FINAL REPORT PPS PROJECT: SALTECH

Project title :	**Tunable Composite Salt Hydrates for Thermochemical Heat Batteries (SALTECH)**
Project number	**TKITOE2021402**
Version :	**22^{nd} January 2024**
Project coordinator :	**University of Twente**
Project partners :	**ATAG Verwarming Nederland B.V.** **Nobian Industrial Chemicals B.V.** **Phase Energy Ltd.** **Universiteit van Amsterdam**
R&D line :	**Warmte en Koude Installaties**
Total project budget	**Total project costs: €743.800 and total subsidy: €400.000**
Starting date:	**01/11/2021**
End date	**21/12/2025**
Reporting period:	**01/11/2021 until 21/12/2025**
Reported by:	**Dr.Mohammad Mehrali**
	m.mehrali@utwente.nl

CONFIDENTIAL PROJECT REPORT

In the confidential project report, the activities and results of the project are described. The following subjects should be discussed

1. INTRODUCTION

Thermal energy storage (TES) is a critical component for integrating renewable energy sources and decarbonizing the built environment. While Thermochemical Materials (TCMs) offer high potential storage densities (1-3~GJ/m^3), current technologies face significant barriers regarding multiscale effects, cyclic stability, and power output. Standard salt hydrates often suffer from agglomeration, poor kinetics, and chemical instability (e.g., corrosion, air sensitivity) which hinders large-scale implementation. The SALTECH project was motivated by the need to overcome these limitations through tunable composite materials.

Objective of the Project

The primary objective of SALTECH was to leapforward TCES technology by developing cost-effective, tunable composite TCMs. The specific targets were to achieve an energy density of >1~GJ/m^3 (at system level) and a cyclic stability of >500 cycles. The project aimed to deliver a modular heat battery design that optimizes heat and mass transfer, utilizing membrane science technology to stabilize salt hydrates.

Project Partners

- **University of Twente (UT):** Coordinator; Material development (TE & MSUS groups) and system design.
- **University of Amsterdam (UvA):** Fundamental study of salt hydrates (crystallization/kinetics).
- **Nobian:** Industrial partner; Salt supply, R&D support, and large-scale production feasibility.
- **ATAG Verwarming Nederland B.V.:** Industrial partner; Heat exchanger design, system integration, and market requirements.
- **Phase Energy Limited:** International advisor; Market potential and consultancy.

Method of Research

The project followed a multiscale approach divided into three Work Packages (WPs):

- **WP1 (Material Development):** Focused on 4D kinetic studies (using X-ray Micro-CT) and the synthesis of polymer-salt composites using phase inversion techniques to control porosity and permeability.
- **WP2 (System Development):** Involved designing a modular vacuum reactor, optimizing heat exchangers, and testing single-cell heat battery performance.
- **WP3 (Management):** Covered coordination, IP management, and dissemination.

2. RESULTS

2.1 Introduction: Strategic Planing and Material Selection

At the inception of the SALTECH project, Sodium Sulfide (Na_2S) was identified as a high-potential thermochemical material (TCM) due to its theoretical energy density. However, initial characterization revealed severe practical limitations: high corrosivity towards reactor metals and the generation of toxic hydrogen sulfide (H_2S) gas upon hydration. Consequently, the consortium made a strategic decision to pivot towards safer, more commercially viable salts: Potassium Carbonate (K_2CO_3) and in Carnallite ($KMgCl_3.6H_2O$). This decision ensured that the developed technology would be safe for residential deployment while still aiming for high energy densities.

2.2 Results

Work Package 1: Advanced Material Development

The core innovation of SALTECH lies in transforming raw salt powders which typically suffer from agglomeration and poor permeability into robust, engineered composites.We have started to optimize TCM granules and by understanding their behavior then we moved to encapsulation process.

Figure 1. Schematic overview of SALTECH project from advance material development toward future high performance and sustainable heat battery

A. Granulation Process for Tuning Porosity

To address the critical issue of bed permeability, we developed a novel granulation protocol using a high shear mixer (Eirich EL1) in. This process was optimized to transform fine K_2CO_3 powder (approx d~10-50 µm) into uniform, porous granules (d~3-4mm).

- **Innovation:** By fine-tuning the binder spray rate and pore former mass percentage, we achieved a "raspberry-like" morphology. These granules possess a hierarchical pore structure that facilitates rapid water vapor diffusion into the particle core.
- **Performance Data:** The granulated K_2CO_3 demonstrated a **3-fold increase in hydration rate** compared to the raw powder. In standardized hydration tests, the granules reached 80% conversion within just 12 minutes, whereas the powder bed suffered from "blocking" layers that impeded reaction progress.
- **Mechanical Stability:** Crush strength tests confirmed the granules are robust enough to withstand the weight of a packed bed without dusting or breaking.

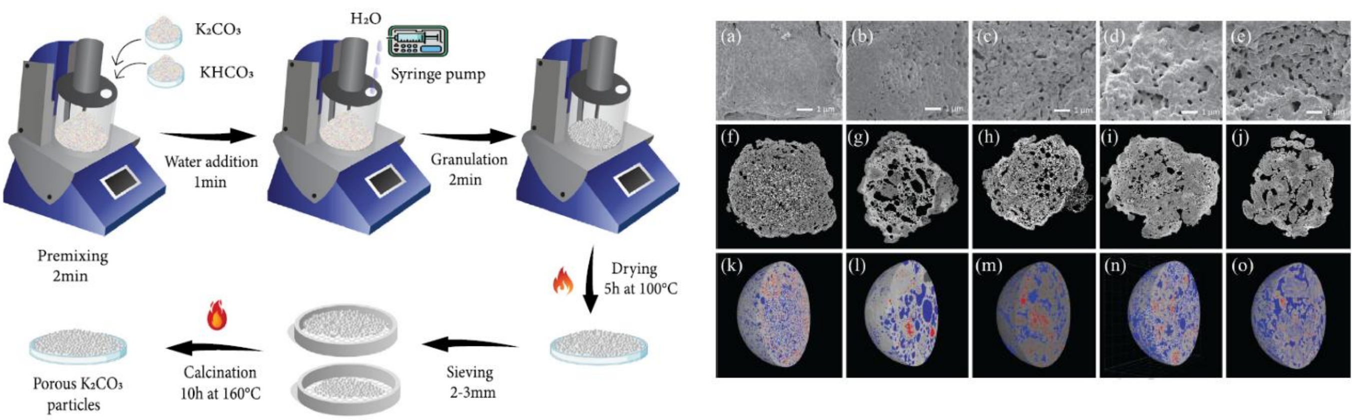


Figure 2. Schematic of the granulation process and porosity formation in salt granules

