Final report

1.1 Project details

Project title	Engelsk titel: EUDP 2016 HT-TES High Temperature Thermal Energy Storage Dansk titel: EUDP 2016 HT-TES Høj Temperatur Termisk Energi Lagring
Project identification (program abbrev. and file)	Journalnr.:64016-0027
Name of the programme which has funded the project	Programområde Systemintegration
Project managing company/institution (name and address)	Virksomhed/institution: SEAS-NVE Holding A/S Afdeling: Udvikling Adresse: Hovedgaden 36, 4520 Svinninge
Project partners	DTU Energy AU Geoscience Energinet Dansk Energi Rockwool A/S
CVR (central business register)	25784413
Date for submission	12/7-19

1.2 Short description of project objective and results

<u>Projektet havde tre overordnede formål og resultater:</u>
Det er muligt med kendt teknologi at bygge et højtemperatur energilager (HT-TES) fyldt med sten, der billigt kan gemme elektricitet fra dage med overskud af energi fra vedvarende energikilder til dage med underskud.

Forskellige stentyper blev undersøgt med hensyn til pris og holdbarhed, så de kan benyttes i et HT-TES.

Det blev undersøgt, hvor ofte energisystemet har brug for et HT-TES, og om det skal tilsluttes et eksisterende eller nybygget kraftværk. Og selvom der vil være konkurrence fra andre teknologier, og forretningsmodellen kan blive udfordret af tariffer og afgifter, så kan der være brug for et HT-TES i fremtidens energisystem. Hvis det bliver bygget i 2025-2030 er det også muligt at have en positiv business case ved at bygge og drive et HT-TES.

<u>The project had three main purposes and results:</u>
It is possible with known technology to build a high temperature energy storage (HT-TES) filled with stones that cheap can store electricity from the days of excess energy from renewable energy sources to the days of deficits.

Different stone types were examined in terms of price and the ability to withstand being heated to 600 °C, so that they can be used in a HT-TES.

It was investigated how often the energy system needs a HT-TES, and whether it needs to be connected to an existing or new power plant. And although there will be competition from other technologies and the business model can be challenged by tariffs and taxes, a HT-TES is needed in the future energy system. If it is built in 2025-2030, it is also possible to have a positive business case by building and running a HT-TES.

1.3 Executive summary

Fluctuating renewable electricity production has always been integrated into the Danish electricity system by strong interconnectivity. However, with an increased deployment of renewable energy in the North Sea region and across Europe, e.g. the Nordic hydro power cannot stand alone as an integration tool. Storages for electricity, e.g. batteries, are often very expensive per kWh and limited in the amount available.

In this project, a high temperature thermal energy storage (HT-TES) has been tested. The HT-TES consists of a pile of rocks in a well-insulated building, heated to 600 °C by an electric heater powered by the surplus from wind turbines. After a couple of days, when energy is needed again, air is heated by the rocks, hot air then heats water to a steam, and steam is passed through a turbine which generates electricity. The residual heat is fed to district heating. The advantages are low cost, big capacity, inexpensive to operate and maintain, and an environmentally friendly way of storing energy. The idea is to connect the HT-TES to an existing CHP (Combined heat and power plant) where it can provide both electricity and district heating.

One of the most important advantage is the low cost, and to live up to that, three objectives have been investigated:

	Objective	The method	The conclusion
The storage	it is important, that the heat can be recovered	A pilot plant was built at DTU Risø Campus and filled with 3,3 m3 of	The project results indicate that rock bed energy storage technically works. The system was optimized from the initial pilot stage to the demonstration plant. There are

	at a high constant temperature over a longer period	rocks (Swedish Diabas) and tested multiple times with hot air.	still improvements that can be made, but it was shown that it is possible to build a plant that can store and release energy using a simple, safe, cheap, and widely available, storage medium such as rocks. This gives hope for future projects where existing infrastructure can be used to establish a full-scale HT-TES.
The rocks	it is important, that the rocks can withstand being heated many times for many years	At the Department of Geoscience, Aarhus University, the rocks were heated in a muffle oven in several experiments up to between 600 and 800°C to test their physical strength and possible alteration upon heating.	In terms of rock materials, the results indicate that magnetite would be best suited. Even with a higher price than some of the other rock candidates the costs of the rock material will possibly be low compared to the overall costs of a HT-TES. The knowledge gained in this project will be utilized in looking at potential applications. Although the rock material plays a crucial role in the performance and capacity of a HT-TES it is not the limiting factor. It should be possible to obtain suitable rocks almost anywhere in the world to heat and store energy. It remains unknown what long-term consequences of repeated and multiple cycles are for rock materials employed for HT-TES at high pressures. This is a field that could be explored further in experiments designed for accelerated tests at higher pressure.
Business case	it is important, that the Danish electric system can use the electricity from the storage	Simulations were carried out in Danish Energy Associations Balmorel model by examining a reference scenario without the HT-TES storage system and compare it with different sce-	The HT-TES concept shows socio-economic feasibility in the long term. Current tariff structure may not support the corporate feasibility of a HT-TES concept. The storage is highly dependent on large fluctuations in the electricity price if the storage should buy and sell electricity directly from the electricity market. Therefore, the analysis shows highest value of the HT-TES concept after 2025. The HT-TES concept may experience positive upsides from heat

		narios, where the HT-TES systems are deployed.	sales and system- and balancing service. In the long term (after 2025) the storage can have a high level of utilization.

1.4 Project objectives

The future energy system – both on a Danish, Scandinavian and European level - will expectedly be based on large amounts of cheap and fluctuating renewable electricity production from solar PV and wind farms. Electricity based on wind and solar can be utilized in the entire energy system and an effective integration of renewables will require a combination of strong interconnection to other countries, increased demand side response through electrification, sector-coupling and flexible conversion of the green electricity to other energy products. Traditionally, fluctuating renewable electricity production has been integrated into the Danish electricity system by strong interconnectivity to Scandinavia (e.g. Norwegian and Swedish hydro power) as an important tool to integrate renewables. The hydro reservoirs in the Nordics has functioned as a "virtual green battery" for the fluctuating renewable solar and wind capacity.

However, with an increased deployment of renewable energy in the North Sea region and across Europe, the Nordic hydro power cannot stand alone as an integration tool. Besides renewable energy integration via grid expansion to other countries, the integration of future renewable energy requires other tools such as "integration over time", which covers technologies and conversions such as electricity-to-electricity storage and electricity for other purposes e.g. electricity to heat, electricity to transport and electricity to green gasses and green fuels.

Generally, a broader integration across sectors can ensure a higher level of flexibility in the electricity system of the future. Electricity- and energy storage is an essential element and will play an important role in the future energy system. Currently, research and development on a wide range of storage technologies are being carried out and the different technologies differ a lot from each other in terms of purpose, efficiency, costs and scalability but there will likely be a demand for different kinds of electricity-/energy storages in the future energy system.

While thermal energy storages have a time perspective of days (max a week), storage of green gasses and green fuels has a perspective of seasons or years. A storage technology such as high temperature thermal energy storage (HT-TES), which is the focus of this project, has the benefit of being able to deliver both electricity for the electricity system (and market) and heat for the district heating system and thereby be able to act within a timeframe of hours and up to 1-2 weeks depending on whether heat or electricity are demanded.

The HT-TES consists of a pile of rocks in a well-insulated building, heated to 600 °C by an electric heater powered by the surplus from wind turbines. After a couple of days, when energy is needed again, cold air is heated by the rocks, which subsequently heats water to steam that is passed through a turbine which generates electricity. The residual heat is fed to district heating. The advantages are low cost, big capacity, inexpensive to operate and maintain, and an environmentally friendly way of store energy. The idea is to connect the HT-TES to an existing CHP (Combined heat and power plant) where it can provide both electricity and district heating.

In the Electricity Price Outlook 2018 from Danish Energy, the analyses examining the potential for long-term electricity storages. The outlook does not look on specific storage concepts such as HT-TES, but solely on the consequences for the energy system if long-term electricity storage is available at competitive prices. The model results show a promising potential for such storages used for integrating more renewable electricity production in the energy system. Most investments in the storage capacity occur around year 2030 (see results for more).

The main objectives for the project were:

1.4.1 The storage - Is it possible to build a HT-TES that produces hot air at a constant temperature?
1.4.2 The rock material - Which kind of stones can be used in a HT-TES?
1.4.3 The business case - Is there a good business case for a full-scale HT-TES?

1.4.1 – Storage
The objective was to design and test a pilot-scale demonstration storage plant for laboratory scale testing. The main tasks for the work package were:

- Initial small-scale experiments in laboratory.
- Preliminary modelling
- Finalization of design details in pilot plant and construction drawings

- Required official approvals for pilot plant
- Construction of plant
- Designing measurement program for pilot plant
- Pilot plant experiments and modeling
- Reporting

Two pilot plants were built; one with horizontal airflow ("Shoebox"), and one with vertical airflow ("Droplet"). Both plants are described in paragraph 1.5 Results.

The project went, for the most part, as planned. During the modelling of the system and the initial system design activities, buoyancy forces in the "Shoebox" were addressed as a potential loss mechanism that could significantly reduce system performance when the air flow is in the horizontal direction. Figure 1 shows the model prediction for the temperature profile in the "shoebox". The model predicts that hot air will rise to the top of the "shoebox", leaving rocks at the bottom of the bed unheated. At some point, hot air will begin exiting the "Shoebox" before the bottom of the box is heated, causing reduced efficiency.

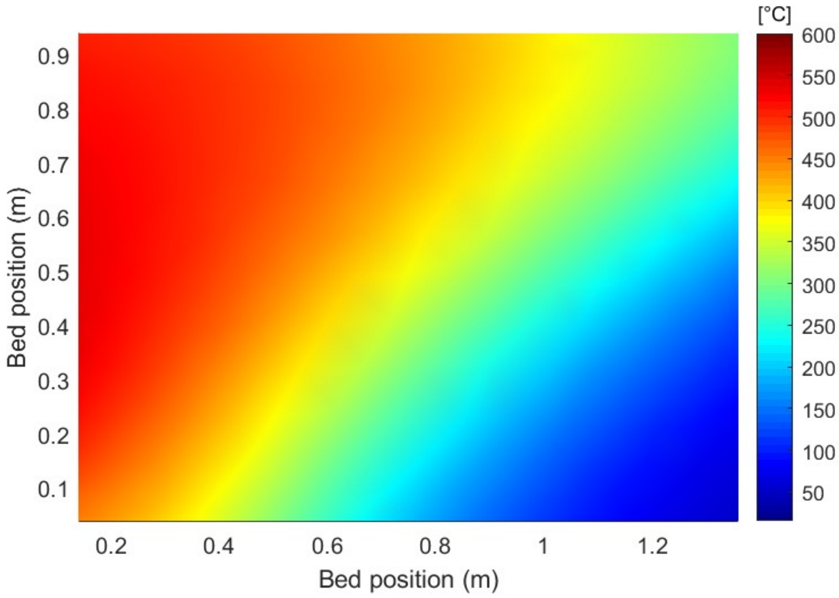


Figure 1. Temperature profile in the "Shoebox" predicted in the numerical model. Hot air enters from the left side, pushing outlet cold air from the right side. There is a large temperature gradient in the vertical direction that increases system losses.

