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High-Temperature Thermal Energy Storage for electrification and district heating

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ABSTRACT

The present work describes development of a High Temperature Thermal Energy Storage (HT-TES) system based on rock bed technology.

A selection of rocks was investigated by thermal analysis in the range 20-800 ˚C. Subsequently, a shortlist was defined primarily based on mechanical and chemical stability upon thermal cycling. The most promising material consists of basalt, diabase, and magnetite, whereas the less suited rocks contain larger proportions of quartz and mica.

An HT-TES system, containing 1.5 m^3 of rock pieces, was constructed. The rock bed was heated to 600 ˚C using an electric heater to simulate thermal charging from wind energy. After complete heating of the rock bed it was left fully charged for hours to simulate actual storage conditions. Subsequently the bed discharging was performed by leading cold air through the rock bed whereby the air was heated and led to an exhaust.

The results showed that HT-TES has a role to play in future, sustainable energy systems. A cost benefit analysis based on projected electricity prices for the Scandinavian region in 2035 showed that a business case is achievable.

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KEYWORDS:

Thermal energy, rock bed, storage, minerals, thermal properties, economy.

BACKGROUND

The member states of the European Union have firm targets for changing their energy supply from fossil and nuclear sources to clean and renewable energy sources mainly in the form of wind and solar power as well as biomass. This change - and the inherent problems about timing mismatches between demand and supply of energy - has been widely discussed in technical reports [1], [2].

Denmark currently has a large amount of coal and gas fired combined heat and power (CHP) plants, which will be phased out by 2050 [3] as required for the transition to renewable energy sources. In 2017 43% of the Danish electricity demand was covered by wind power [4] [5], but the installed wind power capacity is expected to become 2-4 times as large, [6]. To store the energy from this supply new methods are investigated. In this study we present the preliminary results of storing heat in rocks using electricity from wind turbines. The stored heat can be released to convert water into steam to drive a turbine, which produces electricity. Waste heat will be used for district heating. Other groups have studied and developed similar technologies and for more information on such previous work please consult [7], [8], [9] or [10].

MATERIALS AND METHODS

The thermal storage material needs to fulfill certain criteria including high thermal conductivity, high specific heat capacity, high density and thermal stability. We have tested 10 different North/Central European rocks (Table 1) that are already traded by Danish and German aggregate retailers. Their dilatational and calorimetric properties (Figure 1 and Figure 2) were determined, and all rocks underwent heating experiments where they were repeatedly heated and cooled between ambient temperature and 600 ˚C in an oven with atmospheric air.

Table 1. Overview of rock materials subjected to thermal analysis (DSC and dilatometry) in the present work.

Commercial name	Prel. petrological classification	Company contacted
Magnadense	Magnetite	LKAB Minerals
Telnes Ilmenite rock	Ilmenite-norite/gabbro	Kronos
Hyperite	Gabbro/norite	Dansk Natursten
Hircshentanz	Basalt	Basalt AG
Hühnerberg	Basalt	Basalt AG
Pauliberg	Basalt	Basaltwerk Pauliberg
Hardeberga	Sandstone/quartzite	Dansk Natursten
Søndre Sandby	Quartsite	NCC
Dansk Natursten	Granite	NCC
Rønne Granitbrud	Granite	NCC
Swedish Diabase		

It was found that unconstrained thermal expansion from ambient temperature to 600 ˚C causes linear expansion in the range of 1-2% followed by contraction upon subsequent

cooling in every thermal cycle. This will potentially cause changing packing arrangements in the rock bed and could generate a substantial load on the containment walls, also known as thermal ratcheting. Furthermore, different expansion coefficients of the individual minerals in a rock may cause the rock to become weakened and ultimately develop internal fractures and disintegration.

The results of the described thermal analyses indicated a number of characteristic behaviors. Firstly, some samples contained considerable amounts of quartz and the well-known reversible α- to β-quartz transformation at 573 °C [11] was seen in these measurements. This transformation is accompanied by a linear expansion which is not desirable for materials in the present application, since as little expansion as possible is optimal.