B. Sepiolite-Reinforced Granules

We addressed the critical trade-off between porosity and mechanical stability in thermochemical heat storage by reinforcing porous potassium carbonate (K2CO$_3$) granules with sepiolite, a fibrous clay mineral. By integrating 20 wt% sepiolite, the resulting "KS20" granules achieved a significant improvement in mechanical robustness, increasing the maximum compressive load from 26.8 N to 48.4 N through a cohesive, needle-like fiber network that dissipates stress. Unlike pure K_2CO_3 which suffers from severe agglomeration and structural breakdown during hydration-dehydration cycles, the KS20 composite maintained excellent structural integrity and resisted clumping while retaining a high volumetric energy density of 0.9~ GJ/m^3 due to sepiolite's contribution to water adsorption via physisorption.

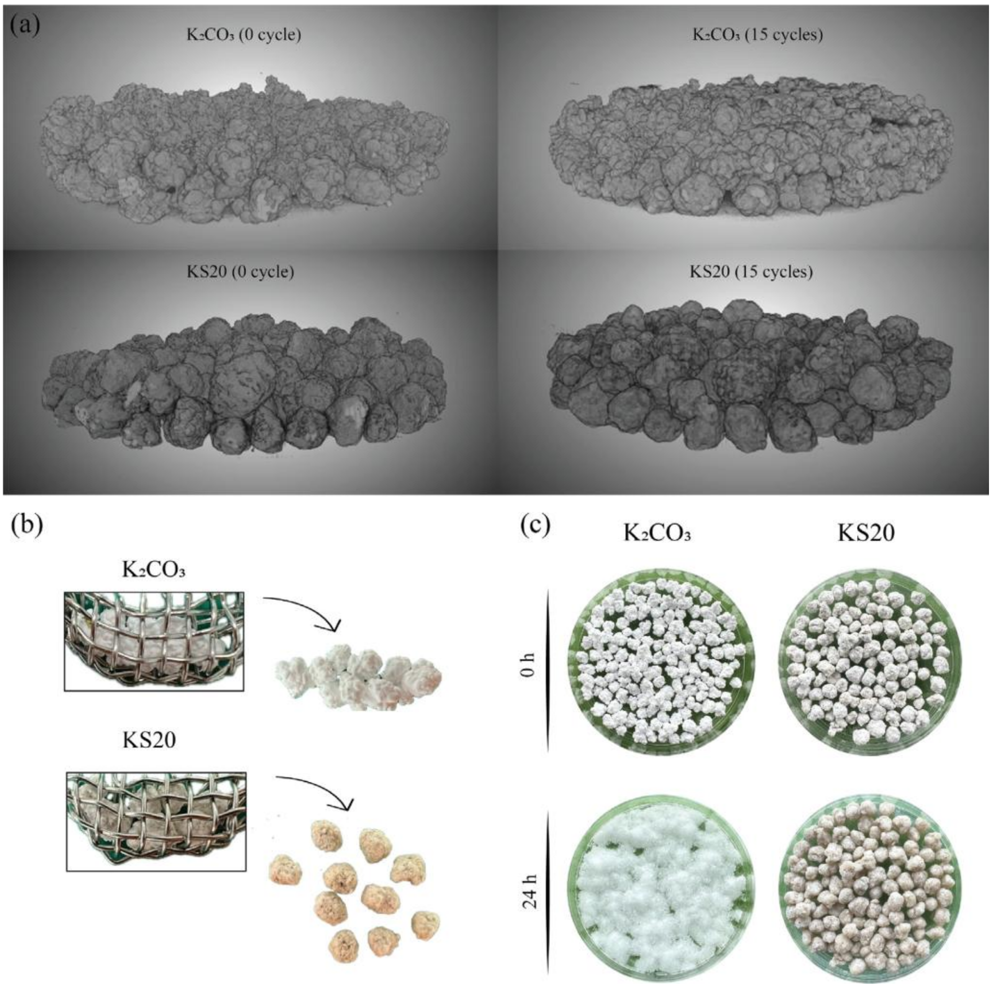


Figure 3. (a) 3D micro-CT images of K_2CO_3 and KS20 granules bed before and after 15 cycles of hydration (30 °C, 40% RH, 6 h) and dehydration (100 °C, 6 h) in the climate chamber. (b) Structural comparison of the granules after 15 cycles under slight pressure in a mesh basket to observe agglomeration. (c) K_2CO_3 and KS20 granules before and after 24 h exposure to room conditions with a relative humidity of 50%.

C. Graphene-Enhanced K_2CO_3 Granules: Boosting Heat Transfer and Cycle Stability

In next step we overcome the inherent limitations of low thermal conductivity and structural instability in potassium carbonate (K_2CO_3) heat storage systems by engineering composite granules reinforced with sepiolite and 1.5 wt% graphene nanoplatelets (GNPs). While pure salt hydrates often suffer from slow reaction kinetics and severe agglomeration, the addition of GNPs significantly accelerated heat transfer, reducing the time required for 90% hydration from 245 minutes to 160 minutes in the initial cycle. Although the inclusion of inert GNPs resulted in a slight reduction in mechanical strength

(48 N to 42 N) 3, the "KSG" composite granules achieved a superior maximum temperature rise of 14°C and maintained a stable energy density of 328–336 J/g over 25 hydration-dehydration cycles. Ultimately, the synergistic effect of sepiolite's structural support and graphene's thermal conductivity prevented the bed collapse observed in pure K_2CO_3 ensuring consistent long-term performance.

