Technical Sciences
Leeghwaterstraat 44
2628 CA Delft
Postbus 6012
2600 JA Delft

www.tno.nl

T +31 88 866 22 00

TNO-rapport

TNO 2017 R11172

CREATE - Openbaar eindrapport

Datum	5 oktober 2017
Auteur(s)	Christophe Hoegaerts
Exemplaarnummer	0100308988
Oplage	
Aantal pagina's	24 (incl. bijlagen)
Aantal bijlagen	
Opdrachtgever	TKI Urban Energy (administratie@tki-urbanenergy.nl)
Projectnaam	Compact REtrofit Advanced Thermal Energy storage, CREATE (Periode 2016/2017)
Projectnummer	060.13592

Inhoudsopgave

1 Achtergrond

In dit openbare eindrapport, ten behoeve van het TKI toeslagproject 140702, worden de uitgangspunten en resultaten beschreven van het project CREATE.

Papieren exemplaren van dit rapport zijn te bestellen bij:
TNO
T.a.v. Secretariaat Sustainable Processes and Energy Systems
Postbus 6012
2600 JA Delft
O.v.v. TNO rapport nummer TNO 2017 R11172

Voor meer informatie kunt u contact opnemen met
TNO
Huub Keizers
Program Manager Energy Built Environment
E-mail: huub.keizers@tno.nl
Mobile: +316 23 90 01 98

Het project is uitgevoerd met TKI toeslag subsidie van het Ministerie van Economische Zaken voor TKI Urban Energy, Topsector Energie. www.tki-urbanenergy.nl.

2 Inleiding

In dit openbare eindrapport worden de activiteiten en resultaten beschreven van het project CREATE in de periode van 18 mei 2016 tot 1 juni 2017.

Voor de totstandkoming van dit rapport zijn verscheidene Engelstalige bronnen gebruikt. Derhalve zullen delen van dit rapport in het Engels gesteld zijn.

3 Gegevens project

3.1 Projectnummer

140702

3.2 Projecttitel

Compact REtrofit Advanced Thermal Energy storage, CREATE (Periode 2016/2017)

3.3 Betrokken partners

Binnen het H2020 project CREATE zijn partijen uit de gehele waardeketen vanaf het begin tot het eind betrokken bij de definitie, onderzoek en productontwikkeling van het compacte energie seizoensopslagsysteem. De kernkwaliteiten van de consortiumpartners zijn grotendeels complementair:

Name Participant	Type of organisation	Role in the project
TNO	*Onderzoeksorganisatie (niet-economische activiteiten)*	Project coordinator, leader of WP1 and WP3. The main scientific contributions: System definition, design and simulation; Lab-scale thermal storage materials and components development, modelling and testing; Safety assessment of storage system
AEE	*Onderzoeksorganisatie (niet-economische activiteiten)*	Leader of WP7. The main scientific contributions: System definition, design and simulation; Lab-scale thermal storage containment and critical components development, modelling and testing; Development of the control software and hardware; Design and perform laboratory tests of the thermal storage system and assist in the field experiment
TUE	*Onderzoeksorganisatie (niet-economische activiteiten)*	Leader of WP4. The main scientific contributions: System definition; Finding stabilization methods for salt hydrates by formulating composites; Characterizing the formulated composites by studying the (de)hydration processes with advanced experimental tools like NMR imaging and XRD and multiscale modelling.
Vaillant	Groot bedrijf	Lead of WP 6. Vaillant will be working on the specification of the system requirements, the development of components and system layout, including control strategy for the compact storage system. With its knowledge of market & customer needs and development of systems for the heating appliance sector, design, implement, and test.
EDF	Groot bedrijf	Lead of WP2-1.The economic value of thermal storage will be evaluated by the selection of relevant energy scenario including time dependant demand and supply of heat. This value will be an input for the specification of the total system

		cost. EDF will also be involved in Policy implications and workshops.
Tessenderlo	Groot bedrijf	Tessenderlo Chemie will participate in the evaluation of the cost analysis of the chemical salt component, hart of the complete storage system, taking into account a range of production quantities and economy-of-scale effects (part of WP 2). In addition, in its role as chemical producer of the salt, Tessenderlo Chemie will take part in the definition, design and simulation of the overall system (part of WP 3). Main task will be the contribution of Tessenderlo Chemie in WP 4, the thermal storage materials optimization. The company can use its experience
Mostostal	Groot bedrijf	Implemention and integration of heat battery at test location
D'Appolonia	Groot bedrijf	Leader of WP2, Task Leader especially of Task 2.4 aimed at assessing Legislation and standardization issues.
Fenix	Klein bedrijf	WP leader for Dissemination, communication and user awareness of the new system and will be active in the WP dealing with exploitation and business modelling.
Luvata	Groot bedrijf	Development of the main heat exchanger in the storage vessel and on the dedicated heat exchanger for evaporation/condensation, with focus on the corrosion resistance, the heat transfer optimisation, structural integrity and costs minimization
DOW	Groot bedrijf	Thermal Storage Materials optimization (material synthesis and encapsulation) technology and participation in the overall system design.
CALDIC	Groot bedrijf	Assess most sufficient way of production of the mixture of the different materials used.

3.4 Projectperiode

18.05.2016 – 01.06.2017

4 Inhoudelijk eindrapport

4.1 Samenvatting

Het doel van CREATE is het ontwikkelen en demonstreren van een warmtebatterij gebaseerd op Thermo-Chemische Materialen (TCMs), die het mogelijk maakt om economisch haalbaar, compact en verliesvrij warmte op te slaan in bestaande gebouwen.

Het project is uitgevoerd binnen een internationaal consortium onder leiding van TNO.