Based on the modelling results, and to confirm these results, we decided to test a small scale "shoebox" storage first. Experimental results from the small "Shoebox" confirmed the modelling results. The impact of the buoyant forces on performance required the consortium to rethink the original horizontal flow design and move to a vertical air flow setup ("Droplet"). This delayed the project by six months and increased the time spent on system design. It also resulted in one patent application for the inlet/outlet configuration used in the vertical air flow design.

After accounting for the delay caused by switching from a horizontal flow to a vertical flow, the rest of the project practically went according to plan. Approvals for the system were obtained and construction of the plant along with data acquisition and test plans were finalized in January 2019. Although future tests are planned, testing related to the project completed on April 30, 2019.

The risks associated with these activities identified during the proposal are given in Table 1. As indicated in the table, none of the identified risk areas caused major changes to the project and the overall goals of the project were achieved.

Table 1. Risks associated with the pilot plants

Nr	Risk	Result
1	The solid is unsuitable for storage	The consortium was able to identify several abundant, inexpensive materials that were suitable for the application. Some materials were tested for over 1000 hr.
2	Competing technologies are being developed so HT-TES technology will not be present	There have been no major breakthroughs in competing technologies. Interest in the project from industry, academia and the general public indicates that the technology remains a viable solution.
3	The relevant knowledge and skills will not be present in the project	The successful demonstration of the pilot plant demonstrates that the necessary skills were present.
4	Existing IP rights	Although there are some difficulties with IP rights, especially those owned by Siemens Gamesa, it was not a major issue. The consortium generated some IP that was used to implement the pilot plant.

1.4.2 The rock material

The rock material to be heated for energy storage was tested at the Department of Geoscience, Aarhus university. The objectives were to find suitable rocks (i.e., with a high heat capacity and density, as well as the right size of rock pieces) that can be multiple times heated to 600°C and cooled without degrading. Moreover, the rocks should be readily available and shipped to Denmark.

Testing of the different rocks was performed in different experiments that are described below and in Soprani et al (2019). There were no problems with the project development, and suitable rocks were identified. Nevertheless, the price (per volume) for the best suited rock material (magnetite) is seven times as high as for the second-best rocks, and the availability of different sizes of magnetite was limited. Consequently, for testing purposes the rocks used in 2 pilot plants (shoebox and droplet) were a diabase from Sweden. The only small difference between magnetite and diabase will be seen in the energy storage capacity.

From the material tests we have not identified any major risks for the project as long as a suitable rock size is used to allow effective charging of the rock bed and minimize the pressure drop. There are still some unknown aspects, which mainly concern the long-term stability and pressure effects due to expansion and oxidation of the rocks. During this project only a limited number of heating cycles could be performed, whereas for a full-scale plant the number of heating cycles lies around 2000 during its lifetime. Equally, the rocks have not been tested in a mechanically confined space (as it will occur in the rock bed) and effects from high stress variations could not be tested.

1.4.3 The business case

A number of smaller gas turbines is currently installed in the Danish system where it would be possible to install a HT-TES storage in combination with the turbines as a retrofit approach. Additionally, the HT-TES storage technology can be installed in combination with larger steam turbines together with a new HRSG (heat recovery steam generator). Finally, a large amount of large CCGT (combined-cycle gas turbines) are installed in other European countries (e.g. Germany), which could be retrofitted to include the HT-TES storage technology.

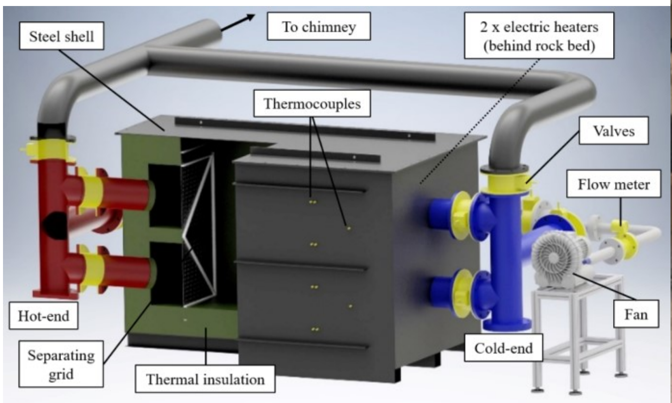
The objective of this energy system analysis is to examine the feasibility of the HT-TES storage and which approach is most beneficial (retrofitting, new HRSG approach or green field, where all components are new).

1.5 Project results and dissemination of results

1.5.1 The storage

The tasks can be summarized as the design, modelling, construction, and testing of both a horizontal and vertical flow thermal energy storages as well as dissemination of results. The first part of the project was the so-called "Shoebox" with a horizontal flow with a total rock volume of 1.5 m^3. For all experiments, we used Swedish diabase that was sourced from Dansk Natursten. The rocks were tested and found suitable for this project by Aarhus University. The rocks are also inexpensive and abundant and would be suitable for industrial applications.

Based on modelling results that predicted that buoyant forces causes warm air to travel to the top of the rock bed and causes the rocks to be unevenly heated (as shown in Figure 1), it was decided to first build a small scale rock bed to evaluate if the model was correct and if the system could be constructed to avoid these losses due to buoyant effects. The small-scale system called "Shoebox" is illustrated in Figure 2. DTU worked with SEAS-NVE to develop the concept and design the system. We also worked together with Rockwool to design the insulation and choose insulation materials.



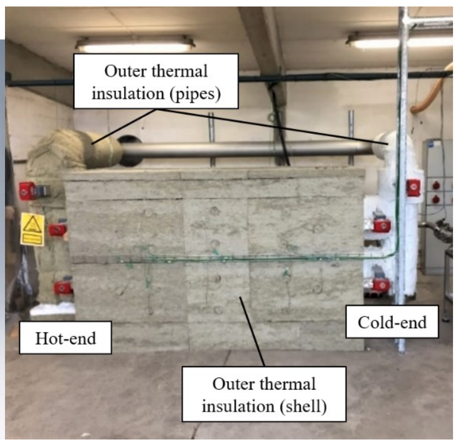


Figure 2.(left) CAD model of the small scale HT-TES (the "Shoebox") with a section view of the hot end, (left) A photo of the equipment from the front view with insulation installed (right).

Testing of the small-scale system confirmed that buoyant forces could be a significant loss mechanism and reduced system efficiency. It was also recorded that when heat is stored over longer periods, the temperature in the rock bed stratifies in the vertical direction, which further reduces system efficiency. Studies were performed to reduce buoyant losses, and this included reducing the rock size and adding horizontal impermeable insulating layers to prevent hot air from flowing in the vertical direction. Both techniques were shown to reduce buoyancy effects, but it was decided that the buoyant effects were still too large and the best design was a vertical flow system, where buoyant effects would tend to concentrate the heat near the top of the system, where it could be more efficiently recovered.

Based on the experience from the small-scale horizontal system, a vertical pilot scale system called "Droplet" was designed by a team consisting primarily of SEAS-NVE, DTU and Niras. Some of the main experiences that were taken from the small-scale system were the rock size and type, the need to minimize losses from buoyant flows, the need to have a housing that allows for expansion of the rocks during heating, the advantage of having separate fans for charging and discharging and practical details such as component selection and pipe sizing. The rocks were the best-performing ones from the small-scale system – Swedish diabase with rock sizes from 8-11 mm. Thermal insulation was built into the base design, with the system buried in the ground insulated with hard insulation on the bottom and sides followed by a 40 cm layer of standard reinforced concrete. Strain gages and thermocouples were installed in the concrete. An illustration of the design of the vertical flow rock bed storage is given in Figure 3. An illustration of the system operation in charge mode is shown in Figure 4.

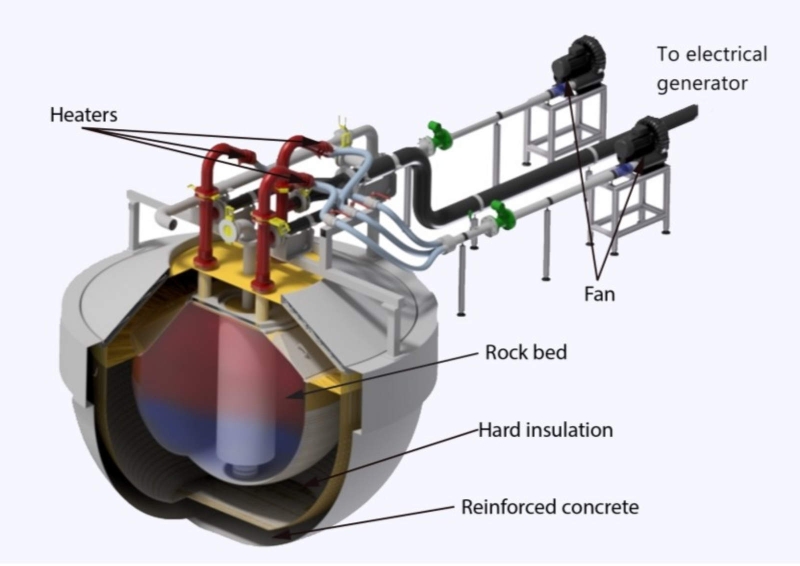


Figure 3. Illustration of the design of the vertical flow rock bed with major components labeled.