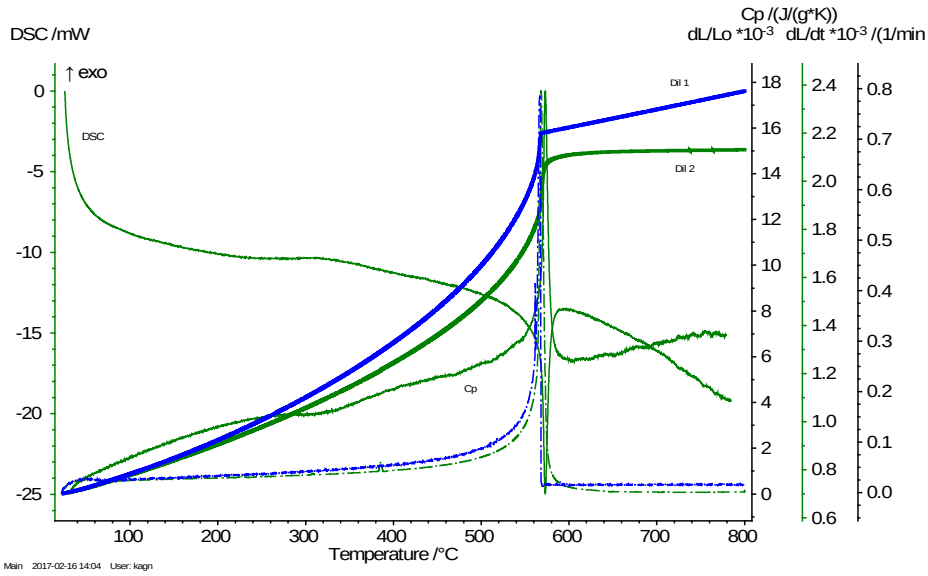

Figure 1. Södra Sandby (Quartzite) – Dilatometry. Bold blue and green curves show expansion for first and second heating respectively. Total linear expansion of 1.5 to 1.8 percent can be seen.

Secondly, it was observed in some cases that during mechanical preparation of samples for thermal analysis, the heated sample was found to be more fragile than the non-heated. The microscopy images reveal that alteration (reddening) was restricted to the rims of individual crystals. Despite several weeks of heating, the alteration reaction appears to be incomplete. The same can therefore be expected for the mechanical degradation.

Thirdly, all samples except one showed heat capacity, C_p, starting at 0.6-0.8 J/(g*K) and rising to 1-1.4 at 800 ˚C. Importantly, repeated calorimetric measurements after the samples were heated in the oven showed lower heat capacities than unheated samples (Figure 2). This implies that caution is needed when applying calorimetry to estimate energy density for HT-TES application: Calorimetry based on fresh samples may lead to over-estimated heat capacity by 20-30 %.

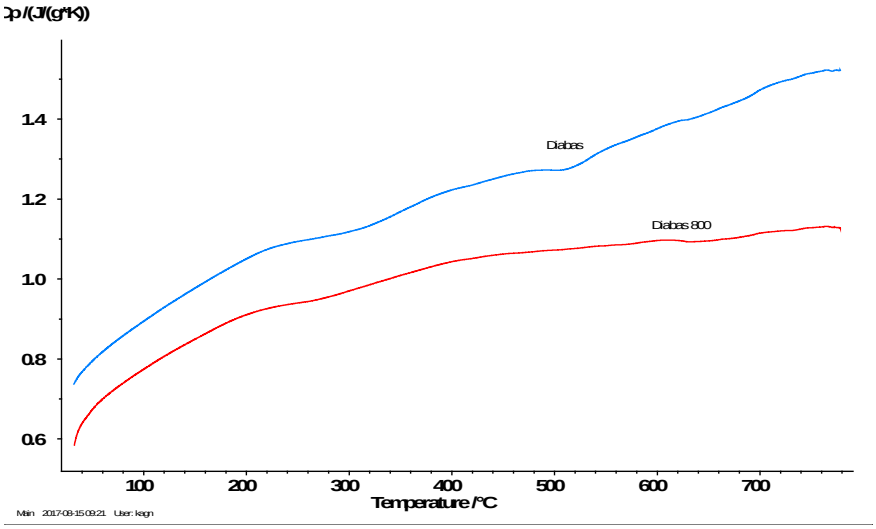

Figure 2. Calorimetry (DSC) results for Swedish Diabase. The blue curve was measured for the raw material, whereas the red curve was obtained for the second temperature scan on the sample after it was heated repeatedly in an oven for two weeks.