Belangrijkste inhoudelijke resultaten voor TNO in de periode van dit TKI toeslag project zijn behaald op de volgende gebieden:
- Definitie van de systeemeisen
- Karakterisatie van het opslagmateriaal Na2S
- Ontwikkeling en test van een labschaal warmtebatterij (1kg opslagmateriaal)
- Uitbreiden en valideren van een numeriek model voor de warmtebatterij

Belangrijkste conclusies waren:
- Uit de materiaalkarakterisatie en testen in de 1kg opstelling is gebleken dat Na_2S voldoet aan de performance-eisen die we stellen aan een opslagmateriaal voor warmtebatterijen, zoals energiedichtheid, vermogen, operationele temperaturen.
- Uit systeemoverwegingen is besloten om binnen CREATE de werkzaamheden op een alternatief TCM materiaal voort te zetten.

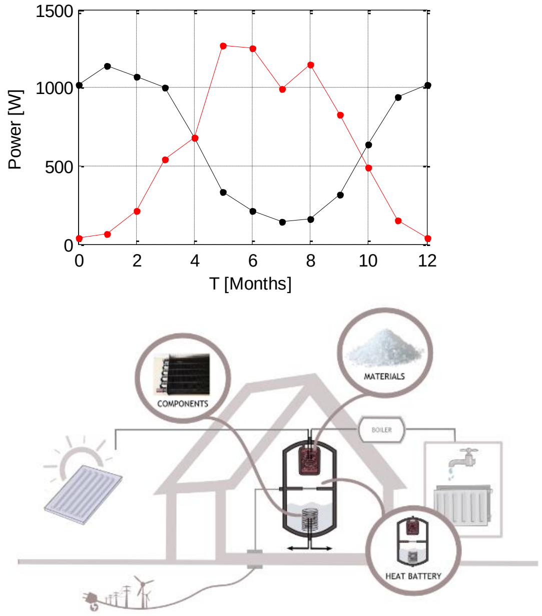
De onderstaande vervolgstappen moeten leiden tot implementatie van deze technologie:
- Doorontwikkeling van opslagmaterialen voor brede toepassing in individuele huizen.
- Op korte termijn doorontwikkelen van een Na2S gebaseerde warmtebatterij voor demonstratie binnen een geschikt toepassingsgebied (early adopter).

4.2 Inleiding (bron: CREATE projectvoorstel)

The recent first global conference on energy storage in Paris, 2014[1], concluded that to achieve the European goal of an energy-neutral built environment in 2050[2,3], harvesting, converting and storage of seasonal solar energy is essential. The 2020 climate and energy package calls already for a substantial increase in renewable energy by 2020. The buildings sector accounts for the largest share of energy consumption (Europe wide approx. 37 %[4]). As two third of the building stock in 2050 is made up of currently existing buildings, the solution should be realised with the

[1] http://energystorageglobalconference.org/
[2] DG ENER Working Paper, The future role and challenges of Energy Storage
[3] ENERGY-EFFICIENT BUILDINGS PPP – multi-annual roadmap and longer term strategy, prepared by the Ad-hoc Industrial Advisory Group, Energy Roadmap 2050 (COM(2011) 885 final).
[4] Technology Roadmap Solar Heating & Cooling, International Energy Agency, 2012. Technology Roadmap Energy Storage, International Energy Agency, 2014. European Technology Platform on Renewable Heating and Cooling (various documents).

current building stock. The CREATE project aims to tackle this challenge by developing a compact heat storage module. This **"heat battery"** allows for better use of available renewable energy sources in two ways: (1) Considering that solar and wind energy are abundant, but inconsistently available, proper use requires storage to bridge the gap between supply and demand, i.e. the intermittent nature of renewables (see figure below)[5]. (2) Heat storage can also increase the efficiency in the energy grid by converting electricity peaks into stored heat to be used later. In this way heat storage increases the energy grid flexibility (e.g. the seamless exchange of energy in different forms, giving options for tradability and economic benefits). Heat storage is therefore considered an indispensable element to facilitate flexibility in the energy grid. The CREATE concept (see figure below) addresses these issues.



Left: non-synchronized heat supply and demand. Amounts of heat needed (black) and available from solar collectors (red), for a typical year and a well-insulated dwelling in Western Europe.[5] Right: Schematic of the CREATE concept. The heart of the system is the heat storage module, i.e. the heat battery. Different sources for heat supply exist, e.g. heat generated by solar collectors on the building or heat-pumps fed by excess electricity from the grid.

4.3 Doelstelling (bron: CREATE projectvoorstel)

The main aim of CREATE is to develop and demonstrate a heat battery, i.e. an advanced thermal storage system based on Thermo-Chemical Materials (TCMs), that enables economically affordable, compact and loss-free storage of heat in existing buildings.

The heat battery targets three **breakthrough elements,** addressed by the CREATE consortium consisting of all relevant partners in the future knowledge and value chain,

[5] "Thermochemical heat storage (TCS) - system design issues", A.J. de Jong, C. Finck, H. Oversloot, H. van 't Spijker, R. Cuypers, Energy Procedia, 2014, 48, 309 – 319.