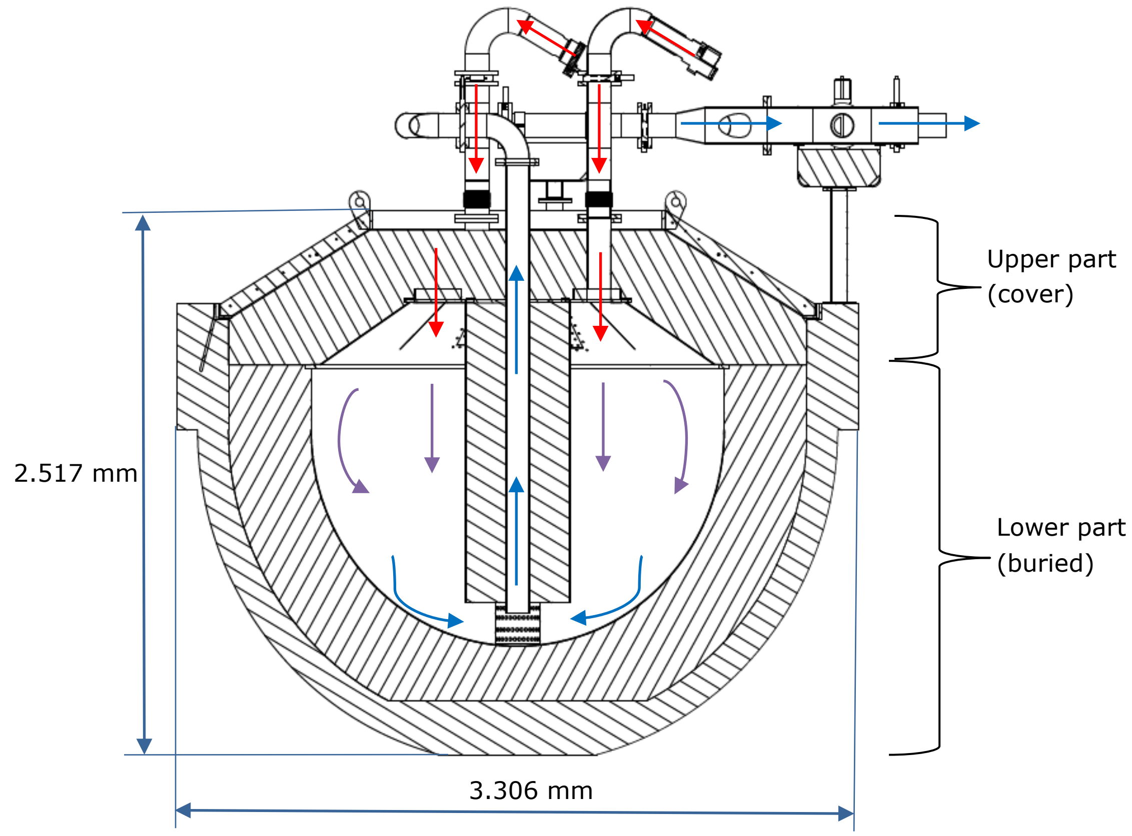


Figure 4 Illustration of the air flow path during the charge mode including system dimensions.

The construction of the system is illustrated in Figure 5. Construction started with excavating a specialized hole in the ground. Then a steel reinforcement cage mounted with thermocouples and strain gages was installed and the entire structure was covered with concrete that was sprayed on. Then a 40 cm layer of hard brick high temperature insulation was installed. A 5 mm stainless steel shell was then installed over the hard insulation and the gap was filled with mortar that was injected through the bottom of the steel shell. Once the shell was in place, it was filled with 5900 kg of Swedish diabase that was sieved between 8-11 mm meshes. This amount of rock corresponds to approximately 1 MWh of thermal storage capacity. Seals between steel components were made with high temperature gaskets. Finally, soft insulation consisting of Super Wool and Rockwool was applied to the top of the rock bed.

Figure 5. Construction of the vertical flow rock bed storage: (a) excavation, (b) spraying concrete onto the steel support frame, (c) installing the stainless-steel shell, and (d) final assembly with heaters, fans and insulation installed.

Testing of the vertical flow system began with a slow charge at low temperature to remove moisture from the system and test components. The first experiments were most importantly to test the functionality of the data acquisition and check for any abnormal behaviour. The temperature of air leaving each heater was monitored and found to be controlled within an acceptable range. The distribution of the inlet air during charging was tested by running the system with all three heaters turned on and also running the system with only two of the heaters turned on.

When only two heaters were used, air from the two running heaters must distribute and charge the rocks near the heater that is not in use. In these experiments, the rock storage was able to recover effectively the same amount of energy using only two heaters as when using all three. This suggests that the inlet air distribution is acceptable, as the inlet manifold installed at the top of the rock bed gives a good air flow distribution. To test the quality of the insulation installed at the top of the storage, an infrared camera was used to measure surface temperature and an example is shown in Figure 6. The infrared analysis showed that the surfaces are generally around 45 °C, although some seams between insulation layers can easily exceed 100 °C. Some heat leaks are also caused by thermocouple installations that will not be necessary for industrial applications. These small heat leaks will affect performance but the insulation has generally been correctly installed with acceptable performance. In large scale applications, it will of course be important to achieve the best insulation performance possible and additional insulation layers may be necessary.

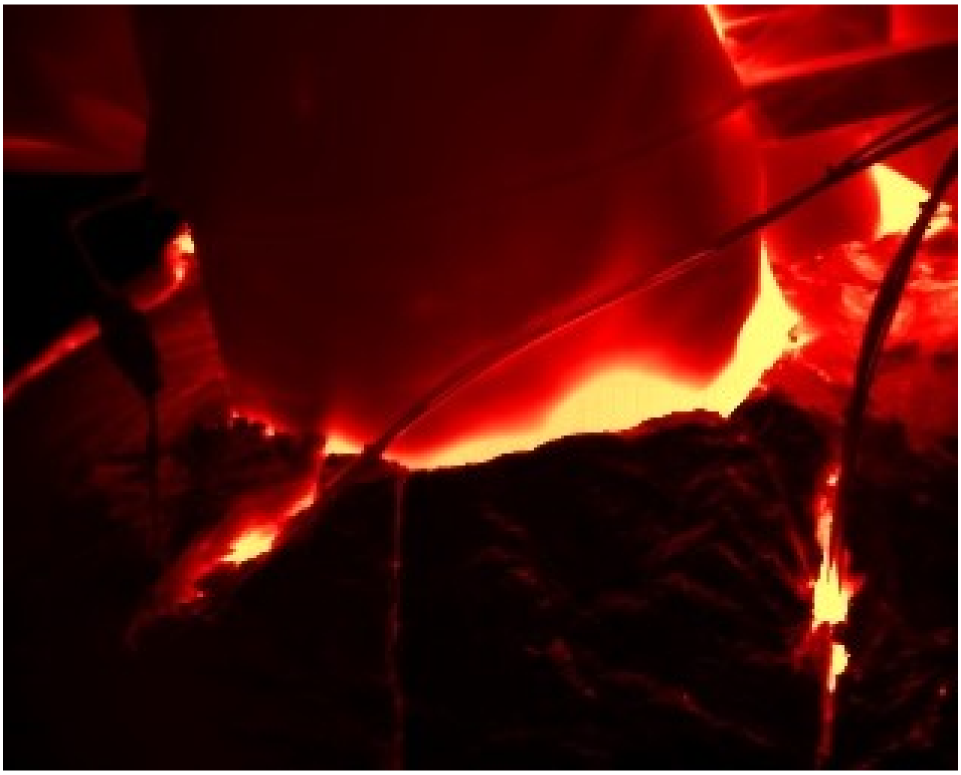


*Figure 6***.** *Infrared image of center column surface after 42 hours of charge.*

The main goals of the project were to show that the bed can store energy in the form of heat and later recover it for electricity production. Due to the scope of the project, we did not couple the storage to an electrical generator but rather measured the thermal output by measuring the flow rate and temperature of the recovered hot air. During evaluation of the setup, the most important figure of merit was the overall round-trip storage efficiency (h_{RT}), which is defined as:

$$\eta_{RT} = \frac{E_{recovered}}{E_{provided}}$$

where E_{stored} is the amount of heat stored inside the rock bed, whereas $E_{provided}$ is the energy provided to the system by the heaters and the fan.

All experiments were run with the heater outlet temperatures set to 600 °C. The air flow rate during charge, charge time, discharge flow rate and discharge time were all experimental parameters. In this report, all results are given for a bed that starts at a "fully discharge" state, meaning that cold air has been blown across the rock for a time sufficiently long to practically remove all thermal energy from the rock bed. Each cycle consists of a charge cycle followed shortly by a discharge cycle.

The pressure drop in the system was also measured and is reported in Figure 7. As shown in the figure, the highest pressure drop component is the heater, which has approximately four times higher pressure drop than the rock bed itself. However, the maximum pressure drop measured is below 2500 Pa (0.025 bar), which is well within the range of most industrial fans for such an application. The maximum fan power consumption is approximately 1.4 kW compared to 45 kW consumed by the electrical heaters.

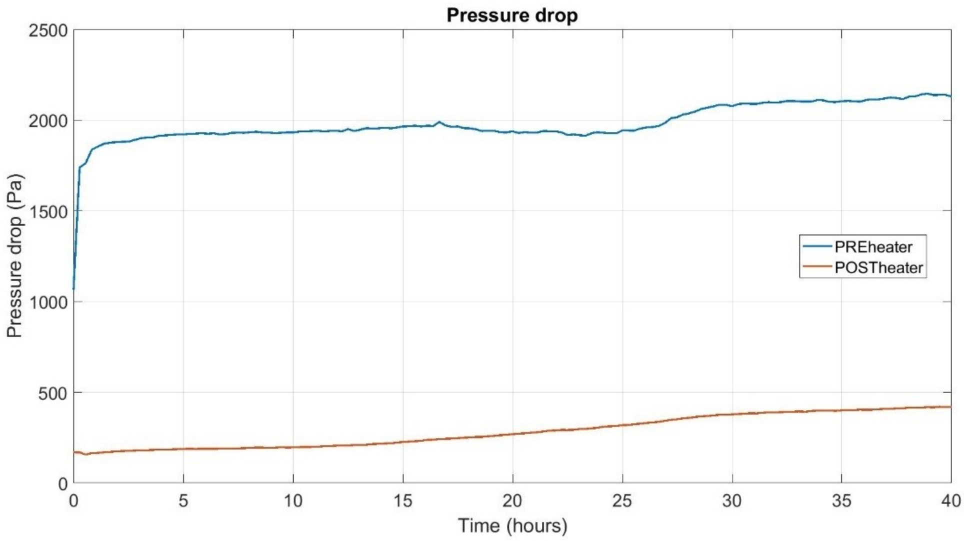


Figure 7. *Pressure drop during a charge phase for 40 hours at 200 m³/h before and after the heaters.*

The temperatures in the middle of the flow channel for a typical charge phase are given in Figure 8. The figure shows how the temperature evolves at different depths in the rock bed as a function of time. The figure shows that the top of the rock bed cannot fully reach the heater outlet temperature, which indicates that there are some thermal losses as well as energy stored in components upstream of the rock bed. The plot shows that there is a relatively steep thermocline, which indicates good heat transfer between the rocks and hot air. It can be seen that hot air does not start to exit the rock bed until a large portion of the rock bed has been heated to near the heater temperature.