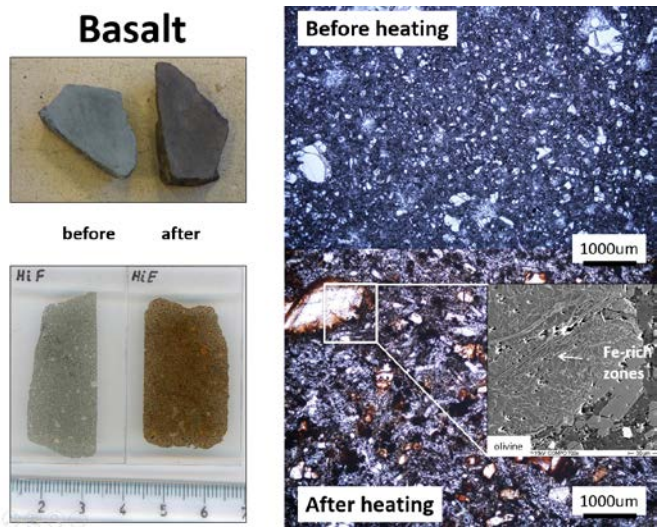

Figure 3. Images of a basalt sample before and after heating. Upper left panels show macroscopic samples (ca. 10 cm in size), and lower left shows thin sections from the respective samples. Reddening due to oxidation is clearly visible. Right panels show microscopy images of the thin sections. The grey tone inset shows a secondary electron image (SE) of part of a large olivine crystal.

After the different experiments it turned out that the magnetite, the basalt samples, and diabase samples appear to be suitable candidates for a rock bed facility. They do not contain quartz, mica or other 'weak' minerals that degrade or change crystal structure during heating. They also have good thermal properties. For the pilot-scale system of an HT-TES setup we chose Swedish Diabase sieved between 20 mm and 40 mm. In most cases, the presence of iron in olivine and pyroxenes caused oxidation during heating (Figure 3). This appeared to be associated with mechanical degradation (loss of strength) after long-term heating experiments. Oxidation was also observed along grain boundaries and small cracks in pure

magnetite rocks (commercial name: magnadense), but here this effect did not appear to cause major loss of strength.

Heat capacities at 500 ˚C where generally between 0.9 and 1.4 J/(g·K) for all rocks that were measured while fresh (e.g. not pre-heated). This is in fine agreement with earlier findings [12]. Since volumetric storage capability is of primary interest for HT-TES, densities were also estimated to range between 2.7-3.1 g/cm^3 for all silicate-rich rocks [12], whereas magnadense (magnetite-rich rock) had a density of 5.1 g/cm^3 [12]. Therefore the volumetric thermal capacity of magnetite is ca. 5 J/(K·cm^3) at 500 ˚C, whereas it is only ca. 3-4 J/(K·cm^3) for the other studied samples. It was further noted that heat capacities decreased substantially when measured after pre-heating the rocks for several weeks (Figure 3), because calorimetry curves of fresh samples reflect chemical alteration processes at varying degree. A systematic study on this has not yet been conducted, but observations imply that calorimetry measurements on fresh samples do not necessarily reflect the long-term thermal properties of the rocks in long-term HTES operation.

EXPERIMENTAL SETUP

To test and monitor the temperature distribution, airflow, and efficiency of an HT-TES system an experimental facility was established, containing approx. 1.5 m^3 of rocks. A diagram of the setup is shown in Figure 4 and drawings as well as a photo are shown in Figure 5.