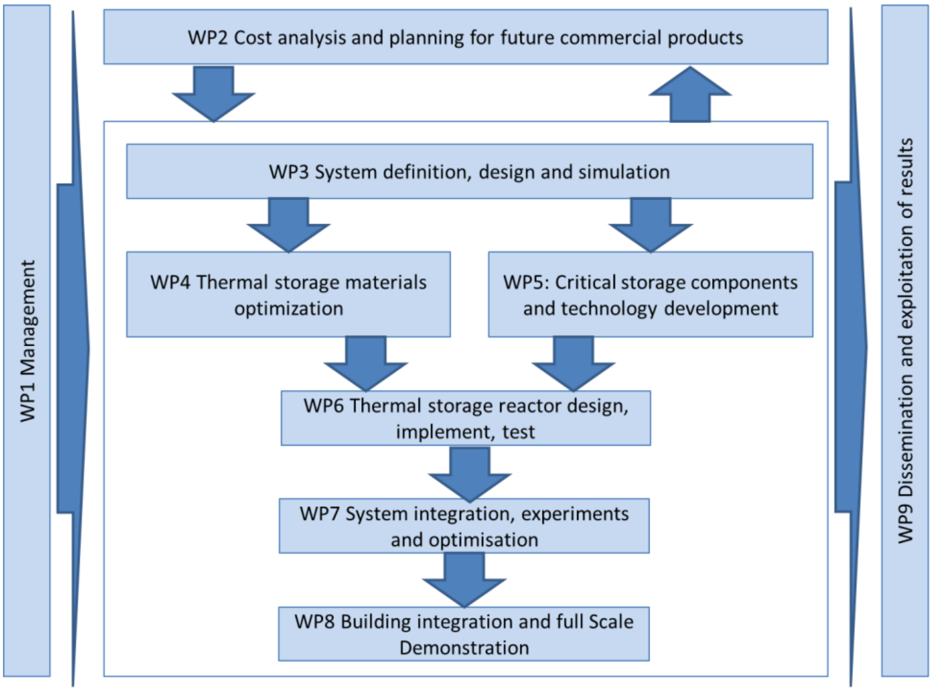
- **Economical affordability:** for the existing building stock we will reach at least a reduction of 15% of the net energy consumption with a potential Return-On-Investment shorter than 10 years. This is achieved by (1) using renewable energy that would otherwise be lost and (2) the reduction of investments in upgrading the electricity grid;
- **Compactness:** novel high-density materials will be used in order to limit the use of the available space to a maximum of 2.5 m^3 thermochemical material. On a system level, 1.5 GJ/m^3 (417 kWh/m^3) is the targeted system energy storage density; on a material level 2-3 GJ/m^3 (555-833 kWh/m^3)
- **No heat losses during storage:** this is an intrinsic material property of thermochemical storage technology, thereby enabling long-term storage.

CREATE will target the following sub-objectives, to overcome the main technical and non-technical barriers regarding thermal storage technology:

- To **develop stable & compact materials with an energy density of more than 1.5 GJ/m^3** (420 kWh/m^3). The thermo-chemical storage materials (TCM) developed within CREATE will have a storage density of more than 6 times that of water and exceed storage density of existing technologies such as PCM's with a factor of 3 or more. The low storage density of these technologies is the current barrier to technology break-through in view of longer term storage (>daily to seasonal). The CREATE solution will require less than 2.5m^3.
- To **ensure efficient and high power energy discharge of as high as 5kW** for a single family home, avoiding necessity of a short term buffer and thus allowing for a simpler and more cost-effective system.
- To **ensure long lifetime** by the preparation of TCM/stabilizer composite materials and the prevention of unwanted side-reactions, e.g. by corrosion or through material impurities. Over 20 years, the modules should perform for over 100 cycles (i.e. 2-10 cycles per annum) with maximum 5% loss in storage capacity.
- To **ensure safe and reliable operation**, through full validation and testing against failure modes and effect analysis and by demonstration of compliance.
- To **develop an affordable technology.** The total storage system needs to be affordable to allow for rapid market uptake. The CREATE project will focus on low-cost and maintenance-free concepts for heat storage (e.g. no moving parts in the storage module, and using cheap active materials – salt and water – as a starting point).
- To **develop the future value chain.** No current supply and value chain exists for the 'heat battery' from the material level up to the system level and grid. CREATE will create just that by having all the required key players in the consortium

4.4 Werkwijze (bron: CREATE projectvoorstel)

The overall approach is shown in the Figure below.



- In **WP1 Management** the overall management work-package for the whole project will take place.
- In **WP2 Cost Analysis and planning for future commercial products** cost, business cases and exploitation models are addressed as well as legislative and standardization issues. This activity will start early in the project as it will be the foundation for the technical research work packages.
- In **WP3 System definition, design and simulation** the system, sub-system and component requirements will be agreed based on Key performance Indicators (KPI's) that will be agreed in the beginning of this work package on the basis of the outcome from WP2. These requirements will flow into the next work packages.
- In **WP4 Thermal storage materials optimization** the materials will be optimized for performance and low-cost production. Thermo-chemical materials, stabilizing additives and production methods will be investigated, benchmarked and optimized. Final outcome is a TCM/stabilizer composite that can be produced at large scales. Materials will be tested in a small-scale lab set-up (<1kg).
- In **WP5 Critical storage components and technology development** critical components, e.g. heat exchanger, evaporator/condenser, vacuum vessel, internal vacuum valve, etc, will be developed to reduce the risk for the storage module development. These components will be tested in a small-scale lab set-up (<1kg).
- In **WP6 Thermal storage reactor design, implementation and test** a first prototype of the storage reactor module on a scale of about 0,15 m^3 will be designed, built and tested. Material and components input will follow from WP4 and WP5. Safety aspects will be considered and safety measures will be implemented.

- In **WP7 System integration, experiments and optimisation** the complete heating system, including control will be integrated based on the storage module developed in WP6. The system will be tested in lab environment and the performance will be validated.

- In **WP8 Building integration and full scale demonstration** the system from WP7 will be integrated into an existing building, which will be occupied. The integration aspects and performance under operational conditions will be demonstrated.

- **WP9 Dissemination and exploitation of results** contains the dissemination, exploitation and communication activities. Further exploitation activities are covered under WP2.

Main TNO tasks in the period mentioned in section 3.4 are:
- WP 1 Coordination of the project and linking together all project components;
- WP 3 System Definition, design and simulation
  - Specification of system requirements as bench-mark measures for further system, component and material development;
  - Obtaining system and control concepts for evaluation;
  - Obtaining performance predictions for system concepts for guidance on system, component and material development.
  - Deliver input for work packages on materials, components, and module development regarding requirements for each module, especially with respect to integration of the components into the demonstration hardware
- WP4 Thermal storage materials optimization
  - Formulation and analysis of of optimal material/stabilizer combinations
  - Lab scale TCM production and optimization (< 1kg)
- Task 5.3 - Testing of critical components with ~1 kg scale lab model of storage module
- Task 6.1 – Thermal storage reactor module modeling (extension and validation of pre-existing models at TNO)
- Task 6.4 – Safety aspects of TCM storage

