

Final report

1. Project details

Project title	FlowStore – A latent isothermal flow battery for industrial steam
File no.	64021-7011
Name of the funding scheme	EUDP
Project managing company / institution	SiOx
CVR number (central business register)	35036059
Project partners	Copenhagen Atomics
Submission date	22 July 2025

2. Summary

Project summary:

- **The purpose of the project**

To demonstrate a new latent energy storage concept based on salt where the energy would be stored in molten salt that could be discharged through partly solidifying the salt in a flow through a heat exchanger and thereby get access to the latent heat. The storage concept could help the process industry in utilizing energy produced from renewables.

- **Results, conclusions and perspective**

- Salt formulations for storage mediums were found
- Heat exchanger type with coating was established
- Optimized design of latent heat storage system was made

Eutectic salt mixtures are used as storage mediums and the desired output temperature can be tuned by eutectic formulations because the eutectic point of a mixture defines the melting temperature. Eutectic mixtures were identified and explored to find the best suited ones and to have a range of temperature options for a future storage system.

A coating helps to ease the flow of partly solidified salt through the heat exchanger. Suitable heat exchanger types and coatings were explored.

The system went through several design iterations and modifications based on learnings from running tests. Especially the pump has required several modifications. The result is that we now have an optimized design for a future test setup. The many challenges with the setup have made it difficult to validate the technology but some good indications came out of the tests that can be build upon in future tests. Most important of these is the access to the latent heat that allows us to get a substantial energy output during discharging.

The storage concept, when fully developed, will help the industry store and use renewable energy directly from electricity or via a high temperature heat pump or high temperature waste heat.

Projektræsumé:

- **Formålet med projektet**

At demonstrere et nyt latent energilagingskoncept baseret på salt hvor energi vil kunne gemmes i en saltsmelte som kan aflades ved delvis at størkne saltet i et flow gennem en varmeveksler og derved opnå adgang til smeltevarmen. Varmelagerkonceptet kan hjælpe procesindustrien med at udnytte energien produceret af vedvarende kilder.

- **Resultater, konklusioner og perspektiv**

- Saltformuleringer til lagringsmateriale blev fundet
- Varmevekslertype med coatings blev etableret
- Optimeret design af latent varmelagersystem blev udført

Eutektiske saltblandinger bliver brugt som lagermedia og den ønskede afladningstemperatur kan justeres ved brugen af en eutektisk blanding fordi the eutektiske punkt af blandingen definerer smeltetemperaturen. Eutektiske blandinger blev identificeret og udforsket for at finde de bedst egnede og for at få en række blandinger at vælge imellem til et fremtidigt varmelagersystem.

En coating muliggør et nemmere flow af delvis størknet salt gennem en varmeveksler. Passende varmevekslertyper og coatinger blev udforsket.

Varmelagersystemet gennemgik flere designoptimeringer og modificeringer baseret op læringen fra test. Specielt pumpen krævede flere modificeringer. Resultatet er at vi nu har et optimeret design til et fremtidigt testsetup. De mange udfordringer med setup'et har gjort det svært at validere teknologien men vi har opnået nogle gode indikationer i vores test som kan danne basis for fremtidige test. En af de vigtigste indikationer var tilgang til smeltevarmen som kan gøre at vi kan aflade en betydelig mængde energi.

Varmelagerkonceptet vil, når det er fuldt udviklet, kunne hjælpe industrien med at gemme og bruge vedvarende energi direkte fra elektricitet eller via høj-temperatur varmepumper eller høj-temperatur spildvarme.