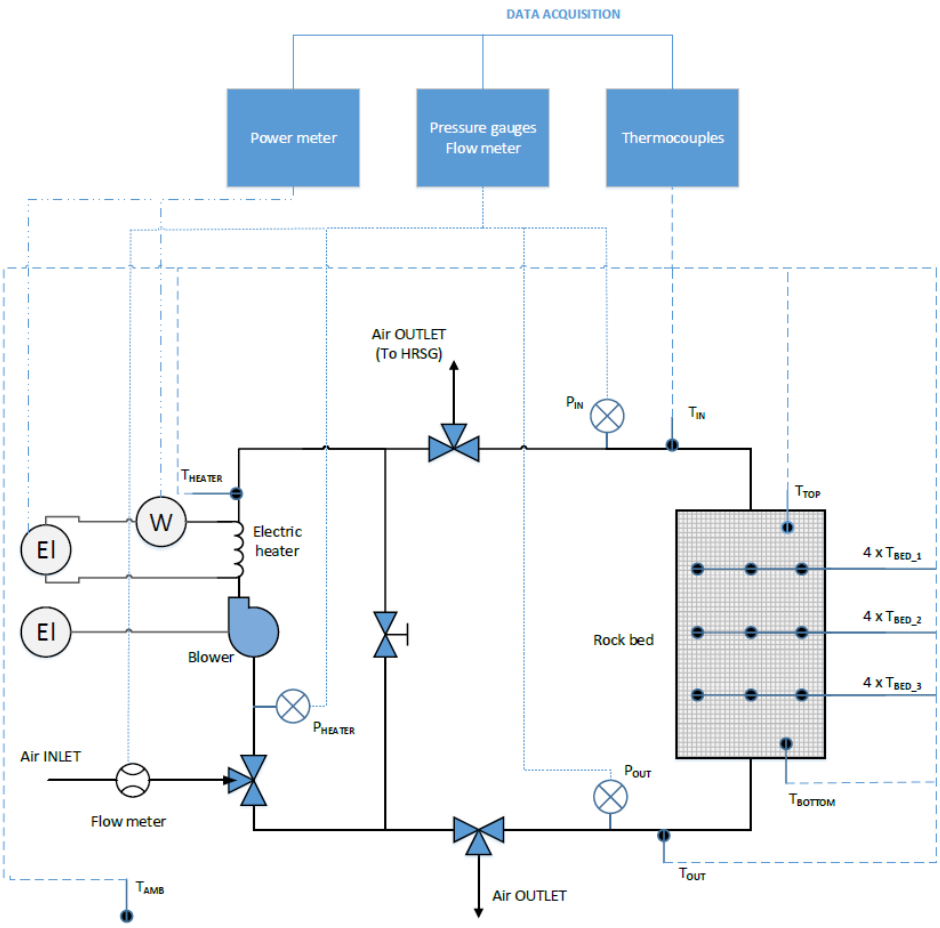

Figure 4. Diagram of the experimental setup. El: electricity supply, W: power meter, P: pressure gauges. T: thermocouples.