4.5 Resultaten A) van het project zelf en B) mogelijkheden voor spin off en vervolgactiviteiten

4.5.1 Resultaten van het project zelf

In the period mentioned in section 3.4 TNO has achieved the following main results:
- Coordination of the project (WP1)
- Definition of system requirements (WP3)
- Characterisation of the storage material Na2S (WP4)
- Development and testing of a lab-scale (1kg storage material) heat battery (T5.3)
- Development of a numerical model for the heat battery (T6.1)

4.5.1.1 WP1

TNO heeft de projectcoördinatie van CREATE uitgevoerd tot 30 maart 2017.
Typische projectcoördinatie taken waren:

- Opzetten van een Expert Advisory Board
- Het opzetten van een samenwerking met het paralelle project TESSe2b
- Het organiseren van project en review meetings
- Onderhouden van het contact met de Europese Commissie

Vanaf 1 april 2017 heeft partner AEE INTEC de projectcoördinatie overgenomen van TNO.

4.5.1.2 WP3 (bron: CREATE periodic report M18)

A reference case and comparison approach have been determined:

- Reference house of IEA SHC Task32 (60 kWh/m2)
- Case A: only gas-fired boiler for DHW and room heating
- Case B: conventional heat storage: with collector area identical to case c:
- Case C: thermochemical storage system: gross volume as defined; 2.5 m^3 available volume for storage material; area of solar collectors will depend on the optimum (based on simulations to be performed), but limited to the maximum roof area

Below some of the main requirements are presented:

Requirement	Unit	CREATE heat battery level	Comments
Storage density	kWh/m^3	167	= 0.6 GJ/m^3
Charging temperature	°C	<100	Requirement from EU call text
Delivery temperature	°C	>60	If 60 °C cannot be reached, a back-up heater has to be integrated in de system
Output power	kW	>2.5	Required average power to supply heat to the building

A set of preliminary TCM requirements have been derived and shared.

A system concept has been selected based on a FMEA analysis, SWOT-analysis and a trade-off process.

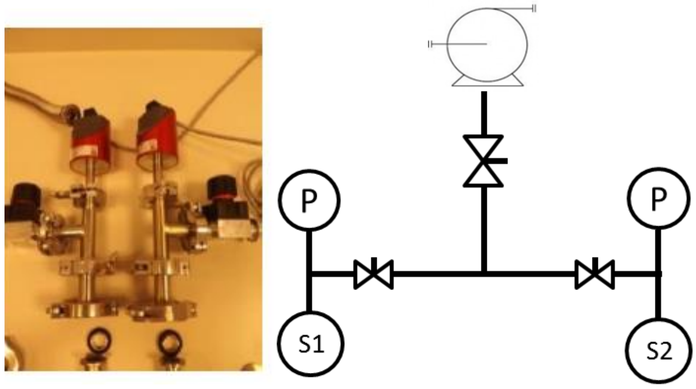
The system concept has been further refined into a Process Flow Diagram (PFD), including all necessary auxiliary equipment.

4.5.1.3 WP4 (bron: deliverable D4.1 - Report on TCM salt/stabilizer composite materials – hoofdstuk 6.5 - Characterization of Na2S based materials)

Several candidate composites of $Na_2S.xH_2O$ have been characterized. The goal of the material characterization task is to provide the essential information that will enable us to select the most suitable material to be used as active material in the heat battery. At this stage in the project, the focus is put on the material's chemical composition and performance.

Outgassing
Outgassing is defined as the evolution of non-condensable gases inside the heat battery and it is known to be detrimental to vacuum setups.

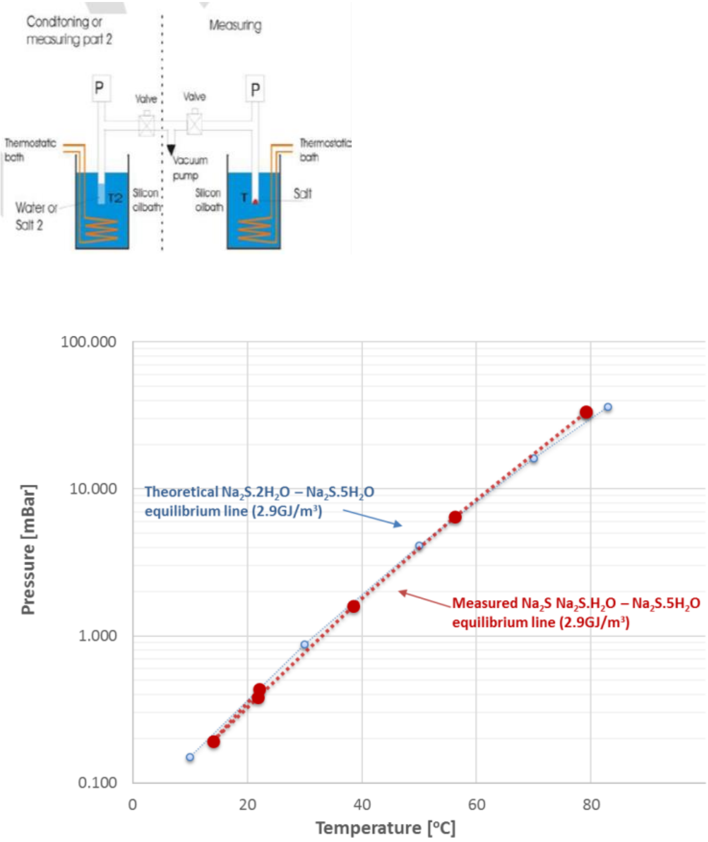
Outgassing of the Na_2S samples was determined using in a first stage an in house developed instrument called a “pT-o-meter”. The setup is built of stainless steel and glass (see image below). The measurements consist of applying vacuum on one Na_2S sample, and measuring the pressure build-up against time and temperature. Should any pressure build-up occur, the respective sample is found not to comply with the vacuum requirements and should be discarded based upon this finding.
In this setup only one sample can be measured at any given time.



Outgassing setup picture (left) and P&ID (right) showing 2 sample cells, 2 pressure sensors, 2 sample valves, 1 main valve and a vacuum pump.