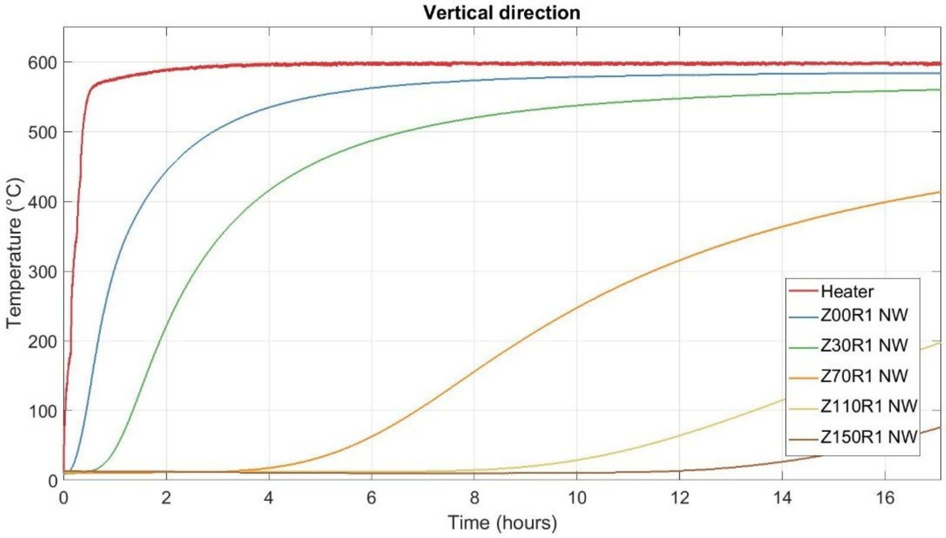


Figure 8. Temperature behavior of thermocouples located in the R1 position (middle of the flow channel) and at different heights for a charge at 200 m^3/h. The line labels represent different depths into the rock bed. For example, Z30R1_NW represented the thermocouple 30 cm deep in the rocks at position R1 and in the northwest sector.

To test the round-trip efficiency and the output power that can be achieved, a series of tests were run by first charging the rock bed for 24 h at a flow rate of 200 m^3/h, which gives a charge rate of approximately 44 kW. The bed was then discharged at different flow rates to see how the output power depended on the discharge rate. The results are shown in Figure 9 and Figure 10. Looking at the outlet temperature, the bed is able to recover air at over 500 °C starting from a heater temperature of 600 °C. Figure 9 shows that the bed is able to produce a fairly constant flow outlet temperature profile that can be used to produce high pressure steam for an electrical generator. As shown in Figure 10, the outlet power depends on the discharge air flow rate. At the discharge fan's maximum flow rate of 300 m^3/h, the rock bed can provide more than 50 kW thermal power for more than 5 h and a power output over 40 kW for more than 12 h.

The power output also ramps up quickly and the rock storage is able to attain 90% of its maximum power output within 6 min of starting a discharge cycle. This shows that a rock bed can be part of a flexible power production system and can react in a relatively short time span. The system is able to discharge at a higher power than it charges. The best efficiency was measured for the fastest charge and discharge rates and was approximately 78%.

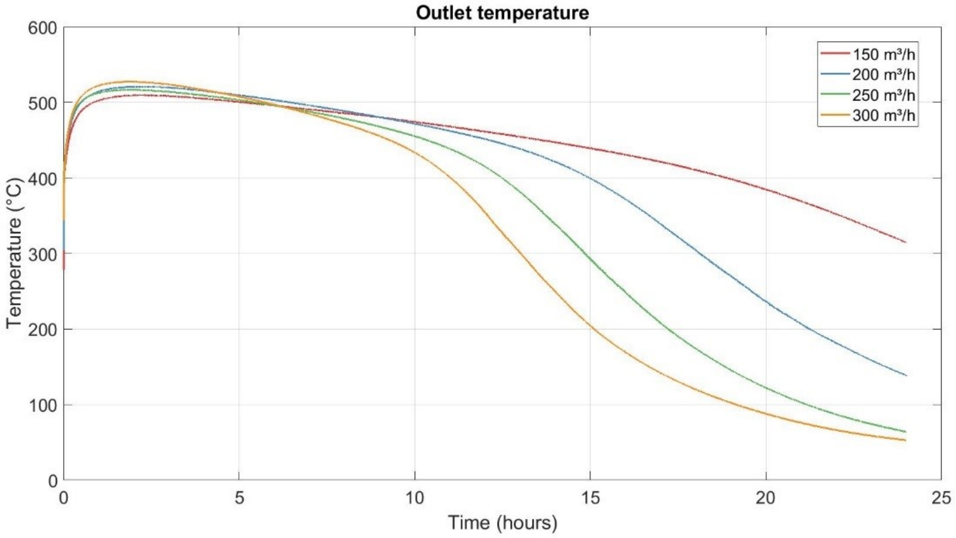


Figure 9 Outlet temperature for the four discharges.

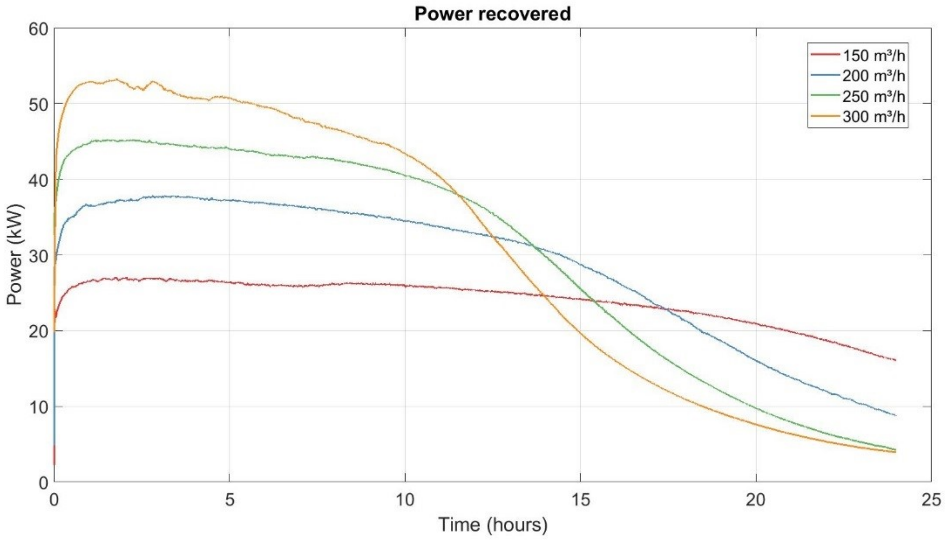


Figure 10 Power recovered during four discharges at different flow rates.

Finally, the temperature in the concrete that makes up the outer layer of the storage and the strain measured on the steel reinforcement in the concrete are reported in Figure 11. Temperatures measured in the concrete reach a maximum of approximately 34 °C, which is well within its safe operating temperature. The relatively low temperature in the concrete indicates that the hard insulation that supports the rocks gives good insulating properties and performs as expected. The strain measured in the concrete is relatively well behaved, indicating that the structure seems to be able to support the thermal stresses associated with charge of the rock bed. However, deep analysis of the structural aspects of the housings and hard insulation is left for future work. Up to this point, there are no indications that there is any structural damage to the system, but a full inspection has not been carried out yet.

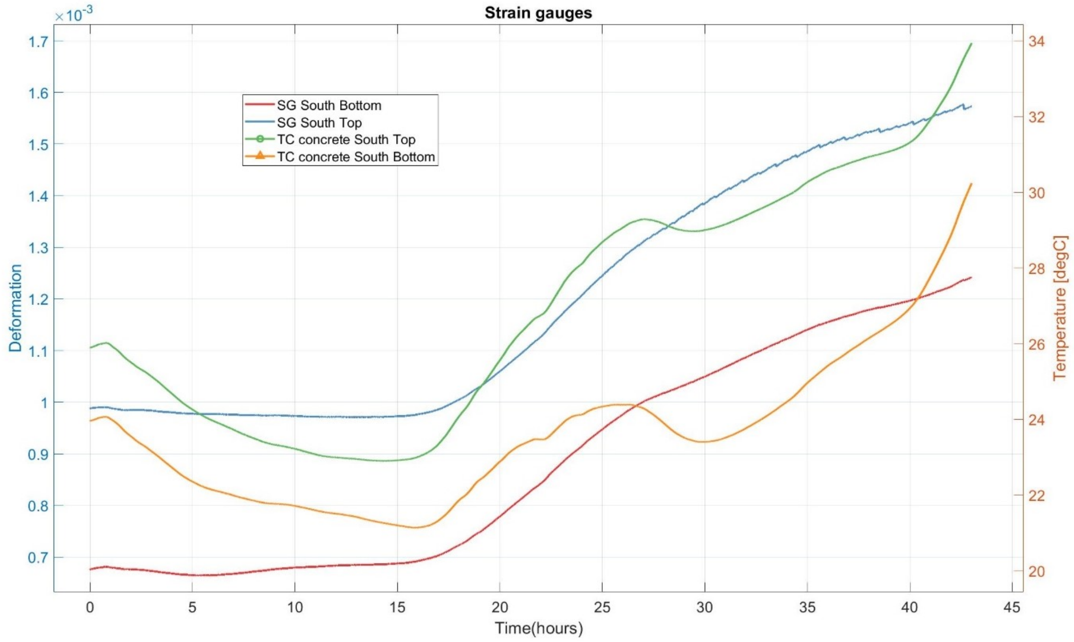


Figure 11. Deformation and Temperature in the Concrete of two Sensors in South Axis during Charge.

1.5.2 The rock material

To find suitable rocks for the thermal energy storage, 14 different rocks of nine different general rock types, ranging in composition from ultramafic (dunite), to basaltic/gabbroic and granitic as well as a quartzite and magnetite, were calorimetrically measured to determine their heat capacity (Figure 12 and Table 2).