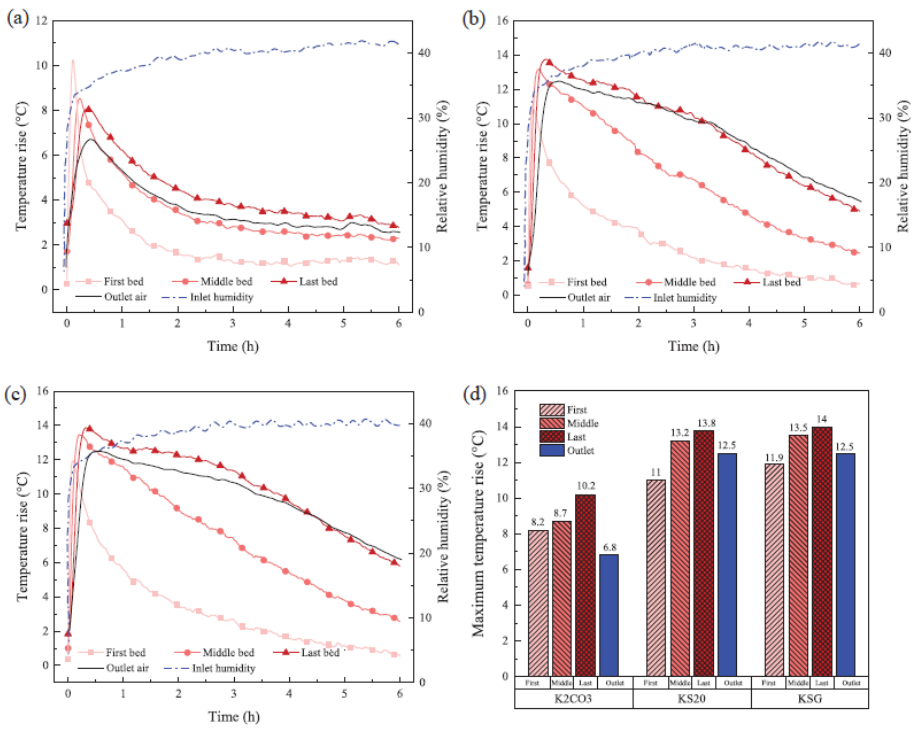


Figure 4. Temperature rise and relative inlet humidity evolution during the second discharge cycle of (a) K_2CO_3, (b) KS20, and (c) KSG granules in the reactor. (d) Maximum temperature rise in the first, middle, and last sections of the bed and in the outlet air for all three materials.

D. Innovative membrane encapsulation for TCMs

To address the critical bottleneck of structural instability in potassium carbonate (K_2CO_3) heat storage systems, the project successfully developed and validated a novel encapsulation technique. K_2CO_3 granules were coated with a porous polyethersulfone (PES) membrane. This semi-permeable shell was engineered to:

- Allow free diffusion of water vapor (essential for the hydration/dehydration reaction).
- Mechanically accommodate the significant volume expansion and contraction of the salt during cycling.
- Prevent particle agglomeration (caking) and disintegration, which typically degrade reactor performance over time.

Experimental characterization confirmed that the membrane encapsulation significantly boosts the robustness of the storage material without severely compromising its thermal performance. Key quantitative results include:

- **Cyclic Stability:** Unlike uncoated granules, which suffer from deliquescence and structural collapse, the encapsulated granules maintained their structural integrity over repeated hydration-dehydration cycles. The flexible outer shell successfully contained the salt while adapting to volume fluctuations.

- **Energy Density:** The encapsulated material achieved a Volumetric Energy Density (VED) of approximately 0.6 GJ/m³. This value remains competitive for compact thermal energy storage in the built environment.
- **Power Output:** Kinetic stability was preserved, with power output stabilizing at approximately **200 kW/m³** at 90% conversion. This indicates that the membrane layer does not create a prohibitive diffusion barrier for water vapor.

The results demonstrate a successful "proof of concept" for stabilizing low-cost salt hydrates. The encapsulation method effectively mitigates the primary failure modes of K_2CO_3 (caking and liquefaction), validating its potential for use in long-term, loss-free seasonal heat storage batteries. This development directly contributes to the TKI Urban Energy goals by enabling more reliable and durable compact thermal storage systems.

