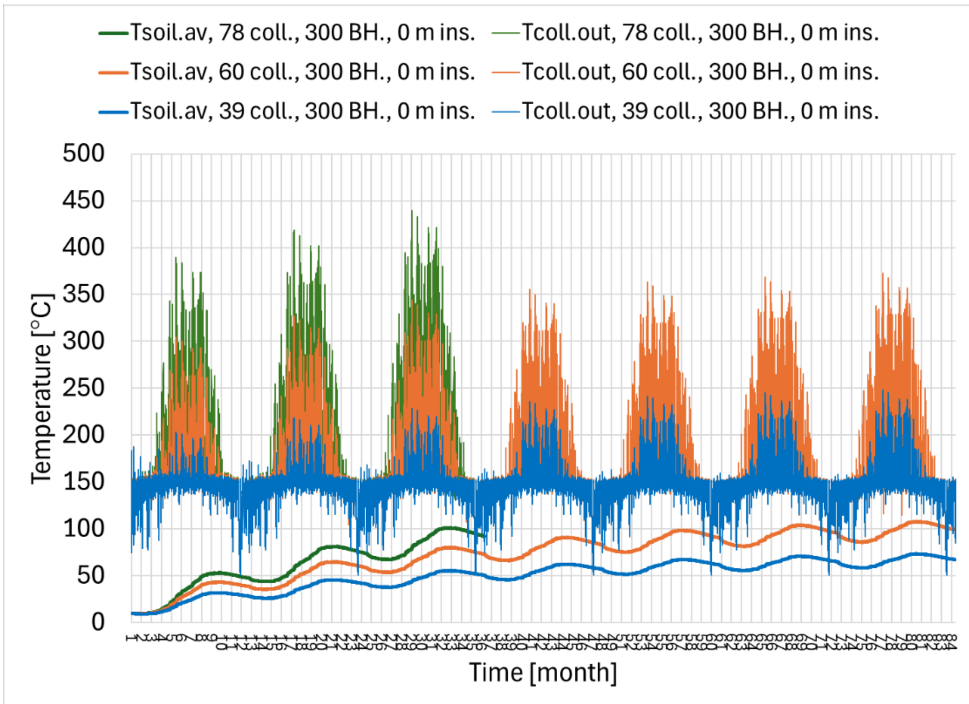

Figure 14: Solar collector outlet and soil temperatures with different solar collector areas and 300 boreholes without insulation on the top

4.2 Conversion from clean-up plant to borehole thermal energy storage

The clean-up site investigated in Trnsys has a volume of 45,000 m³. If this storage operates as the 4 borehole thermal energy storage systems reported in the HEATSTORE project, see Table 2, the estimated capacity of the borehole energy storage will be approximately 568 MWh, taking into account the much lower efficiency reported in the project. This is estimated as an average across the different temperature levels in the 4 reported borehole storages in HEATSTORE. If this converted storage is operated at a higher temperature level the expected capacity will increase, but also the heat loss from the system, which is accounted for the discrepancy in the expected performance and the actual performance in the HEATSTORE project.

A capacity of 568 MWh corresponds to the annual thermal energy demand of around 30 single-family homes built from the 1980s onward or renovated houses from the 1970s, each consuming 19 MWh per year. Alternatively, it could supply 124 newly built single-family homes that meet the energy demand restrictions outlined in the Danish building regulations BR18.

When the clean-up of the soil has been completed the tubes can be reused for storage purposes directly. The synthetic blend of dibenzyl-toluene isomers used as heat transfer fluid during the clean-up could be replaced with a propylene-glycol mixture, since it is no longer necessary to operate at high temperatures as seen during the clean-up period. The synthetic blend of dibenzyl-toluene has a higher cost than propylene-glycol and would bring more value if reused in other clean-up sites. The same applies to the tubes; however, a viable method for extracting and replacing them efficiently needs to be developed.
The site modeled at Lundtoftevej 150-160 is specifically designed to target contaminated soil. If feasible, and if the groundwater level is significantly deeper, the boreholes could initially be

drilled deeper, up to 5 meters above the groundwater table. This would increase the size of the borehole storage after the clean-up process but will also extend the clean-up period because additional soil must be heated. It would be necessary to investigate whether drilling past the contamination poses a risk of additional spread of the contamination

The potential is to convert a clean-up plant into a thermal energy storage. This would allow for thermal energy storage in populated areas, which could either increase the use of renewable energies such as solar thermal collectors or extend the reach of district heating networks in the outskirts of the existing networks.

5. Conclusion

This investigation has explored the potential of repurposing soil cleanup plants into borehole thermal energy storage facilities, offering a dual benefit of environmental remediation and sustainable energy storage. The investigation indicates that contaminated sites, once decontaminated using solar thermal energy, can be transitioned into borehole thermal energy storage systems, enabling energy storage in urban areas where land availability is limited.

The TRNSYS analysis shows that the integration of solar thermal energy in soil remediation is feasible, particularly for volatile organic compounds that can be treated at moderate temperatures. However, challenges remain in optimizing efficiency, as observed in previous BTES projects where heat losses exceeded expectations due to construction methods, groundwater flow, and discrepancies between modeled and actual conditions. Addressing these factors through improved insulation, borehole design, and system integration will be important for increasing storage efficiency.

After the cleanup process, replacing the expensive synthetic heat transfer fluid with a propylene-glycol mixture would further optimize cost-effectiveness. Additionally, the potential for reusing tubes in future cleanup projects highlights the importance of developing efficient extraction and reinsertion methods.

By converting cleanup sites into borehole thermal energy storage, urban areas can benefit from localized energy storage, reducing reliance on fossil fuels and enhancing the efficiency of district heating networks. This approach not only supports the expansion of renewable energy sources, such as solar thermal collectors, but also aligns with broader sustainability goals by repurposing land that would otherwise remain unused. Future research should focus on refining borehole configurations, improving heat loss prevention strategies, and ensuring regulatory compliance to facilitate wider adoption of this innovative energy storage solution.

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