Therefore, in the course of the project, the outgassing measurements were also performed on an instrument developed by TNO to comply with a standard from the Defence area referring to the stability of explosives (STANAG 4556). This instrument and method is called PVST (Pressure Vacuum Stability Testing) and it allows the measurement of outgassing of multiple samples at the same time over periods of a few weeks.

pT -diagrams (using pT-o-meter)
Our in-house developed pT-o-meter (see outgassing setup), allows the measurement of pressure-temperature diagrams (pT-diagram) of the active thermochemical material (TCM). These measurements are essential in determining the pressure-temperature working range of the heat battery.
The setup consists of two compartments, one serving as the water reservoir and the other as the TCM compartment. The Na_2S in the TCM compartment is brought into a known hydration state and then decoupled from the water reservoir. The temperature of the TCM is then changed in a step wise manner and the water vapour pressure is measured. The resulting pressure temperature line is used to determine the operation range of the heat battery and the TCM material energy density.
In the image below, an example of a measured pT line measured for Na_2S is plotted. The measured line corresponds to a material energy density of 2.9GJ/m^3 (determined from the slope of the pT line using van ‘t Hoff equation) and it compares very well with the theoretical pT line of Na_2S.



pT -o-meter setup (left) and pT-diagram (right) of $Na_2S.5H_2O$ measured (red) and theoretical (blue).

Cycling

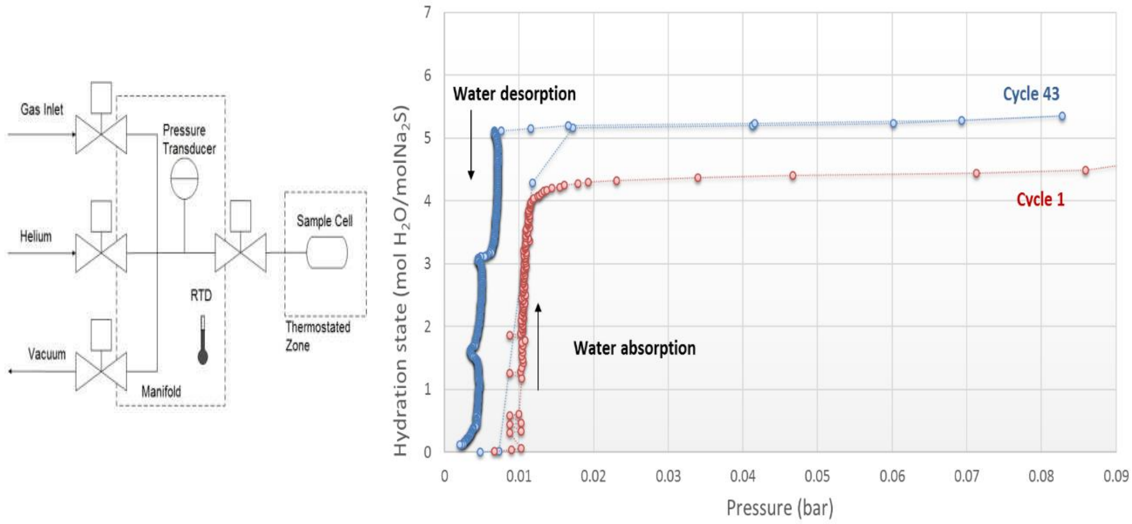
The heat battery is designed to be used for multiple cycles of charging (water desorption) and discharging (water absorption). The stability of the material and energy output upon multiple absorption-desorption cycles is generally called cyclability. The cyclability of the material is tested in the laboratory for a program of 42 cycles. For this purpose, a dedicated cycling set-up is used were temperature and water vapor pressure were cyclically adjusted according to a situation in a realistic setup. Specifically for Na_2S materials, a cycling protocol was performed throughout using a water temperature of 10 °C and cyclically changing sample temperatures between 40 and 80 °C for periods of several hours.

Sorption isotherms (using Quantachrome VSTAR)

The thermodynamic properties of the TCM material obtained from the pT diagrams are validated and further characterized by the measurement of sorption isotherms. For this type of measurements, a commercial instrument called VSTAR and developed by Quantachrome is used.

In the Quantachrome VSTAR sorption analyzer a volume of water vapor can very accurately be dosed to a well-defined mass of sample. Thus, at a fixed temperature,

small amount of water are added (absorption) or removed (desorption) while the pressure is being continuously measured. This water vapor titration makes that an unknown sample can be subjected to ever increasing water vapor pressures at a given temperature, thereby producing the sample's pT-lines. An overview of the equipment is given in the figure below.
In the case of a known sample as it is the case with the Na_2S, the pressure profile obtained from VSTAR is validated with the measurements of pT lines in the pT meter (see section pT-diagrams).
In the figure below, sorption isotherms were measured for Na_2S freshly prepared and after being subjected to 42 cycles (as described in section Cycling). As the hydration state of the Na_2S changes from 0 to 5, the pressure remains almost constant and at the same value measured by the pT-o-meter.
The transition between 0 and 5 hydration state[6] corresponds to an amount of energy stored of 2.9GJ/m^3 as it was also found from the analysis of the pT lines.



Quantachrome VSTAR working scheme (left) and sorption isotherms measured for Na_2S at 60ºC (right) Na_2S fresh (cycle 1 -red) and after 42 cycles of water absorption and desorption (cycle 43-blue)

Conclusion
The measurement and analysis of outgassing, cycling stability, pT lines of the Na_2S materials was performed using several measurement techniques and instruments. The results obtained are consistent with each other and validating in this way the following conclusions:

- The material theoretical energy density of the $Na_2S.5H_2O$ of 2.9GJ/m^3 was confirmed experimentally using two different measurement techniques. (sorption isotherms and pT lines)

[6] The plateaus of the two absorption curves plotted here are apparently at different hydration states. This is in reality an artifact of the measurement procedure. The difference stems from the difference in hydration state of the two samples at the moment of the weighing (which is performed outside the instrument). The real hydration state at the plateau is 5 for both samples and it can be seen from the pressures which correspond to the pentahydrate state ($Na_2S.5H_2O$) as it can be seen from the plot of the pT diagram(see section pT diagrams)

- The Na_2S material was shown to have stable thermodynamic behavior for (at least) up to 43 cycles. This compares to a lifetime of at least 43 years with one annual cycle (charging in summer and discharging in winter)
- The overall Na_2S material performance (stability and energy density) was determined to comply to the system requirements defined in WP3.