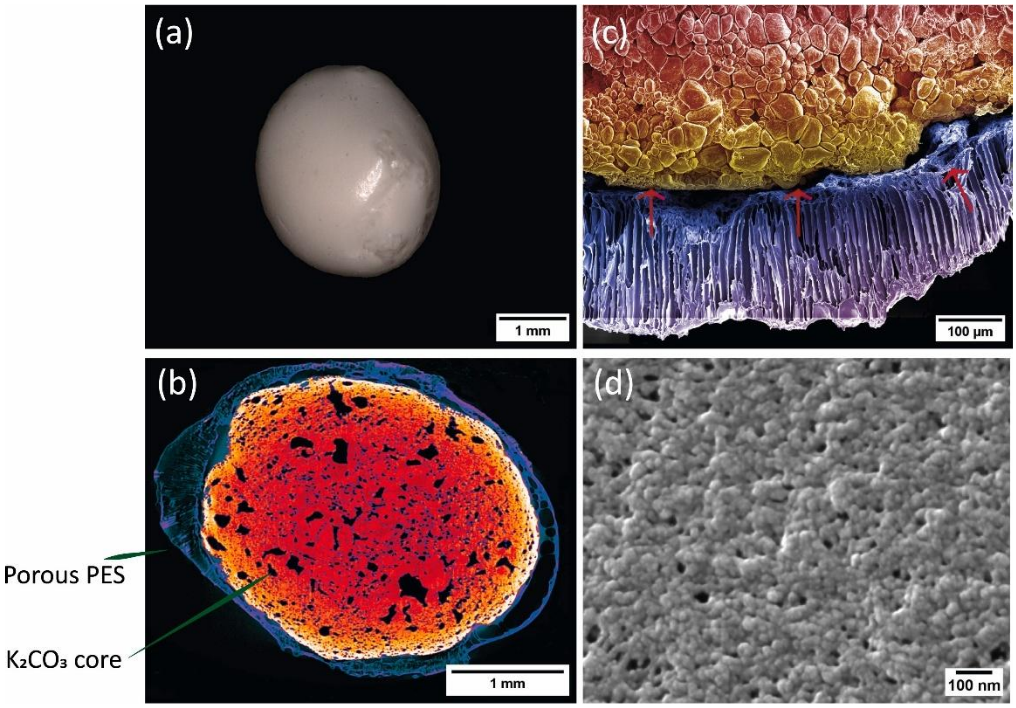


Figure 5. . K_2CO_3 macrocapsule morphology images (a) One macrocapsule particle (b) Micro-CT cross-section (c) SEM interface image of porous PES coating and K_2CO_3 granule (d) Top surface PES coating layer SEM image.

Following the initial validation of Polyethersulfone (PES) coatings, the project advanced to Torlon® (polyamide-imide) to address the mechanical limitations of rigid shells under high volumetric strain. Torlon® was selected for its superior mechanical strength, thermal stability (up to 270°C), and resistance to plasticization. A non-solvent-induced phase separation (NIPS) process was employed to coat porous K_2CO_3 granules (2–3 mm).

The most significant breakthrough in this phase is the development of a **functionally graded "smart" shell** that solves the critical trade-off between mechanical robustness and reactivity. By precisely tuning the Torlon® concentration to 13 wt%, we engineered a unique bilayer microstructure: an outer "finger-like" layer that acts as a high-speed highway for water vapor, and an inner "sponge-like" cushion that absorbs the massive 20–30% volumetric expansion of the salt without rupturing. This optimized architecture delivered a standout **72.8% survival rate** in confined reactor bed testing—where uncoated salts typically fail catastrophically into a solid block—while maintaining a high energy density of **530–580 kJ/kg**. This proves that low-cost salt hydrates can be effectively stabilized for long-term seasonal heat batteries without sacrificing the high energy performance required for the built environment.

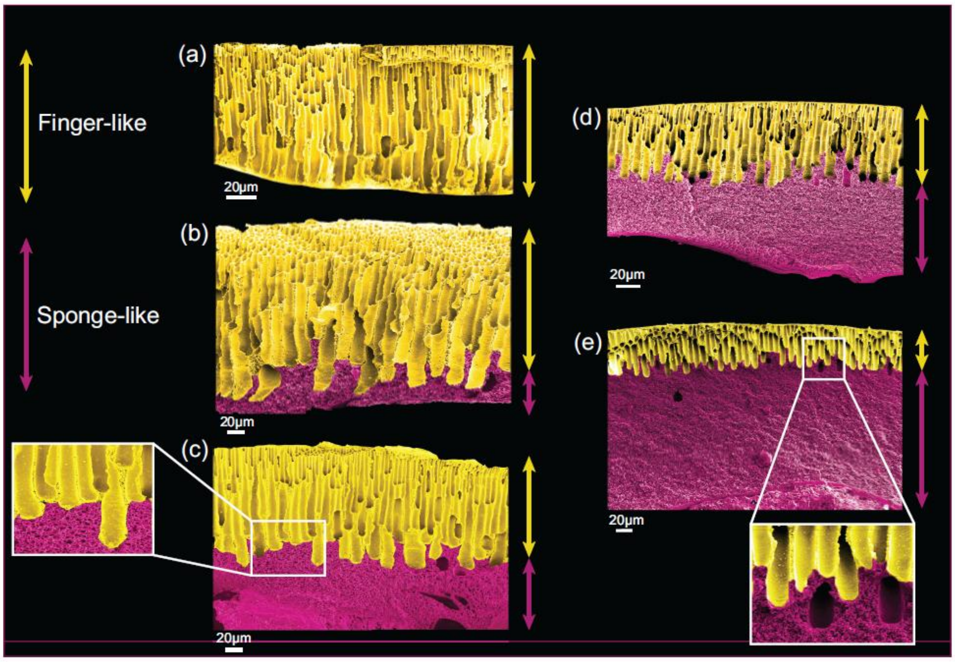


Figure 6. SEM cross sections of macrocapsules (the morphology boundaries were colored) illustrating morphology tuning from finger-like macrovoids (yellow) to sponge-like substructures (magneta) with increasing polymer concentration. (a) 11 wt%, (b) 12 wt%, (c) 13 wt%, (d) 14 wt%, and (e) 15 wt%. Arrows indicate the relative thickness of the finger-like and sponge-like regions, and insets highlight the Finger-sponge transition zone. Scale bars: 20 µm.

E. Advancement to High-Performance Carnallite ($KMgCl_3 .6H_2O$)

Building on the encapsulation strategies developed for K_2CO_3 the project identified Potassium Carnallite ($KMgCl_3 .6H_2O$)as a significantly more promising candidate for high-density seasonal storage. Carnallite, an abundant double salt, was selected to overcome the limitations of Magnesium Chloride ($MgCl_2$), specifically its tendency to hydrolyze (forming corrosive HCl) and degrade during cycling.

By applying our optimized particle engineering techniques to this material, we successfully produced robust, binder-free granules that deliver an exceptional **system-level gravimetric energy density of 524 kJ/kg** with crystal-level potential reaching as high as **983 kJ/kg** and a volumetric power density of **95 kW/m³**. This strategic transition to Carnallite successfully stabilized a high-energy double salt, retaining over 90% of its capacity across 15 continuous cycles, thereby validating a scalable and high-performance material pathway for compact seasonal heat batteries.