3. Project objectives

The objective was to demonstrate a new concept for utilizing the latent thermal energy that can be stored in salt. This energy is released when the molten salt solidifies. Because of the inherent low thermal conductivity of salt, it is difficult to extract the heat from the solidifying salt fast enough to utilise it in an industrial process. Through this project the objective was to demonstrate on a small scale how the heat could be extracted from partly solidifying salt (a slush) in a flow through a heat exchanger and thereby gain access to the latent heat. This concept, of creating a salt slush in a heat exchanger, would allow one to access

the latent heat by circumventing the low thermal conductivity of the bulk salt. By running the slush in a loop with a storage tank where the solidified salt is accumulated at the bottom, almost all the molten salt can be discharged and turned into solidified salt: only a minor amount of the salt in the flow is solidified at a time during discharge but by separating the remaining molten salt and continuously run it through the loop almost all of it can be solidified/discharged.

Because the latent heat of the salt is utilized the heat input temperature does not need to exceed the heat output temperature required for a specific industrial process. Because this heat storage concept is isothermal in nature it is very suitable for utilizing waste heat or high temperature heat pumps or other heat sources where the accessible heat is limited in temperature and therefore it can potentially be an important technology for the green transition of the process industry. The project therefore originally aimed at demonstrating a discharge cycle by producing steam.

The energy technology is comprised of 3 main systems. 1) A salt system based on an eutectic salt mixture, 2) a coated heat exchanger to transfer the heat from the crystallisation of the salt (the latent heat), and 3) the salt loop with a heat source, storage tank, pump and piping system to loop the molten salt through the heat exchanger and back to the tank.

Salt mixtures were investigated. Based on nitrate salts, eutectic mixtures were theoretically investigated and chemical analysis were made using DSC. Different candidates were found to fit different operating temperature ranges and characterized based on fundamental parameters such as melting point, thermal stability, density, thermal conductivity, specific heat, and heat of fusion. The salt used for testing the storage setup (the molten salt loop) was a sodium potassium nitrate salt. Furthermore, a YARA-salt with glassy-like solidification characteristic were analysed and will be an alternative candidate to the nitrate salts because of its special undercooling properties that can be utilized in the discharge flow.

Coating of heat exchangers. The coating was based on SiO_x in-house coating technology. We investigated a range of similar but alternative coatings to the one we have in-house both for physical and chemical improved properties but also for a more cost-efficient alternative. Different formulations were investigated in relation to coating surface homogeneity as it is important for coverage and smoothness of the coating which inflicts on the surface repellent property. Of the best suited alternatives no one showed better performance than our in-house coating when it comes to repellent properties. Some alternative coatings can be applied in a thicker layer which could be relevant for longevity of the coating. Our in-house coating shows the highest hardness though, which is an equal important factor of the longevity. The in-house coating was used in tests performed on the salt loop test setup. The coating process is a wet chemistry dip coating process where the precursor wet the heat exchanger surface to make a semi solid coating. This coating is then hardened at elevated temperatures and subsequently treated with a single molecule layer of repellent chemical groups based on a silane coupling chemistry. The best suited heat exchangers where plate heat exchanger gasketed where copper brazed is a cheaper alternative.

A molten salt loop was developed for heat transfer tests and as a basic model system for larger storage designs. The main components are a storage tank with heating elements, pump for salt, piping with bypass for salt loop, oil tank for cooling loop, oil cooled heat exchanger, pump for oil, piping with bypass for oil loop, nitrogen blanketing for oil tank, trace heating system, instrumentation mainly in the form of controllers and sensors, and insulation. A note on the cooling loop: the original application planned for a steam loop for the discharge cycle. Instead an oil loop was chosen as it is safer and easier to work with in the experimental phase simply because there is no high pressure. A double walled stainless-steel tank was built and fitted with resistive heating elements in between as heat source. The heating elements were controlled by a Raspberry Pi controller and had a temperature feedback mechanism not to burn the salt during heating. A lid with an integrated vertical submersible gear pump and a salt crystal filter system was build and fitted