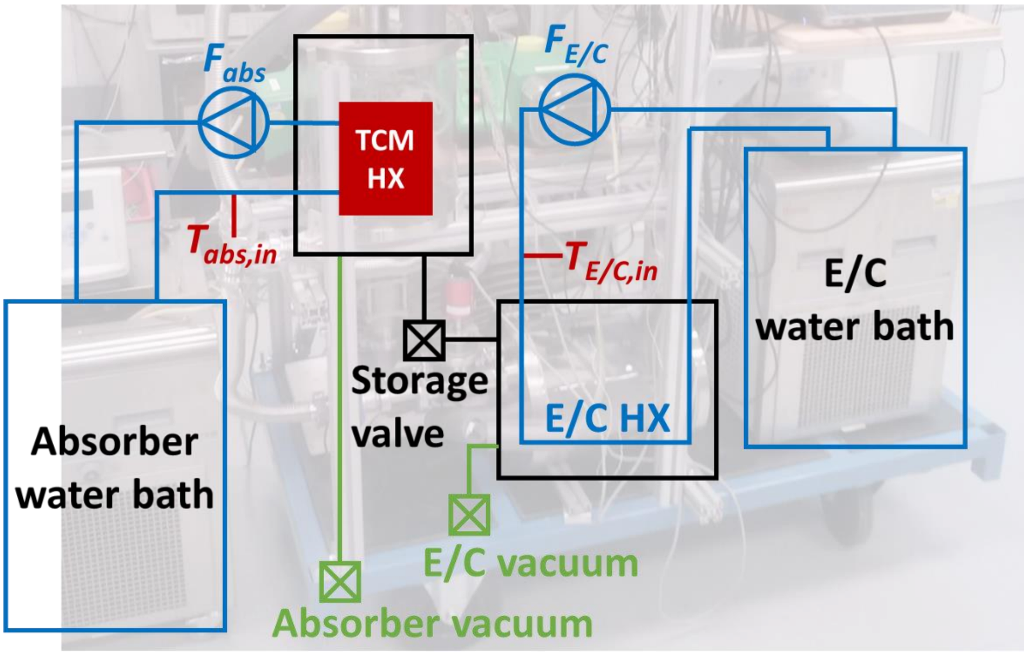
4.5.1.4 T5.3 (bron: TNO memo Measurement plan for 1-kg setup)

The 1-kg setup fundamentally consists of two vacuum vessels, one containing room for an experimental heat exchanger (HX) to be filled with thermochemical material (TCM), the other with an amount of water and a heat exchanger for evaporation/condensation (E/C). Both heat exchangers are connected to external fluid-conditioning baths. Both vessels are connected with a (manual) valve in between. Both vessels can be independently pumped by a vacuum pump. All controls are manual, so operation of the setup is currently limited to the opening hours of the lab, limiting individual sessions to ~8 hours. The HX fluid temperatures are measured using Pt100 4-wire temperature sensors, all other temperatures are measured using type-T thermocouples.

For the validation run a 10x10x10 cm volume heat exchanger has been used. The TCM used for this validation run were Na_2S pellets created for the MERITS project (previous TNO coordinated project).

There are seven control parameters:

1. Temperature of the fluid into the absorber HX, $T_{abs,in}$;
2. Temperature of the fluid into the E/C HX, $T_{E/C,in}$;
3. Fluid flow rate through the absorber HX, F_{abs};
4. Fluid flow rate through the E/C HX, $F_{E/C}$;
5. State of the storage valve between both vessels;
6. State of the valve between the TCM vessel and the vacuum pump;
7. State of the valve between the E/C vessel and the vacuum pump.



Schematic of 1-kg setup showing all control parameters

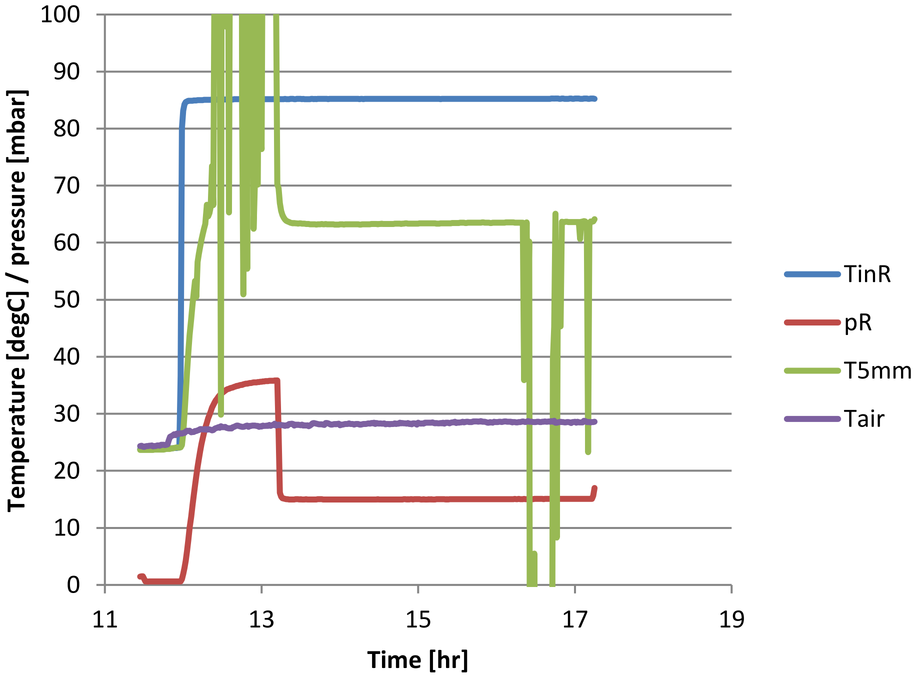
In addition to the control parameters, there are many more observable parameters. Some of these include the pressures in the absorber and E/C vessels, the outgoing temperatures of the absorber and E/C HX, and the temperatures of the TCM and absorber HX itself.