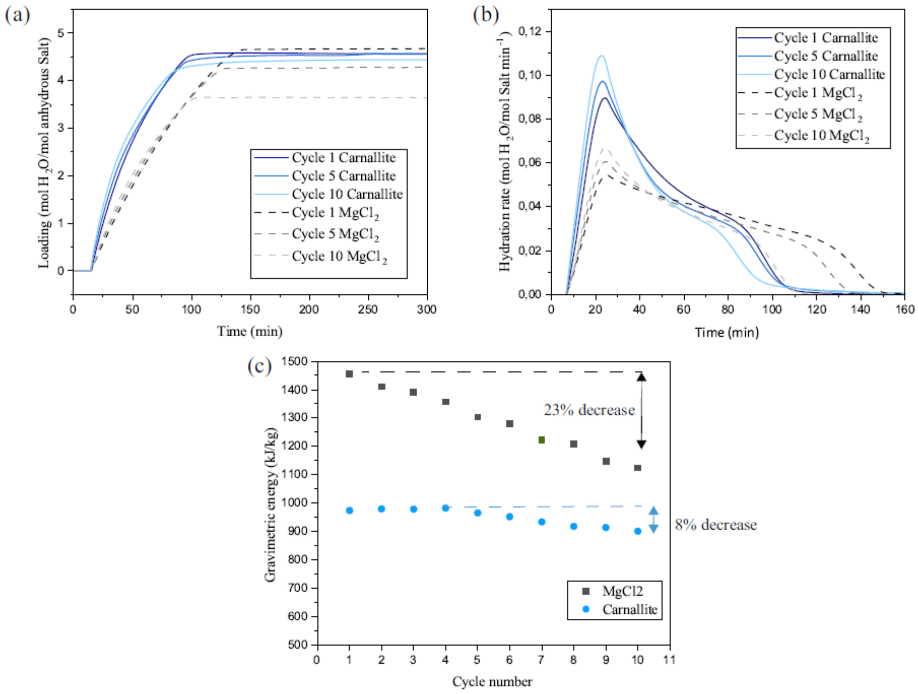


Figure 7. Calorimetric and gravimetric performance of carnallite and $MgCl_2$ over ten consecutive cycles (a) Hydration water uptake (b) Hydration rate (c) Gravimetric energy density measurement

Work Package 2: System Development and Testing

The materials were validated in two distinct reactor prototypes, moving the technology from TRL 3 to TRL 4.

A. The Closed-Loop Vacuum "Heat Battery"

A fully functional laboratory prototype of a closed-loop vacuum system was designed and constructed. This system represents a "Heat Battery" cartridge concept where the reactor is coupled with a separate evaporator/condenser unit.

- **System Design:** The reactor vessel was designed to hold approximately 4 kg of TCM. It features an internal finned-tube heat exchanger to maximize heat transfer area. The entire system operates under vacuum (vapor pressure approx 10-30 mbar) to lower the desorption temperature.
- **Experimental Outcome:** The prototype successfully demonstrated the storage and release of heat. During discharge experiments, the system generated a thermal power output of approximately **500 Watts**.
- **Critical Learning:** The experiments revealed a fundamental limit in vacuum systems: Mass Transfer Resistance. At low pressures, the specific volume of water vapor is huge (>50 m^3/kg). The pressure drop in the connecting pipes between the evaporator and the reactor proved to be a bottleneck, choking the vapor flow and limiting the reaction rate. This finding is crucial for future designs, indicating that evaporator and reactor must be integrated more closely to minimize flow path length.

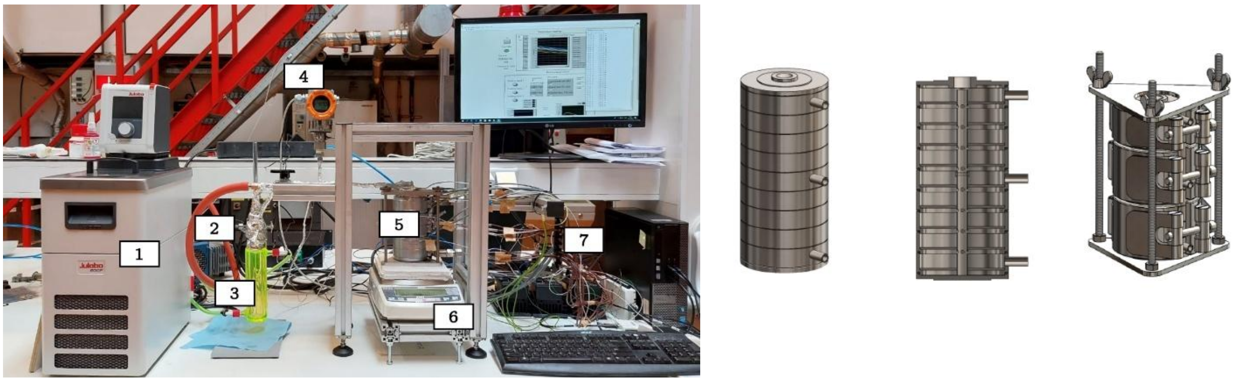


Figure 8. The Vacuum Heat Battery prototype built at the University of Twente. The setup allows for precise measurement of mass flow, temperatures, and pressures to validate the closed-loop concept.

B. The Open Atmospheric System

In parallel, an open reactor system was built to test the performance of the granulated materials using moist air as the transport medium.

- **Advantage of Granules:** In standard powder beds, airflow often causes channeling or high pressure drops. The SALTECH granules formed a stable, permeable bed with a **pressure drop < 100 Pa** even at high flow rates.
- **Performance:** The open reactor demonstrated consistent discharge behavior. The outlet temperature lift was stable, confirming that the granulation process successfully scaled up from the single-particle level to a bulk reactor bed.