onto the tank. The pump motor was placed above the lid controlled through a potentiometer with protective breakable feedback. The gear pump teeth, shaft and housing were modified for better allowed heat expansion. The shaft was modified for longer reach and fitted with flexible couplings for better out-of-axis movement and protective shock absorbance. The molten salt inlet was modified to avoid vortexing and air entrainment. A clamp system for the salt crystal filter was developed and mounted below the pump house. Salt inlet and outlet tubing were fitted through the lid. This design of integrating pump and piping in the lid allowed for easy access to the tank and easy dismantling of the components connected to the tank. The outlet-and inlet tubing connect the heat exchanger to the tank. This comprises the salt loop. An oil loop was connected to the other side of the heat exchanger to transfer heat out of the system during discharging. An oil loop was chosen because is relative safe and easy to work with on an experimental setup compared to a steam loop where high pressure is a concern. The oil loop consists of: a tank with resistive heating elements to be able to start discharge at elevated temperatures not to from excessive salt crystallization that could potentially block the system, a pump, a cooling section to transfer heat out of the complete system, and a nitrogen blanketing based on a nitrogen generator system. The whole system was heat traced and insulated.

These 3 mentioned subsystems make up the energy technology developed in the project and has been demonstrated to a level where the system can run but not continuously and satisfactory. The issues are related mainly to the pump and heating of the salt tank. From learnings throughout the project an improved design has been developed and much of it implemented but the present status is that the pump needs to be replaced and heating elements arranged differently. A modification design for a new pump has been established. Because of the issues related to running the system, experimental results have been limited but still some important indications of the salt crystallization behaviour were obtained and will form the basis for further investigations on an improved setup.

4. Project implementation

A large part of the project has evolved on track but with change of roles for the build of the setup and with delays by the end of the project when running the tests because of many technical issues in the setup. Most milestones have been reached but a final proof-of-concept of the technology was not reach by the deadline due to the many technical issues.

During the project people left positions and therefore we needed to onboard new people during the project. Furthermore, it was decided that Priess would not build and design the experimental setup as first planned (WP4) but instead focus on a scaled-up design suggestion at a later stage in the project when the experimental work had reached a certain mature level. But as described elsewhere, due to the technical issues, that part of the project was not realized far enough and therefore Priess have not spend many hours in the project as it unfolded. SiOx and Copenhagen atomics took over the task of designing and building the experimental setup because Copenhagen atomics already had experience in building salt loops. Furthermore, the ultrasonic enhancement idea (WP3) was not tested, again due to the setbacks in the work with the experimental setup and it was not possible to implement the ultrasonic technology within time of the project. The rest of the work in the different work packages proceeded on track and the milestones were reached except for the M4 and CM1 which is commented further below.

There is a risk of components not tolerating the temperature of the salt. There has been a risk of not being able to measure precise enough heat transfer data due to inconsistent flow measurements.

There is a risk of clogging of the system due to crystallization of the salt and a “runaway” effect where crystallization initiates further crystallization. There is a risk of decomposition of the salt at the zones where heating elements transfer heat to the salt because of elevated temperatures or non-functioning thermo couples.

Most of the work packages were followed according to plan but roles were shifted in WP4 where SiOx and Copenhagen atomics took over the build of the test setup. Furthermore, the final demonstration did not reach a level where the storage system has been fully demonstrated. Milestone 1-3 were reached. Milestone 4 involved producing steam but the system was changed to implement an oil loop instead of a steam loop. The commercial milestone of a letter of intent was not reached as the technology was not developed far enough in the project.

The largest group of problems encountered were related to the test setup. When thermally cycling the setup, components expand and contract and different materials expands differently. This was of course expected but unforeseen problems still arose, and foreseen problems accounted for was still turning out to cause problems. Many of these problems are listed in the following and many had to be troubleshooted during the test phase.