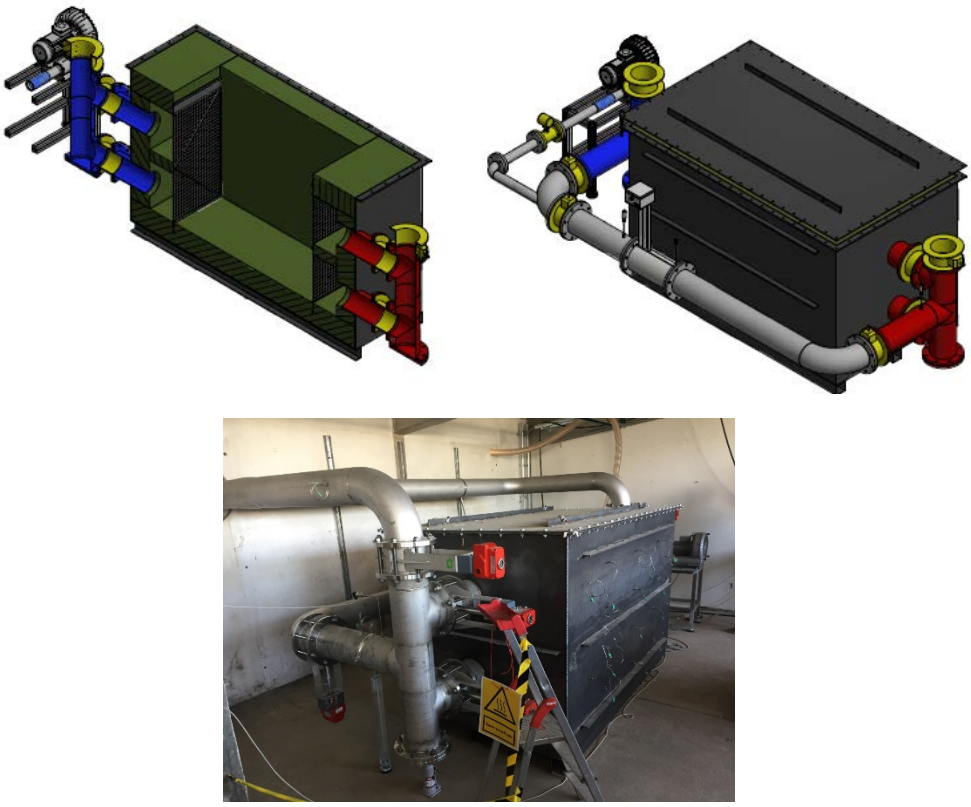

Figure 5. Top: a solid and cross-section CAD models of the HT-TES system. The fan is seen in the upper left and the heater is seen in the right figure on the front tube. Bottom: a photo of the facility.

The rock bed itself is 1 m by 1 m in cross section (referring to the air flow direction) and 1.5 m long. As can be seen in Figure 4, atmospheric air is electrically heated to a preset temperature and blown through the rock bed, heating up the stones. After a preset charging period the store is filled and can be left at high temperature, thereby storing the thermal energy. Retrieval of the energy is done by reversing the airflow. Ambient air is led into and through the rock bed and the airstream is heated by the stones to a high temperature when it exits the bed. If the hot air leaving the rock bed is above about 530˚C it may be used to drive a steam turbine and thus (re-)generate electricity. All valves, tubings etc., exposed to hot air in the setup, can withstand 600˚C.

The airflow velocity through the rock bed can be regulated and is controlled by the air temperature, the maximal heater power, the maximal available pressure of the blower and the pressure drop over the rock bed. The maximally available airflow of the employed blower is 375 and 250 m^3 per hour at pressure drops of 0 and 23 kPa, respectively. During the experiments, the fan usually operates at pressure drops in the range of 0.05 - 1 kPa. The power of the heater can be controlled to a maximum of 30 kW.

The overall electricity to electricity efficiency is expected to be in the range of 30-40% for a well-designed system. However, in countries and regions, where district heating is used, the waste heat from the generation process can be utilized for district heating, and thus, improve the overall energy efficiency considerably. District heating networks are found in many larger European cities and in Denmark district heating accounts for heat supply to more than 60% of households. Thermal energy for such systems is often provided by CHPs. Economic calculations have shown that the contributions from selling heat are considerable in the total economy of the HT-TES facility [13].

RESULTS AND DISCUSSION

Ideally, a very steep temperature cline that divides the hot and the cold regions of the rock bed (i.e. one end heated to 600˚C and the opposite end still kept at room temperature) can be maintained until the entire bed has reached 600˚C and a temperature cline is no longer present. Theoretically, the temperature cline between the two regions can be vertical for infinite heat transfer area between the gas and rocks. Experimentally, a tilted temperature cline is observed with a transition zone characterized by intermediate temperatures. Figure 6 shows the temperature evolution in time of some crucial regions of the rock bed during a charge/discharge cycle. Temperatures are measured at the outlet of the heater, in the open rooms at the entrance to the rock bed (pre-rooms, cf. Figure 5 upper left) and at four vertical positions at the hot side, middle and cold side of the rock bed in the flow direction. In total there are 12 temperature measurements in the rock bed. In the experiment shown in Figure 6, the heat outlet is set to 640˚C, but thermal leaks on the hot side of the rock storage cause the temperature to drop and expose the rocks to a maximum temperature of 530 ˚C. On discharge, ambient air is fed to the cold side of the rock bed and hot air is recovered. The maximum temperature of the recovered air is approximately 460 ˚C