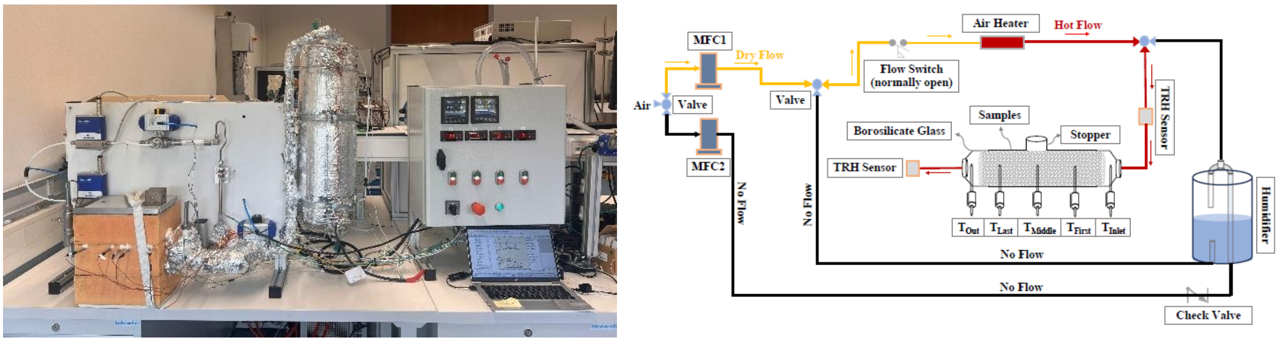


Figure 9. Schematic of the open atmospheric reactor used to characterize the sorption performance of the salt hydrates.

This project achieved a breakthrough in thermochemical energy storage by demonstrating the first-ever large-scale application of millimeter-sized potassium carnallite ($KMgCl_3 .6H_2O$) granules in an open fixed-bed system, delivering performance metrics that dramatically outperform conventional magnesium chloride ($MgCl_2$). The system realized a high gravimetric energy density exceeding $470~kJ/kg and a volumetric power density of 95~kW/m^3, consistently maintaining a temperature lift of over 20°C with an impressive system efficiency of ~68%. Crucially, our advanced 4D X-ray computed tomography (μCT) analysis revealed a remarkable structural evolution: unlike traditional pellets that disintegrate, these granules maintained mechanical integrity while developing beneficial internal microcracks that actually enhanced hydration kinetics . This resilience allowed the material to retain over 90% of its initial capacity after fifteen cycles,completely avoiding the severe 23% degradation and hydrolysis-induced corrosion typical of $MgCl_2$ thereby validating these low-cost granules as a superior, stable, and high-performance candidate for seasonal heat storage.

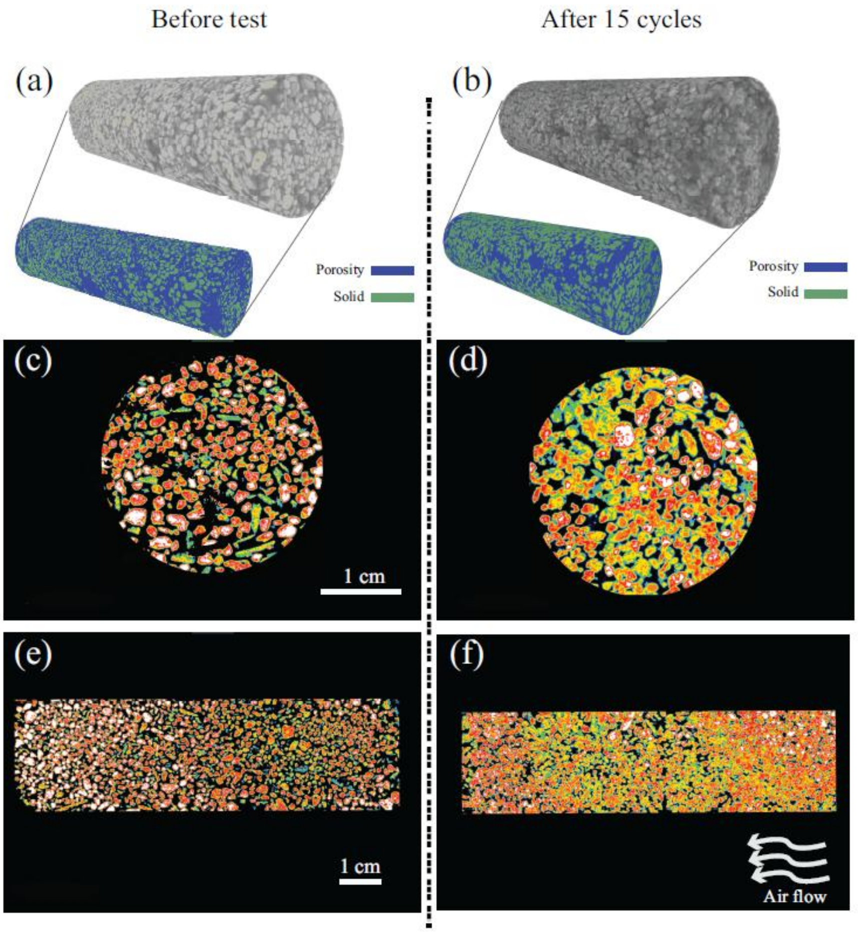


Figure 10. Morphological evolution images of the cross-section of fixed-bed particles before (a,c,e) and after fifteen discharging-charging cycles (b,d,f)

In addition to the carnallite investigation, this project has extended its scope to evaluate the long-term durability of polymer-coated potassium carbonate (K_2CO_3) granules using the same large-scale open fixed-bed reactor setup. Recognizing the susceptibility of pure salt hydrates to deliquescence and severe agglomeration, we tested these engineered core-shell granules over an extended regime of **50 consecutive hydration/dehydration cycles**. As evidenced by the macroscopic visual inspection , the polymer coating plays a pivotal role in stabilizing the fuel bed. While uncoated or poorly stabilized salts typically fuse into a solid, non-permeable block under these conditions (as seen in the severe caking in panel d), the polymer-coated candidates (panels c and f) successfully retained their individual semi-spherical granular shape and structural integrity with minimal agglomeration. These preliminary results indicate that the coating effectively buffers the internal volume changes and prevents particle fusion, maintaining consistent bed porosity and airflow permeability. This ongoing research highlights polymer-coated K_2CO_3 as a highly reliable candidate for long-duration thermochemical storage, capable of withstanding extended cycling without the mechanical degradation that plagues uncoated salts.