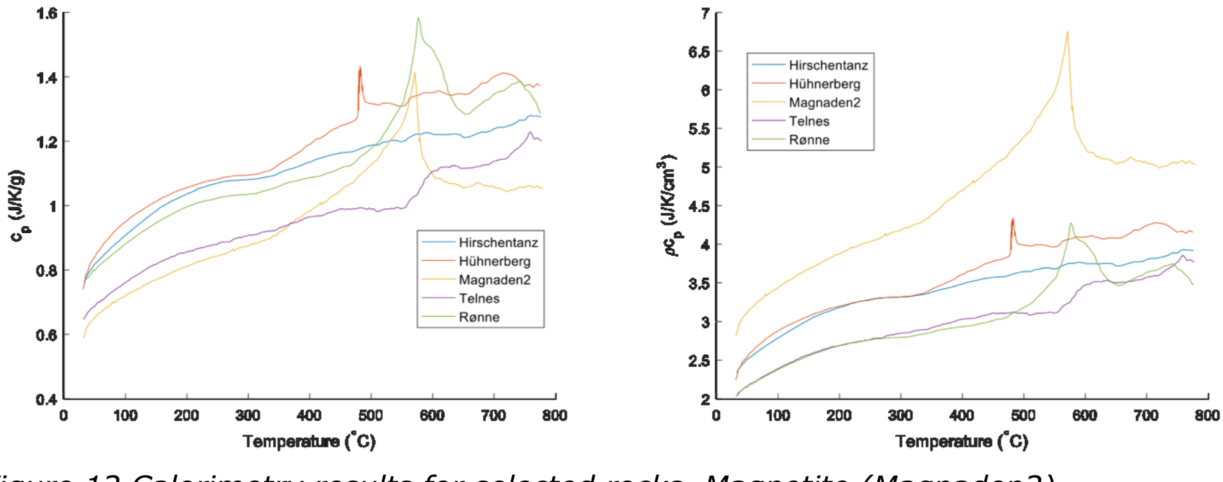


Figure 12 Calorimetry results for selected rocks. Magnetite (Magnaden2) shows a pronounced peak at around 580°C where the Curie temperature for magnetite is reached and magnetite becomes non-magnetic.

Equally, their densities were determined because this together with the heat capacity controls the overall heat storage capacity for a given volume of rock. Several basalts coming from different quarries in Germany and Austria were tested, but their mineralogy and textures vary only little, hence, their performance and properties were similar.

Table 2. Summary of the thermal properties of rock types that were considered. Average specific heat (c_p) values are calculated over the temperature range 40-600 °C. Measurements were both conducted for unheated rocks and for rocks that were pre-heated for 2 weeks at 600 °C.

Nr.	Petrologic classification	Origin	Suitable for high temperature	Average c_p, raw (J/K/g)	Average c_p, after heating (J/K/g)	Density (g/cm^3)	Average c_p times Density, pre-heated (J/K/cm^3)
1	Magnetite	Sweden	Yes	0.93	0.82	4.68 ± 0.23	3.8
2	Dunite	Norway	No	n/a	n/a	2.74 ± 0.10	n/a
3	Ilmenit-norite/Gabbro	Sweden	Yes	0.90	0.82	2.82 ± 0.28	2.2
4	Gabbro/norite	Sweden	Yes	n/a	n/a	2.65 ± 11	n/a
5	Anorthosite	Norway	Yes	1.08	0.95	2.71 ± 0.09	2.6
6	Diabase	Sweden, Finland	Yes	1.13	0.96	2.75 ± 0.0o	2.6
7	Basalt	Germany, Austria	Yes	1.08	n/a	3.09 ± 0.39	n/a
8	Quartzite	Sweden	No	n/a	n/a	2.66 ± 0.07	n/a
9	Granite	Denmark	No	1.18	n/a	n/a	n/a

The rocks were heated in a muffle oven in several experiments up to between 600 and 800°C to test their physical strength and possible alteration upon heating. Subsequently, the rocks that were heated in the laboratory, but also those that were heated in the shoebox pilot plant were investigated with a microscope using thin sections to assess the mineralogical and textural changes.

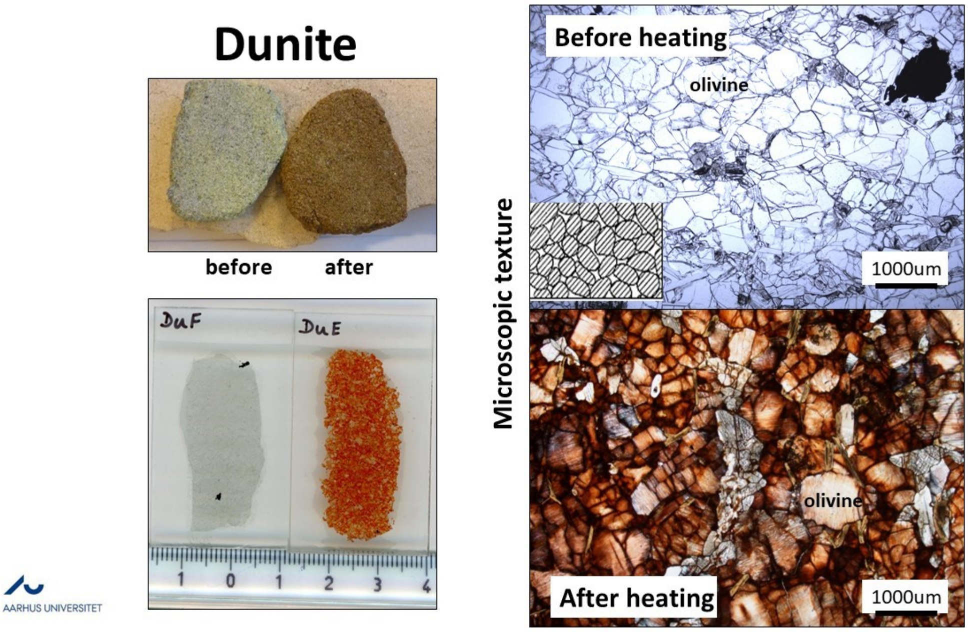


Figure 13 All rocks changed their colors to a reddish color, which is a sign of oxidation. Left side: macroscopic view of sample and thin section, right side: photomicrograph of dunite before and after heating.

Based in these initial tests, it was evident that most of the tested rock types appeared to remain stable upon heating. However, to our surprise, some rocks turned out to be clearly unsuitable for HT-TES. E.g. dunite consists of a mineral (olivine) with high heat capacity and density and is theoretically stable at high temperatures. However, this type of material turned out to completely disintegrate when heated to 600 °C. The best performance was found for magnetite, which showed minimal oxidation to hematite, while maintaining its strength (see also Table 2). The material tests succeeded in determining a suitable rock type for the HT-TES system. However, there are further tests to be done that will assess the long-term stability of the rocks and simulate conditions in the rock bed under pressure.

The results are published in a paper by Soprani et al (2019) and were presented at international conferences. Moreover, the results of the rock materials were also part of dissemination activities for the overall project (see separate description). The rock material tests were part of 2 Bachelor theses at Aarhus university.

The media coverage of the overall project triggered several inquiries regarding the rock material, and it is planned to continue testing more materials and as outlined above address some of the outstanding issues (e.g., long-term stability, pressure effect in the rock bed during thermal expansion).

1.5.3 The business case

Assumptions regarding the HT-TES storage

The HT-TES storage consists from an energy system modelling perspective– in broad terms – of two systems. A storage system, which in reality is the hot rocks and corresponding capsule, and a recovery system responsible for the electricity production (discharge of the storage). The recovery system of the plant consists of the HRSG (Heat Recover Steam Generator - converts the hot air to steam under high pressure), a steam turbine with generator (producing heat and electricity) and piping connecting the storage and the HRSG unit in order to circulate the heated air to and from the storage itself.

The storage system
In the simulations, it is assumed that the storage has a 40-hour charge-/discharge cycle which corresponds to 2500 MWh with a thermal capacity of 62 MW. The capacity can be utilized for electricity and district heating production at an efficiency of close to 100%. The final size and capacity of the storage should be optimized before realizing the project. The cost of the storage system is together with building consultants estimated to 43 million DKK (2,3 €/kWh).

The recovery system
Three possible designs for the recovery system have been analyzed:

- A **retrofit** system, where the HRSG and turbine of an existing power plant are reused and retrofitted to the storage system.
    - The electricity efficiency of this solution is 24% and has an electricity capacity of 15 MW.
    - As a result, an electricity production of 600 MWh on a full charge-/discharge cycle can be achieved.
    - If heat is produced at the same time, 46 MW and 6600 GJ can be achieved on a full cycle.
    - An estimated price of 64,5 million DKK excluding the storage system.
- A solution, where a **new HRSG** is build and an existing turbine reused.
    - Electricity efficiency of 30%, electricity capacity of 18,5 MW and an estimated cost of 235 million DKK.
- An entire new **green field plant**, where a new HRSG and turbine (optimized to get highest possible efficiency) are build.
    - Electricity efficiency of 40% and an estimated cost of 430 million DKK.
    - To achieve the highest possible electric efficiency the heat recovery system is not in use in this plant configuration.

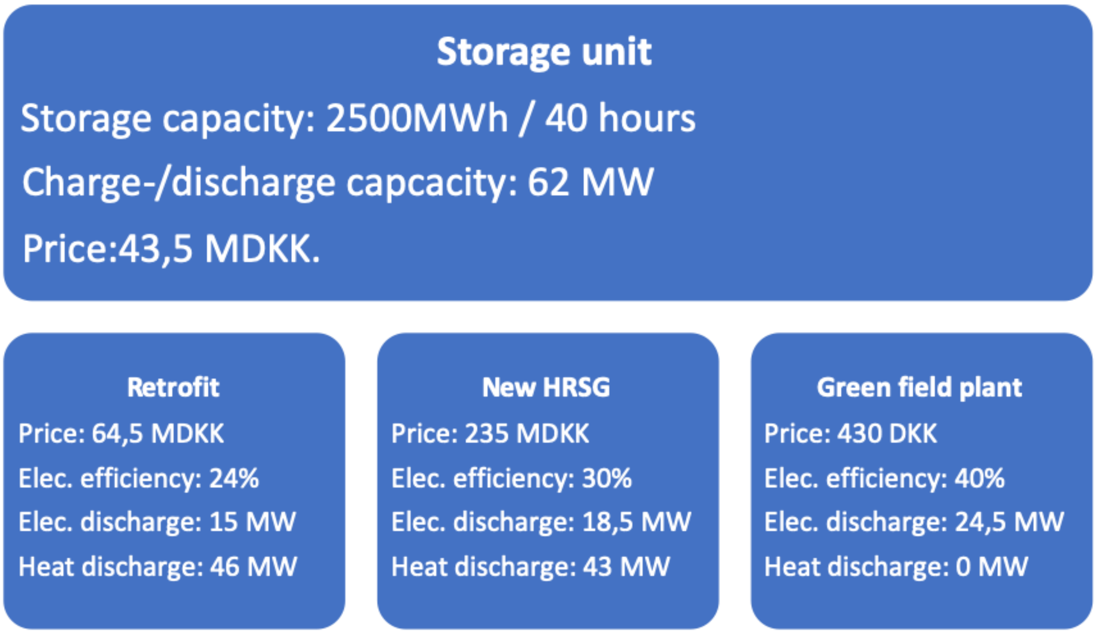


Figure 14 – Assumptions and preconditions for the HT-TES storage system

Simulation tool and methodology

The simulations are based on the Danish Energy Association's Balmorel model, which is used in the Electricity Price Outlook 2018. The applied scenario assumes a stable increase of fuel- and CO_2 prices and lower prices for renewable energy technologies. These assumptions result in larger fluctuations of the electricity price in the future, which are essential for the feasibility of the HT-TES storage system[1].