During the validation run various charge and discharges sessions were performed. The goal of this run was to verify that the setup performs as designed, that useful and valid data is obtained, and that the results compared well with earlier data on a well-known material (here the Na_2S TCM from the MERITS project). We focus on a cycle of four days of charging and one day of discharging near the end of the validation run.

Summary of cycle with parameter variations

	$T_{abs,in}$ [°C]	$T_{E/C,in}$ [°C]	F_{abs} [ml/min]	$F_{E/C}$ [ml/min]
Charges	85	10	198	468
Discharge	30	10	198	468

The figure below shows some representative data of the first charging period. The blue line shows the temperature step in the reactor inlet temperature, controlled by the water bath. Both the pressure inside the reactor (red line) and the temperature inside the TCM (green line, with jitter due to sensitive electric leads) follows this temperature increase. The increase in the ambient temperature (purple line) may be related or not. The lab space contains many water baths/circulators that function as heat sources unrelated to the 1-kg setup, but that still influence the ambient temperature.



Validation run, first charge at 85 °C.

There is a large temperature difference (~13 °C) between the reactor HX water and the TCM, both during the pre-heating and during the actual charging. These temperature differences consistently show up during all steps of the experiment, both during charging and discharging. This seems to point to a bad thermal transfer between the TCM and the HX work fluid.

Once the temperatures and pressure reach an equilibrium state, the thermal losses to the ambient can be calculated from the temperature difference between the inlet and outlet water temperatures. This is the general way in which the power into the reactor is calculated. To calculate the net power into the TCM during the actual charging, a static thermal loss to the ambient is assumed, which is calculated from the stable situation just before opening the valve between both vessels.

Slightly after 13:00 hours, the valve between both vessels was opened. The pressure drops close to that of the vapour pressure of water at 10 °C, which is 12.7 mbar. This indicates that the cooling power of the evaporator/condenser is large enough to dominate the process. The dehydration of the TCM cools the material as well. Though not very visible here due to the jitter, typically the TCM temperature shown by the green line drops ~5 °C when the charging starts.

The figure below shows the temperature difference of the reactor HX water and the gross and net powers calculated during the discharge of heat from the battery. Because the temperature difference between the HX and ambient is much smaller during the discharge, the static energy loss is much smaller as well (~2 W). As can be seen from the power graphs, the TCM had not yet fully discharged at the end of the measurement period. Extrapolating from the known data can be done linearly as a first approximation. Both values of the discharged heat can be compared with the stored heat over the four charging periods and the theoretical maximum calculated above. Interestingly, the average powers for the charging and discharging are very different, suggesting that the speed of the two processes in this setup are rather different.

The final results show that the 1-kg setup achieves about 94% of the energy density that was achieved during the MERITS project. This, and the proper functioning of both the control and read-out systems indicate that the 1-kg setup is well-suited for testing the critical aspects of the combined system components i.e. the developed thermochemical material from work package 4 with scaled heat exchangers from work packages 5 & 6.

Summary of results:

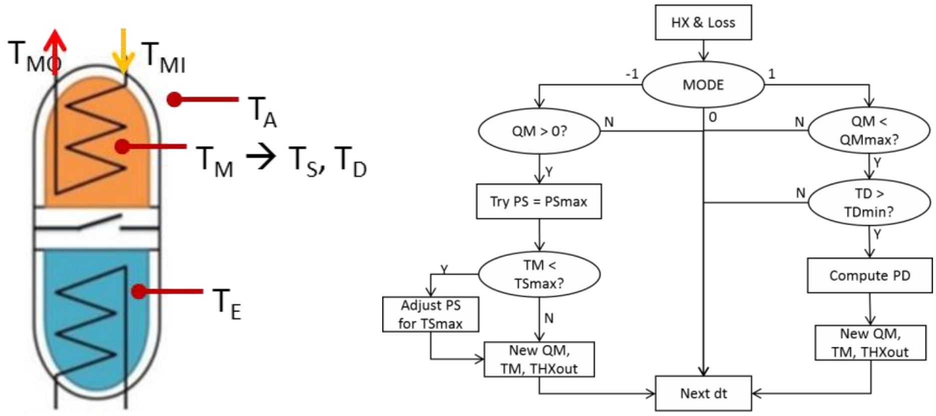
1. Construction and validation of a 1-kg lab-scale model of storage module, with TCM temperatures up to 85 °C;
2. The 1-kg scale setup achieves about 94% of the stored energy density compare to the systems developed in the MERITS project using the same material;
3. A peak power during discharge of 46 W was observed. The average power during discharge was ~20 W;
4. Temperature differences within the TCM are relative large, both with itself, and with the heat exchanger and the work fluid.

4.5.1.5 T6.1 (bron: CREATE periodic report M18)

Reactor numerical model developed. Version 1.0 has capabilities to:

- Exchange heat with Short Term Buffer
- Sensible heating/cooling of reactor by HX with T_{MI}, T_{MO}
- Heat loss of reactor to ambient T_A
- Store heat Q_M in TCM when at desorption temperature T_D
- Extract heat from TCM at sorption temperature T_S
- E/C temperature determines T_D and T_S
- Ideal HXs for reactor and E/C
- Module dimensions, parameters scale with max stored heat Q_{Mmax}
- Control → Module in Idle, Sorption or Desorption mode

State Transition Diagram of Model 1.0 for the TCM reactor.