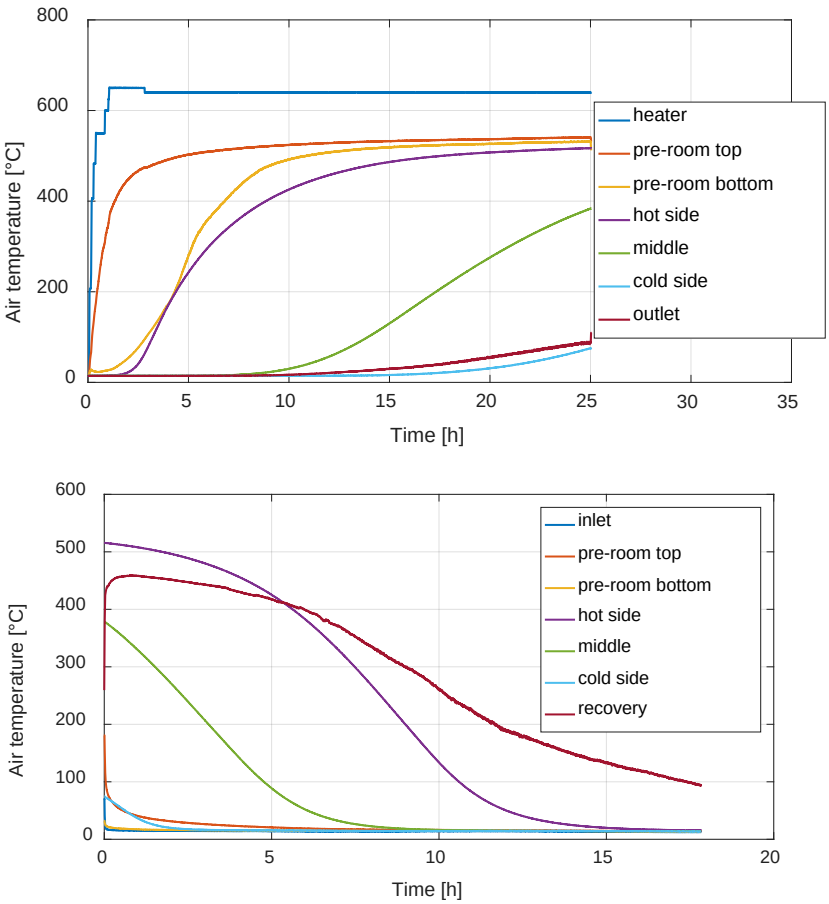

Figure 6 . Top: Experimental temperatures for charging. Heater temperature is controlled to 640 ˚C. Bottom: Experimental temperatures for discharging.

The results show weaknesses of the chosen horizontal design, as the recovered temperature was significantly lower than the charge temperature, and the recovered temperature began to decrease faster than expected. It is suspected that buoyancy forces caused by the large change in air density when cooled from over 500 ˚C at the inlet of the rock bed to ambient conditions reduce storage performance. The buoyancy effects are analyzed using the same experimental data from the experiment shown in Figure 6. The temperatures at the top and bottom (in the direction of gravity) are plotted at the hot and cold sides of the rock storage during charging in Figure 7.