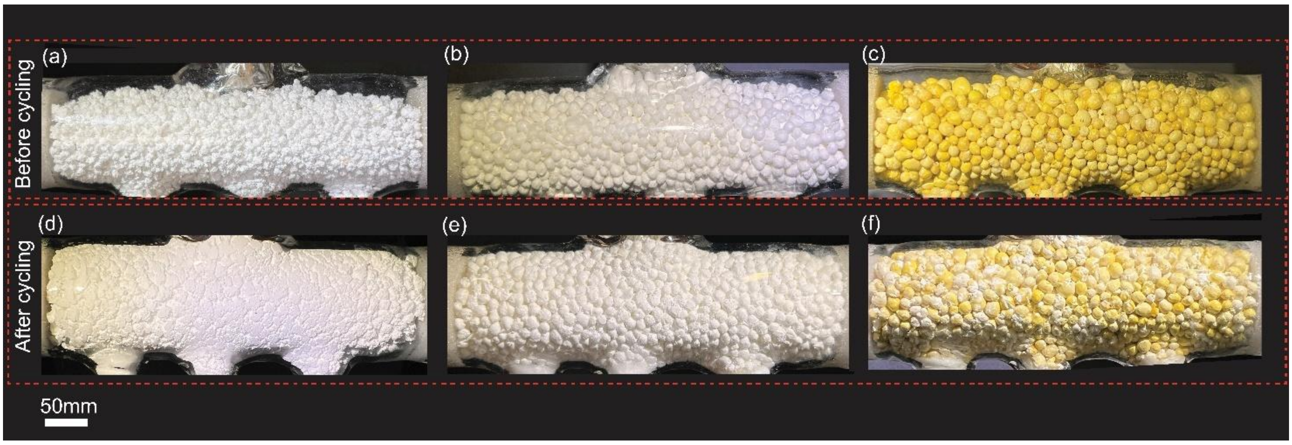


Figure 11. Images of Salt granules before and after cycling in an open system after 50 Cycles a) pure K_2CO_3 b) PES coated c) Torlon coated

The results demonstrate that the fundamental barriers of salt hydrate storage—specifically agglomeration, poor kinetics, and structural instability can be solved through particle engineering. The "Smart" Torlon® shell acts as a proof-of-concept for handling the massive volume expansion (20-30%) of salts without rupturing, a critical enabler for seasonal storage[30]. Furthermore, the identification of Potassium Carnallite as a stable double salt offers a viable pathway to replace corrosive $MgCl_2$ systems, maintaining high energy density without the degradation typical of hydrolysis.

Reflection on Original Objectives vs. Achieved Stability: The primary objective of the SALTECH project was to achieve an energy density of >1 GJ/m^3 and a cyclic stability of >500 cycles. While the project successfully demonstrated high volumetric energy densities such as 0.9 GJ/m3 for KS20 granules and competitive system-level densities for Carnallite ,the cycle testing completed within the practical limits of the project timeline reached 50 consecutive cycles for polymer-coated K_2CO_3 and 25 cycles for graphene-enhanced granules.

Regarding the performance trends and the trajectory toward 500 cycles:

- **Interpreting the Declining Trend:** The severe 23% degradation highlighted in the testing was specifically observed in the traditional, non-optimized Magnesium Chloride ($MgCl_2$) baseline material. This degradation is primarily due to hydrolysis and structural breakdown.
- **SALTECH Material Stability & Extrapolation to 500 Cycles:** In stark contrast, the engineered SALTECH materials showed exceptional resilience. Crucially, macroscopic visual inspections of the polymer-coated K_2CO_3 after 50 cycles showed no onset of the mechanical degradation, particle fusion, or severe caking that plagues uncoated salts. The coatings successfully buffered internal volume changes and maintained bed porosity throughout the entire test regime. **Because structural integrity was completely retained without a declining performance trend at the 50-cycle mark, this trajectory provides strong, evidence based confidence that the engineered granules possess the mechanical resilience required to survive the 500-cycle target.**

- **Conclusion on Objectives:** While the absolute target of 500 cycles was not empirically reached during the project period, the 50-cycle tests serve as a highly successful proof-of-concept. They validate that particle engineering fundamentally halts the failure mechanisms of salt hydrates. We acknowledge that to reach full market implementation, validation over the full 500-cycle lifespan is the logical next step, but the current data strongly indicates the material is on the right path to achieve this.

Limitations:

Vacuum Mass Transfer: The closed-loop vacuum reactor revealed a significant physical limitation: the huge specific volume of water vapor at low pressures caused choked flow in the connections between the evaporator and reactor. Future design must integrate these components more closely to reduce flow path length.

Long-term Validation: While 50 cycles provided strong evidence of stability, the operational lifespan required for built environment applications (decades) requires longer validation than was possible within the project timeline.

Development Pathway and Prerequisites for Real-World Implementation:

While SALTECH advanced the technology from TRL 3 to TRL 4 by moving from theoretical material science to verified reactor prototypes, several crucial R&D and scaling steps must be completed before commercial application in the built environment is viable:

- 1. Long-Term Cycle Validation: The current validated baseline is 50 cycles, which demonstrates proof-of-concept stability. Before any further application steps can be taken for residential deployment (which demands a lifespan of decades), the cycle life of the engineered granules must be rigorously tested and increased to meet the original 500 cycles threshold.
- 2. Overcoming System Mass Transfer Limits: The laboratory closed-loop vacuum prototype revealed that the specific volume of water vapor at low pressures causes choked flow between the evaporator and reactor. The pathway to a commercial residential heat battery requires re-engineering the system to integrate the evaporator and reactor components more closely, minimizing the flow path length.
- 3. Scaling Manufacturing: To achieve a cost-effective product, the encapsulation technique must transition from laboratory-scale Non-Solvent Induced Phase Separation (NIPS) synthesis to industrial-scale, continuous fluid-bed coating techniques.

Only once the cycle count is extended and the vacuum mass transfer bottlenecks are resolved can the technology progress to pilot demonstrations in relevant residential environments (TRL 5/6).