In Model 1.0 options for external control are very limited since physical behaviour is enforced by the design (autonomous control by the model)

On this basis, the Model 2.0 was set up:

- Control outside module → Only valve open/closed
- Power not assumed fixed by control, but from physics & control
- HX models for reactor & E/C → Predict ΔT
- Heat loss module to E/C
- Warnings if TCM melting, E/C freezing
- More flexibility to change internal parameter settings

4.5.2 Mogelijkheden voor spin-off en/of vervolgactiviteiten

Het CREATE project is ongeveer halverwege de geplande doorlooptijd. Het project zal in het najaar van 2019 worden afgerond met de demonstratie van warmteopslag gebaseerd op de onderzochte thermo-chemische materialen in een demo woning in Warschau, Polen.

Daarnaast zullen parallel nieuwe projecten worden opgestart, waar deze kennis zal worden toegepast.

4.6 Discussie, conclusie en aanbevelingen

Conclusies:

- Uit de materiaalkarakterisatie is gebleken dat Na_2S voldoet aan de performance-eisen die we stellen aan een opslagmateriaal voor warmtebatterijen, zoals energiedichtheid, vermogen, operationele temperaturen.

NB: Na2S heeft van de momenteel bekende TCM materialen de beste performance (energiedichtheid) in combinatie met de laagste kosten heeft (< 1 EUR/kg materiaal). De EC heeft tijdens de uitvoering van de werkzaamheden haar zorgen geuit over de keuze van Na2S als opslagmateriaal (toxiciteit). De EC heeft hierbij aangegeven vooralsnog de voorkeur te geven aan een intrinsiek veilig opslagmateriaal met het oog op brede implementatie in individuele huizen (consumentenmarkt). Vandaar dat in CREATE op uitdrukkelijke wens van de EC verder gewerkt zal worden aan een alternatief TCM materiaal om toe te passen in de CREATE demonstrator.

Aanbevelingen:

- Doorontwikkeling van opslagmaterialen voor brede toepassing in individuele huizen.
- Op korte termijn doorontwikkelen van een Na2S gebaseerde warmtebatterij voor demonstratie binnen een geschikt toepassingsgebied (early adopter).

5 Uitvoering van het project

5.1 De problemen (technisch en organisatorisch) die zich tijdens het project hebben voorgedaan en de wijze waarop deze problemen zijn opgelost

In het kader van het TKI project hebben zich geen problemen voorgedaan.

5.2 Toelichting op wijzigingen ten opzichte van het projectplan

Niet van toepassing voor het TKI project. Echter, voor wat betreft CREATE is het coördinatorschap overgedragen aan partner AEE INTEC, vanwege projectmatige overwegingen.

5.3 Toelichting wijze van kennisverspreiding

De voortgang van de TNO activiteiten binnen het CREATE project zullen in het komende halfjaar overleg gedeeld worden met de projectpartners van het meerjarenplan compacte conversie en opslag.

5.4 Toelichting PR project en verdere PR-mogelijkheden

Binnen CREATE wordt disseminatie naar de buitenwereld georganiseerd door een van de partners. Voor CREATE zijn een website (www.createproject.eu), LinkedIn-profiel, en facebook-profiel aangemaakt dat regelmatig wordt ge-update.

6 Beschrijving van de bijdrage van het project aan de doelstellingen van de regeling (duurzame energiehuishouding, versterking van de kennispositie)

Versterking kennispositie:
Nationaal en internationaal neemt de interesse in compacte warmteopslag toe. Voorbeelden hiervan zijn recent afgeronde Europese projecten als E-hub, EINSTEIN (realisatie laboratoriumopstellingen thermische opslag in zeoliet, het FP7-MERITS (demonstratie thermochemische opslag in zouten voor woningen) en het TKI project TESSEL (demonstratie thermochemische opslag in silica voor woningen).; en het lopende TKI project MJP CCO (ontwikkeling deel technologieën en CCO roadmap).
Met het project CREATE (opschaling gebruik thermochemisch materiaal en verbetering energieopslagdichtheid) is een belangrijke stap gezet in de ontwikkeling van compacte warmteopslag , met potentieel een hoge compactheid en lage kosten in vergelijking met de materialen van de state-of-the-art.
Nederland verstevigt met dit project zijn koplopersspositie op het gebied van thermochemische opslag.

Bijdrage aan de doelstellingen van de regeling:
Door de toepassing van compacte seizoens- of lange termijnopslag wordt het mogelijk om een
groter aandeel van de warmtevraag duurzaam in te vullen door het verschil te overbruggen tussen aanbod van warmte en koude en het gebruik hiervan. In de toekomst is dit van belang voor vrijwel alle Europese woningen.
Hierdoor wordt het gebruik van fossiele brandstoffen in de gebouwde omgeving terug gedrongen en hierbij kan compacte warmteopslag als een van de belangrijke enablers gezien worden om aan de 2050 CO2 doelstellingen te gaan voldoen.
Uitgaande van het gegeven dat de compacte opslag tenminste een belangrijke rol kan spelen in de markt van warmtepompen en zonneboilers kan het huidige potentieel in Europa worden ingeschat op meer dan 1 miljoen systemen per jaar, groeiend naar ca. 10 miljoen systemen in 2020, waarin compacte opslag een rol van betekenis zou kunnen spelen. Uitgaande van een referentie ruimteverwarmingsvraag van 150 MJ/m^2 levert dit bij 1 miljoen systemen en 120 m^2 woonoppervlak 180 Peta-Joule aan besparing op. Dit is een reductie van 10 Megaton CO2 emissie.

7 Overzicht van openbare publicaties

Ten behoeve van verdere kennisverspreiding is dit openbare eindrapport gemaakt wat beschikbaar is, bv. via de projectsite van TKI.

Daarnaast is de volgende conference paper beschikbaar:
A novel heat battery to save energy & reduce CO2 emission, R. Cuypers et al, Eurosun 2016, October 2016
http://proceedings.ises.org/paper/eurosun2016/eurosun2016-0057-Cuypers.pdf

8 Ondertekening

Delft, 5 oktober 2017

TNO

Ronald van den Berg
Afdelingshoofd

Christophe Hoegaerts
Auteur