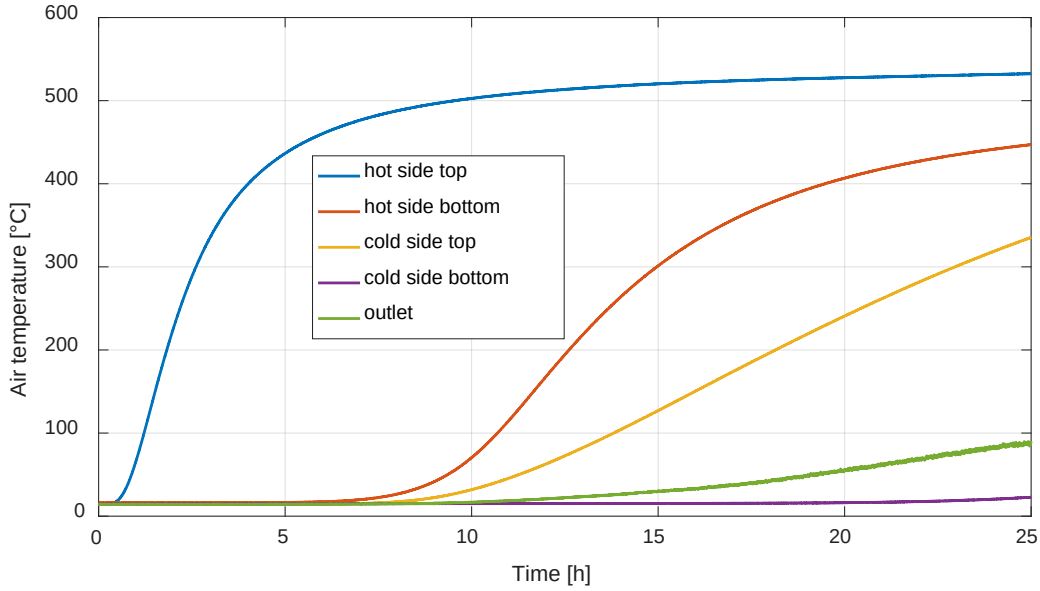

Figure 7. Temperature dependence on the vertical location in the rock bed during charging.

Buoyancy forces dominate the temperature cline in the rock bed. It can be seen that the bottom layer of the rock at the hot side is typically well over 100 ˚C cooler than the top and only starts to catch up in temperature after 20 hours. At the cold side, the top also begins to heat up much sooner than the bottom causing warm air to flow out of the bed while a large portion of the stones are still very near their initial temperature, meaning that heat is lost to atmosphere. Thus, the design used for the preliminary experiments creates difficulties in utilizing the storage facility efficiently.

Secondly, reversing the airflow (thus discharging the facility) does not yield air at high temperature because cold air will exit from the low layer and mix with the hot air exiting from the top layer. This effect increases as the state of charge decreases upon discharging because still colder air soon starts to mix with the hot air from the bed top. Furthermore, if the store is left to rest partly charged (as in Figure 6) for a prolonged period, a stratification process takes place and leads to high temperature in the entire top layer of the bed and low temperature in the entire bottom layer. Discharging from that state will be even worse than discharging from the state in Figure 6, since cold air exits immediately, and thus, the yield temperature will be well below the charging temperature. Several initiatives are considered to improve the operation, but they are left to future work.

MODELING STORAGE APPLICATION IN THE FUTURE ENERGY SYSTEM OF DENMARK

The potential of an HT-TES facility in the Danish energy system was estimated based on several scenarios. In contradiction to the cost study done in [14], which addressed the setup parameters, we made an overview approach. Firstly, prices for each component of the thermal energy store were found including charger, discharger (including steam turbine) and the storage facility itself (rock bed, tubing, construction and insulation). The data is shown in Table 2 below. The optimal dimensioning of the storage, charger and discharger was found as an output from an optimization tool (Sifre). The maximum storage size was set to 1 GWh. From Table 2 it can be seen that the optimal size of the charger is ca. 56 MW, which

corresponds to 18 hours of full charging. The discharger, which is more expensive, is dimensioned to only 5.5 MW electricity, which corresponds to 12 MW thermal energy and ca. 3½ days of full discharging of the storage.

Table 2. Overview of CAPEX and OPEX in Danish currency (DKK) and related invested capacity for a high temperature thermal energy storage facility of 1 GWh_{th}. The data has a preliminary character and is associated with uncertainty.

Unit	CAPEX [DKK/MW]	OPEX [DKK/MW/y]	Yearly investment Cost [MDKK]	Invested capacity
Charger	625,000	6250	2.9 MDKK	55.6 MW_el
Discharger	4,580,000	180,000	2.8 MDKK	5.5 MW_el / 12 MW_th
Storage	2,620	0	0.2 MDKK	1000 MWh_th
Revenue			7.76 MDKK	

Using electricity price projections for 2035 in the West Danish region as published by Energinet (the Danish TSO) [6] the below distribution for hour 3000 to 3500 was predicted assuming unchanged wind power potential and planned expansion of installed wind power capacity. The simulation shows that a weekly storage cycle appears to be the optimal use of an HT-TES system and considerable revenue was calculated (Table 2). As seen in the table the cost of the storage facility itself was found to be very low. It must be stressed that this is still a first estimation of costs and revenues, however this first assessment does not include the value of the waste heat in district heating, which has been demonstrated to contribute significantly to the revenue in earlier studies [13]. Sensitivity analysis of the costs for the storage showed that even if the costs of the storage facility itself were 10 times as much as used in the calculations, there would still be a positive business case.