The simulations are carried out by examining a reference scenario without the HT-TES storage system and compare it with three scenarios, where the HT-TES systems are deployed (one scenario for each configuration approach as described previously). The revenue stream of the HT-TES storage system is calculated as the costs for buying electricity (to charge the system) subtracted from the sales price of electricity (selling the electricity in the market when discharging the system). Furthermore, the O&M and CAPEX costs subtracted and a net present value (NPV) is calculated; one for each configuration approach.

In the energy system analysis, the storage system is located in Western Denmark (DK1 price area) and the HT-TES storage system is operated from a total electricity system cost perspective, which is assumed to be an approximation for a socio-economic optimal system. In other words, tariffs and taxes related to the electricity consumption of the storage system are not considered and the purpose of the analysis is solely to examine the potential of the HT-TES storage system in a future energy system. Since the heat from the storage can be utilized in the district heating system, a heat price of 100 DKK/MWh is included in the net present value calculations. Currently, it is uncertain at which price a HT-TES storage can sell the heat, as the production is optimized in regard to the electricity system. For the following net present value and cash flow calculations, a discount rate of 4% and a project period of 20 years are used.

[1] See more at https://www.danskenergi.dk/udgivelser/elpris-outlook-2018-perspektiver-elproduktion-mod-2035

Results: Retrofit approach

Retrofitting an existing facility to accommodate the HT-TES storage system is the cheapest approach (CAPEX cost of 107 million DKK). As seen in figure 15, the revenue streams from sale of electricity and heat are relatively low (a few million DKK per year) in the first years since the electricity price fluctuations are limited (which should drive the business case of such a storage system). The revenues increase towards 10 million DKK in 2025 and 17 million DKK in 2030 as a result of the more fluctuated electricity price. After 2030, the discounted revenues stabilize around 17 million DKK per year.

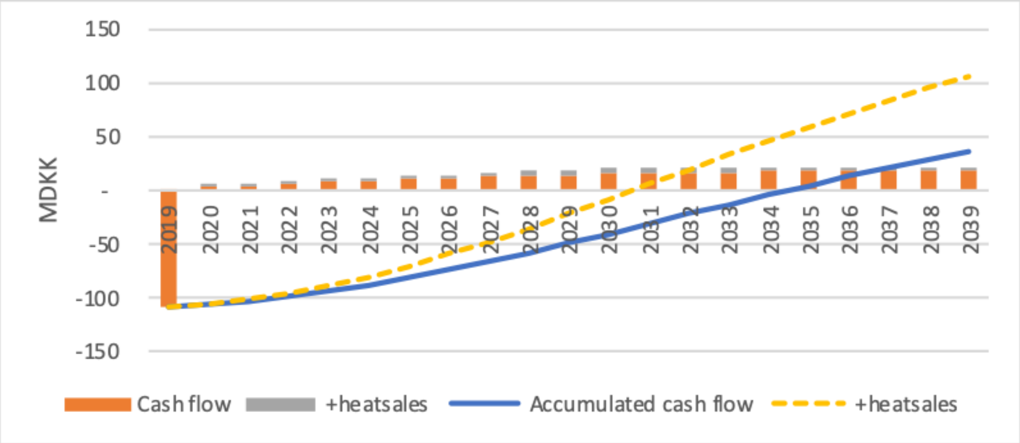


Figure 15 – Cash flows of HT-TES (15 MW retrofit plant)

The pay-back time of the HT-TES storage system in a retrofitted approach is around 12-15 years depending on whether or not the heat is sold for district heating (and at which price it can be sold).

Results: New HRSG component

The HT-TES storage concept in combination with a new HRSG component is significantly more expensive than the retrofit approach where the HT-TES is combined with the already existing HRSG component on a power plant. However, investing in a new HRSG component allows for a optimization of the electricity efficiency coefficient, where an efficiency of 30% would be obtained. The total CAPEX cost of such a system – as previously mentioned – is approximately 278 million DKK.

Figure 16 shows that the HT-TES system has a higher revenue stream than in the retrofitted approach.

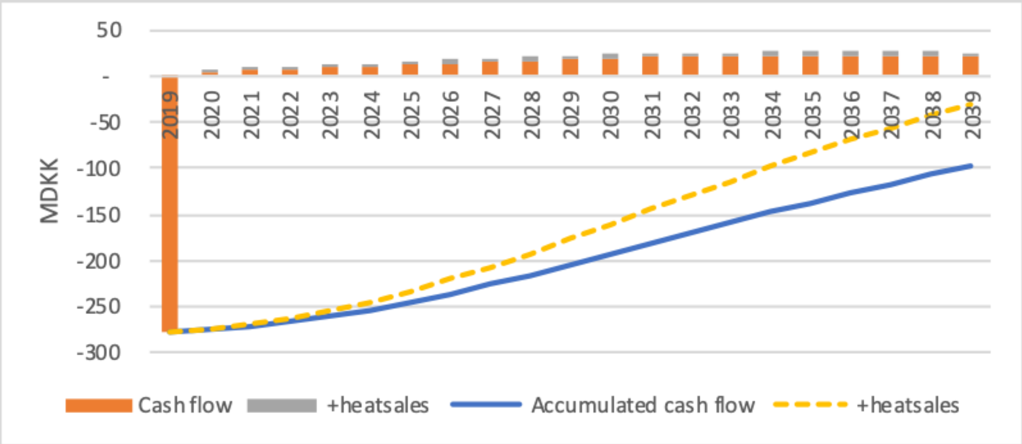


Figure 16 – Cash flows of HT-TES with new HRSG component (18,5 MW)

The HT-TES storage system has a positive cash flow of 12 million DKK in 2025 and over 20 million DKK after 2030. The pattern from the retrofit case with low revenue streams in the first years (less price fluctuation) and increasing revenues towards and after 2030 is observed. The higher efficiency of the new HRSG is reason for a higher income. However, the increased income is not able to offset the more expensive investment which results in a net present value (after a 20-year period) of -100 and -25 million DKK depending on if heat sales are included.

Results: Green field plant

As previously described this scenario consists of: The investment in a new HT-TES storage system, a new HRSG component and a new turbine. The components are optimized in order to achieve the highest electricity efficiency coefficient possible. With this goal the green field plant does not produce any heat. The electricity efficiency is assumed to be 40% and has a total CAPEX cost of approximately 473 million DKK.

Figure 17 shows that the green field plant has a discounted income from electricity sale of approx. 30 million DKK per year from 2030. However, the significant investment cannot be covered by this income (over a 20-year period) which results in a negative net present value of -215 million DKK. If the green field plant is deployed in year 2020 (as assumed in the analysis), the cost of the plant should be not more than 250 million DKK in order to achieve a positive net present value over 20 years.

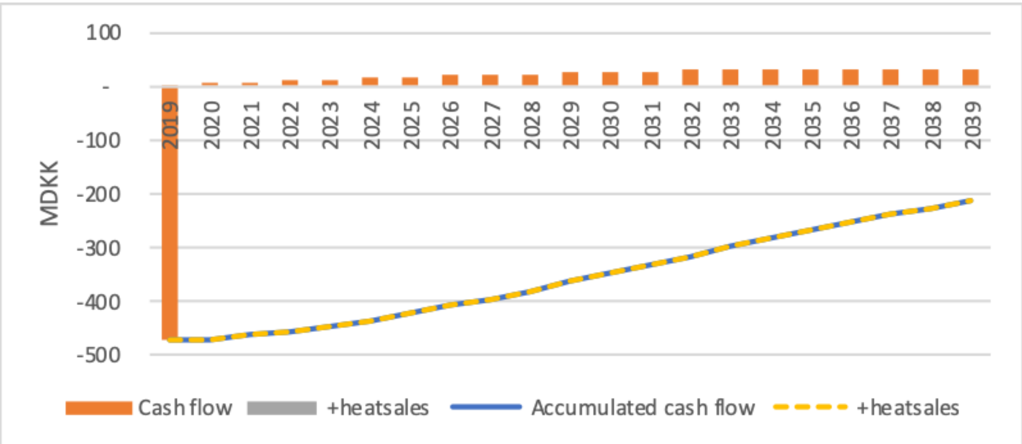


Figure 17 – Cash flow for a new green field plant (24,5 MW, electricity only)

Cannibalization from other storages

The analysis shows that electricity storages in a future energy system (with a lot of fluctuating renewables) has a high value even though the value declines a little with the size of the storage. If a HT-TES storage system is deployed which is 10 times larger than the system assumed in the retrofit case, the cash flow will "only" be 8 times higher (and not 10). As expected, there will be a cannibalization effect with more and more storages introduced into the system. A way to minimize the cannibalization effect is to expand the market for flexibility services, which is a service that the storage can deliver.

The same cannibalization effect can occur if other storage or flexible technologies are introduced[2]. With a balanced deployment of storages and flexible technologies in sync with the demand, the market for such technologies will most likely increase significantly over time – especially in the period after 2025.

Corporate economics with current regulation

Since the HT-TES storage system should be combined with a power plant, a connection to the high-voltage transmission grid will most likely be available. If so, this would mean that the costs for a new connection can be neglected and that the storage system should only pay tariffs to the TSO (in DK: Energinet). Currently, the tariff in Denmark is 8 øre/kWh for consumption and a feed-in tariff of 0,3 øre/kWh. In addition, under the current rules the HT-TES will most likely pay process tax for electricity consumption of 0,4 øre/kWh.