The pump planned to be used in the project turned out to have an essential flaw in that it could not tolerate the salt crystals. Therefore, a gear pump had to be modified during the project. After end build of the test setup the pump still went through necessary modifications during the test phase. The pump house did not fit the gear properly at high temperatures and after modification the gear turned out to be a little too loose causing the gear to lock on itself from time to time. The shaft was modified with flexible couplings which should allow for thermal vertical expansion but unfortunately not sufficiently. An extra spline drive shaft is needed as well. Back flow in the pump head due to the gear modification made the flow measurements (based on pump rotation) unreliable. A protective bypass in the system that would protect the pump in the case of a quick pressure build-up was designed wrong such that it would not relieve the pressure from building up. Instead, a pressure switch should be used.

The thermocouples and heating elements caused problems during the test runs. The thermocouples to provide feedback to the heating element control were placed unfortunate such that they would not give the real skin temperature of the salt. This was designed to ease implementation but it turned out to cause the elements to turn off repeatedly resulting in very slow heating. Many thermocouples stopped functioning (they were of bad quality for high temperature environment) and had to be replaced. One thermocouple stopped functioning such that a lack of feedback caused the heating element to give off too much power such that the salt burned. More heating elements were needed to supply more heat faster for shorter heating time of the salt. The distance of heating elements to the inner tank surface was not designed properly. Inhomogeneous heating of the top and bottom of the tank also caused problems with too large a temperature gradient inside the tank.

The expansion of salt was not accounted for in the right way when designing the inlet of the pump. The pressure sensors were of low quality at high temperatures.

In conclusion it has been challenging to reach a point where experiments could be conducted properly on the test setup. The learnings from all the technical issues have provided knowledge on how to properly design the test setup for future investigations.

5. Project results

Many objectives in the project were obtained such as salt exploration, the coating of heat exchanger, the design plan and component integration and the test setup build. But some objectives were not obtained such as the test of ultrasonic enhancement and sufficient trial runs with enough data collections to sufficiently demonstrate the technology. The obstacles were related to all the technical issues described earlier and mitigation were done and attempted during the test phase.

The technological results that did come out of the project so far is an improved design of a test setup based on learnings from technical issues and failures together with learnings on how to run it properly. With implementation of a new pump and a rearrangement of heating elements an improved test setup can be made.

Indications of latent heat extraction from salt slush in the heat exchanger was obtained but not to a satisfactory and sufficient extend to validate the technology and the idea. This was unfortunately not possible on the final reached state of the test setup at the end of the project.

No commercial results were obtained.

The target group is the process industry needing heat/steam for production.

The project results have not been disseminated outside of the partner group.

6. Utilisation of project results

The technological results will form basis for further investigations of the technology internally by SiOx (and the parent organization Heliac). An improved test setup will be used to obtain data where a new modified pump will be implemented together with rearranged heating elements for improved homogeneous heating of the salt.

There were no commercial results during the project. The project led to employment of an engineer at SiOx that will continue in the company after end project period.

There are several players in the TES field above 100C but few with actual commercialised products for the process industry. No one use the exact solution proposed through this project to our knowledge.

Slow or almost non-existent adaptation of high temperature heat storages in the industry so far can be a barrier. Through project collaboration with industrial an industrial partner to make a show case at an actual industrial site could be one way to overcome such a barrier.

A slow transition to the use of renewable heat in the process industry could be another barrier but if a certain price point is reached with the technology the versatile charging options can help make its case (it can be charged by heat from electricity when there is excess from overproduction from renewables).

Policies to phase out natural gas and expand renewable electricity can be supported by high temperature storages that can move peak energy production. The scope of our energy technology is exactly this for an industrial setting and such a storage solution will furthermore support the grid by offloading energy when there is excess.

7. Project conclusion and perspective

The salt loop test setup design is feasible and can form the basis for further investigations that can validate the technology and idea behind.

The next step is to use the knowledge gained and the improved design to rebuild the test setup for further experimentation. Furthermore different salt formulations will be tested on the loop. Additionally the ultrasonic enhancement idea could be implemented. Upon successful demonstration a scaled up system should be designed and built possibly at an industrial site for implementation in a smaller production setting.

8. Appendices

- Add link to relevant documents, publications, home pages etc.