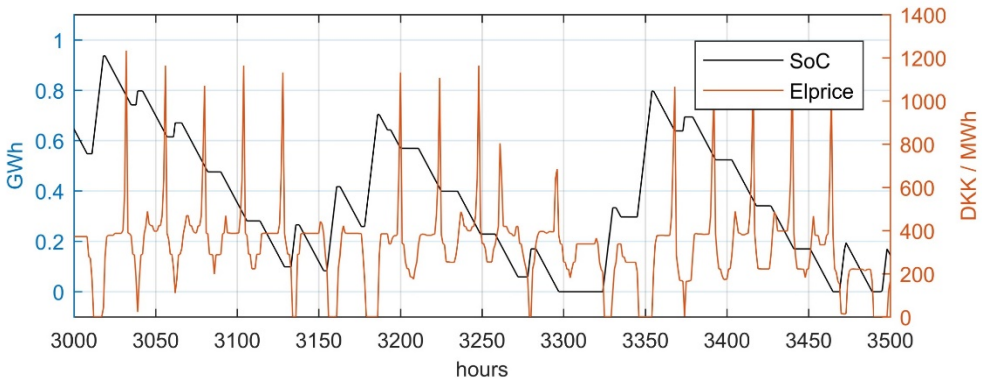

Figure 8 . Projected 2035 electricity prices in the West Denmark region as well as the resulting state of charge (SoC) of a one GWh HT-TES operated (buying and selling) on the same electricity market.

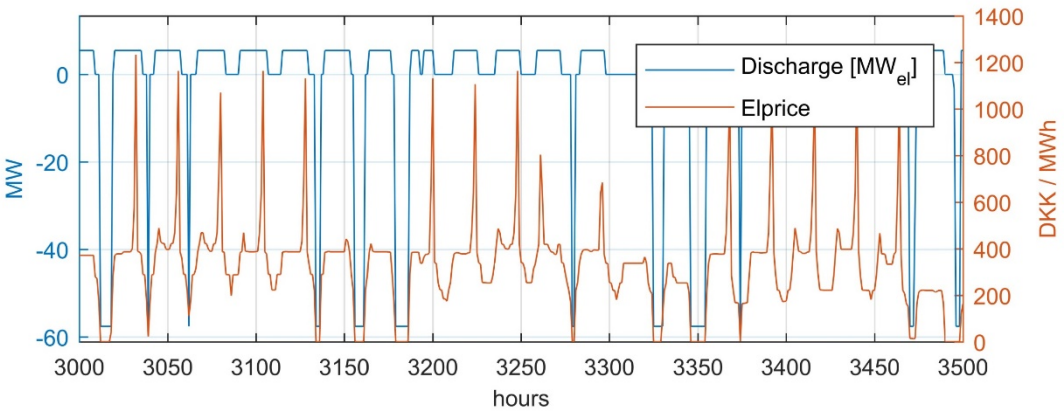

Figure 9. Projected 2035 electricity prices in the West Denmark region and discharging/charging power (MW_{el}) of a 1 GWh_{th} storage facility.

CONCLUSIONS

The initial material studies have clearly shown that significant care must be taken to select appropriate rocks/minerals for an HT-TES before a major investment is made. Materials must be resistant to thermal cycling between ambient and high temperature (600-800 ˚C), which needs to be tested in accelerated experiments to demonstrate durability.

Even though the present work has not been fully completed, the results obtained to date indicate that a horizontal design of a rock bed-based high temperature thermal energy storage facility is likely not to be viable even though the horizontal design is the cheapest to realize in terms of invested capital. The temperature distribution in the rock bed upon charging appeared to be not optimal. Leaving a partially charged system for hours led to a temperature stratification, which should be avoided. However, more work will be done to optimize the system.

ACKNOWLEDGEMENTS

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