When the storage is optimized towards maximizing the value for the system (and thereby neglecting tariffs), the storage uses in all three cases 50 GWh in 2025 for charging and 100-110 GWh in 2030 and 2035. If the tariffs mentioned above should be paid by the storage, it would result in a cost of over 4 million DKK per year in variable tariffs and over 8 million DKK per year from 2030. This payment would reduce the net present value with 75 million DKK over the lifetime of the project. Since the electricity consumption is similar in all three cases the tariff payment is similar as well. This means that the retrofit plant would end up with a positive net present value of 20 million DKK over the lifetime of the plant (including heat sales) and a negative net present value if heat sales are excluded. The two other configurations (new HRSG and green field) would still be negative – just 75 million DKK more negative.

[2] Examples: Siemens ETES rock-storage, electrolysis and hydrogen storage, which can deliver similar flexibility to the electricity system.

1.5.4 Dissemination of the project.

Creation of website:
The sub website seas-nve.dk/energilager was created in late 2016 and later the main webside www.energilager.nu. Several press releases have been posted on seas-nve.dk in the period of late 2016 to mid-2019.

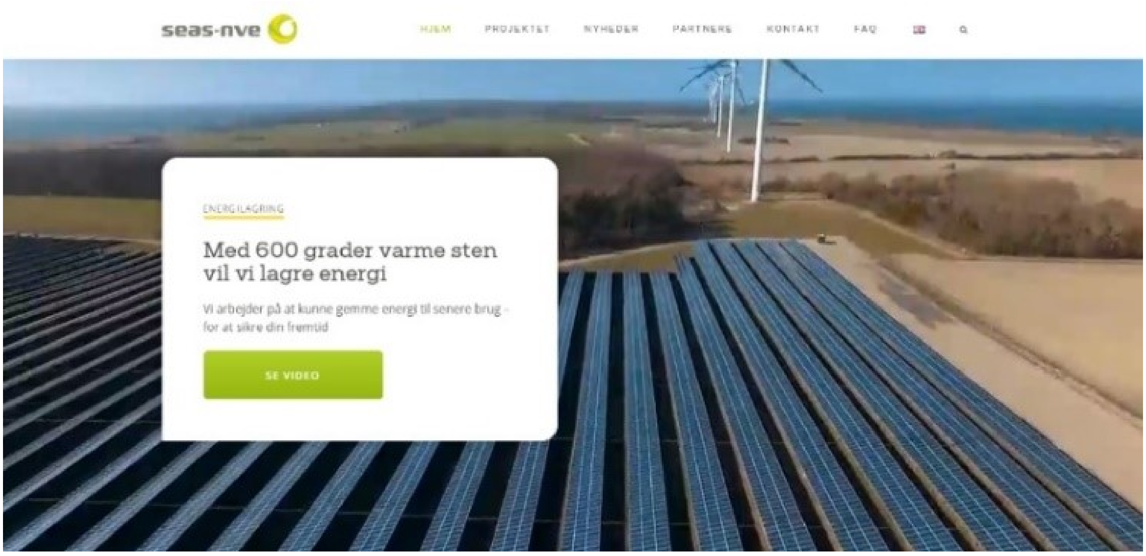


Figure 18 www.energilager.nu

Altogether the websites and press releases has generated more than 15,000 page views including more than 5,700 visitors to the energilager.nu website alone. The numbers are excluding SEAS-NVE IP-addresses.

Communication activities for youth and school children:

During three days in September 2018 SEAS-NVE took part in Ungdommens Folkemøde (Danish Youth Rally). SEAS-NVE focused on the HT-TES project, showcasing the project to more than 30.000 participating school children and students. For three days SEAS-NVE hosted two workshops about the HT-TES project for more than 70 school children and students.


Figure 19 - Danish youth rally

DTU has been active in outreach to high schools and universities by communicating with students who include the device in a project or for tours of classes. Some of these tours are shown in Figure20.

Figure 20 - Tour for an eighth-grade class (left) and a tour for a group from Roskilde University and two ninth-grade students (right).

Open house at DTU Risø Campus:
11th May 2019 the Committee of Representatives of SEAS-NVE visited the HT-TES pilot at DTU Risø together with the entire SEAS-NVE Board of Directors.

Figure 21 – open house at DTU Risø Campus

Press/PR activites:
During the 2,5 years the HT-TES project has been a case in several press, PR and communication activities. SEAS-NVE have e.g. issued following press releases:

- Når vi kan gemme energi, kan vi løse klimakrisen (https://www.seas-nve.dk/koncernen/presse/nyheder/naar-vi-kan-gemme-energi-kan-vi-loese-klimakrisen-005)

- Minister: Stenlager kan inspirere hele verden (https://www.seas-nve.dk/koncernen/presse/nyheder/minister-stenlager-kan-inspirere-hele-verden-004)
- Grøn omstilling med tusindvis af skoldhede småsten (https://www.seas-nve.dk/koncernen/presse/nyheder/groen-omstilling-med-tusindvis-af-skoldhede-smaasten-003)
- SEAS-NVE og Clever engagerer ungdommen (https://www.seas-nve.dk/koncernen/presse/nyheder/seas-nve-og-clever-engagerer-ungdommen)
- Opvarmede sten skal løse fremtidens energiudfordringer (https://www.seas-nve.dk/koncernen/presse/nyheder-og-pressemeddelelser/2016/pm-energilager)

National, regional and local media have been reporting about the project both on site, through live interviews, written articles and as case in broader discussions about energy storage as it was the case in December 2018 where national broadcasting (DR TV Avisen) visited our site and used the HT-TES project as a case in the COP24 discussions.


INDLAND

Kan 600 grader varme sten være løsningen på at lagre vedvarende energi?

En af de store udfordringer for den grønne omstilling er, hvordan vind- og solenergi kan lagres billigt.

CHRISTINA NORDVANG JENSEN, JOSHUA HOLLINGDALE OG MICHAEL KRAGELUND
12. DEC. 2018 KL. 21.30 BEMÆRK: ARTIKLEN ER MERE END 30 DAGE GAMMEL
[o] LÆS OP

Siden tirsdag har energi-, forsynings- og klimaminister Lars Christian Lilleholt (V) vist den grønne fane ved COP24 i den polske by Katowice og forsøgt at slå et slag for vindenergi.

(https://www.dr.dk/nyheder/indland/kan-600-grader-varme-sten-vaere-loesningen-paa-lagre-vedvarende-energi)

The result has been 72 news-paper articles, radio interviews, TV spots etc. in the period from November 2016 to May 2019 excluding the reach to 3,2 million PR contacts alone during the days in March, where the HT-TES pilot at DTU Risø was officially opened.

Both TV2 and DR Radio and TV and almost all Danish daily press covered the event and opening of the HT-TES project:

NØGLETAL

Antal omtaler	76
Quality Score	48
PR-kontakter i mio.	3,2
Budskab*	99%

*Andel af budskab baseret på antal artikler

Medietype	PR-kontakter i mio.	Antal artikler
TV	1,17	7
Online	1,02	22
Print	0,57	37
Radio	0,46	10

Videos and Social Media:

<u>VR video on YouTube:</u> 4,631 views of SEAS-NVE | Oplev vores energilager indefra (VR) Furthermore, the video generated 25.843 views on Facebook:

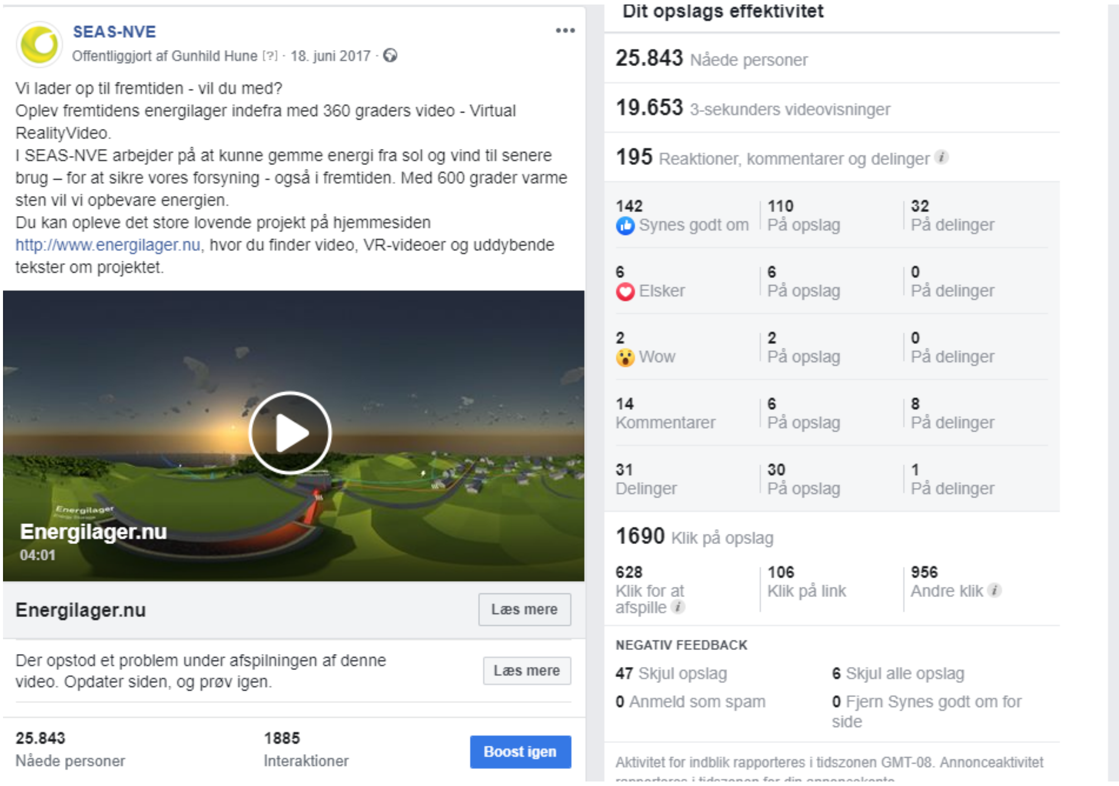


Figure 22 - Facebook

<u>Brand video – Danish on YouTube:</u> 2900 total views of both SEAS-NVE | Med 600 grader varme sten vil vi lagre energi and SEAS-NVE | Med 600 grader varme sten vil vi lagre energi V2 Furthermore, the video generated 82.829 views on Facebook:

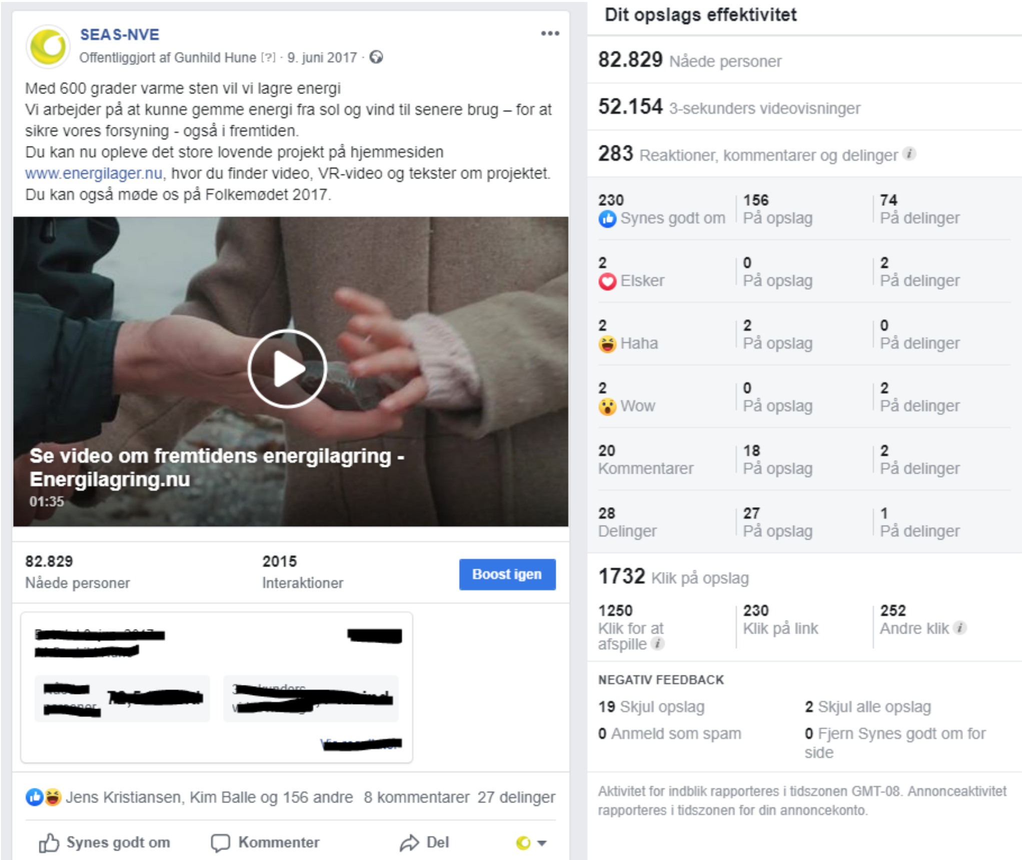


Figure 23 – 82.829 views on facebook

<u>Brand video – English on YouTube:</u> 296 total views of both [Energy Storage]() and [Energy storage v2]()

<u>Explanation video on YouTube:</u> 2,359 views of [Forstå energilagring på to minutter]()

<u>Dialogue on Social Media</u> In general, the dialogue on Social Media has been very positive and full of curious and hopeful questions. The questions can be divided into technical interest, general curiosity, positive and cheerful comments. Se examples below:

Figure 24 – Dialogue on social media

<u>International interest and dissemination</u> State of Green, several Danish Embassies (Denmark in the World) and international medias have been mentioning, retweeting and posting links and articles about the project. Se example below

Figure 25 – From the Danish embassy in Ireland

Dissemination from DTU's standpoint has consisted of presenting results at international conferences, publishing peer-reviewed journal papers, reporting results to popular media and giving tours of the facilities to the general public.

Results of the project have been presented at the Conference for Sustainable Development of Energy, Water and Environment Systems 2018 (including a paper in the conference proceedings) and the International Energy Conference REMOO in 2018 and 2019.

The experimental results will be presented as a lecture in the PhD course "Modern Energy Research" at DTU in November 2019. A journal article on the horizontal flow rock bed has been published in Applied Energy and another paper on its modelling is under review at Applied Thermal Engineering. Additional research articles are planned, especially on the experimental results for the vertical flow system.

The technology and experimental facilities have been the subject of one master project at the Polytechnic University of Turin, two master projects at the Polytechnic University of Milan, one master project at DTU, a bachelor project at DTU and three bachelor projects for visiting French students.

Other events:
18th March 2019 the HT-TES pilot at DTU Risø was officially opened by Danish Minister of Science, Technology, Information and Higher Education,

Jesper Hjulmand, CEO at SEAS-NVE, and Claus Nielsen, University Director, DTU and 100 project stakeholders and representatives from almost all Danish medias. See results of the press coverage above.

During the Danish People's Meeting at Bornholm in 2017 the HT-TES project was presented during the event "Hvordan får vi grøn energi, når vind og vejr svigter?". Also in 2018 and 2019 the HT-TES project was used as a case during discussions and events.

The project has also attracted interest from industry and academia and groups from a number of private companies and universities have taken a tour of the facilities and discussed possibilities for future thermal energy storage projects.

1.6 Utilization of project results

The results and experience gained in this project have opened new collaboration possibilities and new research topics. Future research projects may include optimization of rock beds regarding flow configuration and rock selection, more thorough studies of rock properties, assessing the lifetime of such a system, and exploring novel system designs such as induction heating of rocks such as magnetite. The topic may also be included in future course materials. The results have been communicated widely and inquiries have been answered. However, detailed plans or results have not been released.

The results of the project have been used to produce research papers and conference presentations that establish DTU Energy as a group doing significant research in thermal energy storage. DTU's main goals regarding the technology are to participate in similar development projects that will bring the technology closer to the market as well as future research projects funded by Danish, EU and similar agencies. The experimental equipment, data generated and thermofluid models that have been developed are expected to be the foundation for future funding applications and student projects. DTU Energy has already received partial funding for a PhD project studying the coupling of the rock bed to a biomass gasifier from the *Christian og Anny Vendelbos Fond*. The student is expected to begin after the summer holiday. The success of this project has changed DTU Energy's internal strategy regarding energy storage and now sensible thermals energy storage is one of the main energy storage media that the department considers along with chemical and battery storage.

The analysis of various rock materials indicates that several possibilities for exploiting local, 'off the shell' materials exist. The results further show that heat capacity in terms of thermal energy density pr. volume varies substantially for the different considered materials (70 %). This is possibly going to be important for the overall profitability of an eventual HT-TES facility.

A commercial HT-TES storage system would obviously optimize its operation in relation to the actual tariff and tax payment and not necessarily in relation to the entire system economy. Therefore, the loss from a corporate economics point-of-view could be reduced a little, but there will be a socio-economic loss if the storages are not optimized towards the system. Therefore, it is relevant to assess whether the current tariff structure supports the correct initiatives in a future energy system where electricity storage will play an important role. Work regarding the tariff system is already in progress.

The challenges for the HT-TES storage concept in relation to its socio-economic feasibility is assessed as limited if the HT-TES can support an efficient integration of fluctuating renewable energy in the future energy system. From a corporate feasibility point-of-view, the HT-TES can be challenged by a tariff and tax structure that does not support a uniform investment incentive from both a socio- and corporate point-of-view.

In general, the HT-TES storage concept will compete with similar storage and flexible technologies that are able to deliver the same services (in the same time horizon) as the HT-TES. If the competing storage technologies are all able to integrate fluctuating renewable energy in a socio-economic efficient way, it must be expected that the cheapest and most efficient technology will dominate the market. Therefore, one of the most important tasks in the future for the HT-TES project are to increase the efficiency of the technology while decreasing investment and operation-/maintenance costs of the HT-TES.

Potentially, the HT-TES storage can also participate in other energy markets than the day-ahead (spot) market. For example, the HT-TES storage could bid into the intraday (balancing) market and thereby contribute to the hourly balancing between production and consumption within the actual operation day. Additionally, participation in the regulating market and thereby deliver ancillary services can also be an option. Both markets can provide the HT-TES storage with additional income streams.

1.7 Project conclusion and perspective

Storage – the conclusion

- The project results indicate that rock bed energy storage technically works.
- The system was optimized from the initial pilot stage to the demonstration plant. There are still improvements that can be made, but it was shown that it is possible to build a plant that can store and release energy using a simple, safe, cheap, and widely available, storage medium such as rocks. This gives hope for future projects where existing infrastructure can be used to establish a full-scale HT-TES.

The rocks – the conclusion

- In terms of rock materials, the results indicate that magnetite would be best suited. Even with a higher price than some of the other rock candidates the costs of the rock material will possibly be low compared to the overall costs of a HT-TES.
- The knowledge gained in this project will be utilized in looking at potential applications.
- Although the rock material plays a crucial role in the performance and capacity of a HT-TES it is not the limiting factor. It should be possible to obtain suitable rocks almost anywhere in the world to heat and store energy.
- It remains unknown what long-term consequences of repeated and multiple cycles are for rock materials employed for HT-TES at high pressures. This is a field that could be explored further in experiments designed for accelerated tests at higher pressure.

Business case – the conclusion

- The HT-TES concept shows socio-economic feasibility in the long term.
- Current tariff structure may not support the corporate feasibility of a HT-TES concept.
- The storage is highly dependent on large fluctuations in the electricity price if the storage should buy and sell electricity directly from the electricity market. Therefore, the analysis shows highest value of the HT-TES concept after 2025.
- The HT-TES concept may experience positive upsides from heat sales and system- and balancing service.
- In the long term (after 2025) the storage can have a high level of utilization.
- Lowering the costs of the system is more important than increasing the efficiency.
- Because it is based on a simple principle that could be almost everywhere applied, the competition is potentially large.
- Equally, alternative energy storage systems such as batteries, Compressed Air Energy Storages (CAES) are also competitors to a rock bed HT-TES.

Annex
Relevant links

http://energilager.nu/en/home/
https://www.dr.dk/nyheder/indland/kan-600-grader-varme-sten-vaere-loesningen-paa-lagre-vedvarende-energi
https://samvirke.dk/artikler/energilagring-gronnere-strom-begynder-med-et-hul-i-jorden
https://www.seas-nve.dk/
https://www.energy.dtu.dk/english
https://energinet.dk/
https://www.danskenergi.dk/
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