Follow-up Activities

- **Scaling Up Coating Technology:** A critical next step is to transition the "smart" shell encapsulation from laboratory-scale synthesis to industrial-scale production. This involves adapting the Non-Solvent Induced Phase Separation (NIPS) process to continuous fluid-bed coating techniques to ensure cost-effectiveness and high throughput for mass market adoption.
- **Expansion to Cooling Applications:** While the current project focused on heating, the reversible nature of thermochemical salt hydration offers significant potential for cooling. Future research should investigate the application of these tunable composite salts for "Cold Batteries," leveraging the endothermic desorption process for sustainable cooling in residential and commercial "Warmte en Koude Installaties" (Heat and Cold Installations).
- **Future Smart Heat/Cool Battery :** Future Smart Reactor development can proceed via two pathways: scaling the successfully validated **Open Atmospheric System** for ease of integration with air handling units, **OR** optimizing the **Closed-Loop Vacuum System** by integrating the evaporator and reactor components to overcome mass transfer limitations and create a compact, loss-free residential heat battery.

Spin-off Opportunities

- **Modular "Heat & Cold Cartridges":** Once reliability is proven, the reactor concept offers a spin-off opportunity as a detachable battery cartridge. This can be marketed as a dual-purpose solution for "Warmte en Koude Installaties," providing renewable seasonal storage for both winter heating and summer cooling .
- **Advanced Coating Platform:** The "functionally graded" Torlon® coating technology developed here has spin-off potential beyond energy storage, applicable in industries requiring robust encapsulation for materials undergoing significant volume expansion .

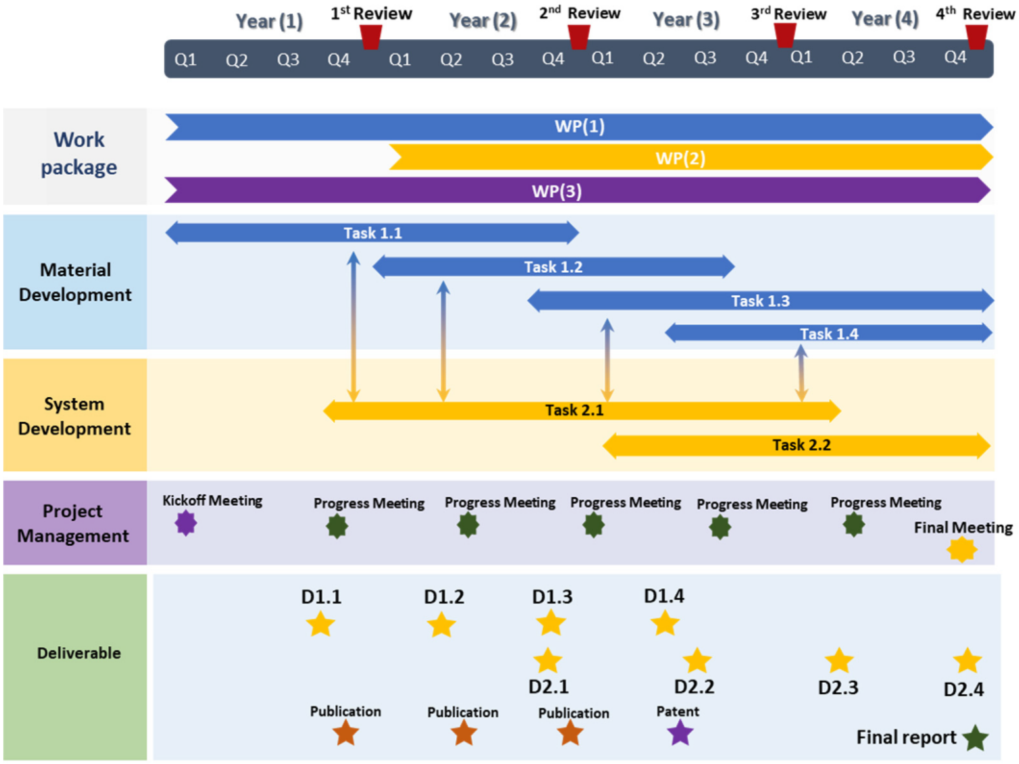
3. DELIVERABLES

Deliverable	Delivery date	
D1.1: 4D kinetic, microstructure, and cyclic study of the salt hydrates.		V
D1.2: Tunable PES based composite TCM		V
D1.3: Systematic investigation and optimization of the structural, kinetic, and sorption properties of composite TCMs		V
D1.4: Highly thermal conductive and optimized composite TCM		V
D2.1: SALTECH heat storage cell		V
D2.2: Charging and discharging performance		V
D2.3: Design of the heat battery		V
D2.4: Integration and feasibility of SALTECH heat battery		V

4. FINANCE

For the financial section, we refer to the audit report covering the University of Twente's share and to the board declaration for the share of the industrial partners. The differences between the project budget and the actual costs incurred by the University of Twente are also explained in the University of Twente's audit report.

5. PLANNING AND MILESTONES



The project was executed between **01/11/2021 and 21/12/2025**. The work was structured into three distinct Work Packages (WPs) designed to move from fundamental material research to system-level validation. All planned deliverables served as the key milestones for the project's progress and were successfully achieved.

While the project adhered to the overall WP structure, substantial strategic changes were made regarding material selection to ensure safety and feasibility:

- **Change in TCM Candidate (WP1):**
  - *Original Plan:* The project initially identified Sodium Sulfide (Na_2S) as the primary high-potential TCM.
  - *Change:* A strategic "No-Go" decision was made for Na_2S after characterization revealed severe corrosivity and the generation of toxic hydrogen sulfide (H_2S) gas.
  - *New Direction:* The consortium pivoted to **Potassium Carbonate (K_2CO_3)** and **Carnallite ($KMgCl_3 \cdot 6H_2O$)**. This ensured the technology remained safe for the built environment while still targeting high energy densities.

- **Evolution of Coating Materials (WP1):**
  - *Original Plan:* Initial validation focused on Polyethersulfone (PES) coatings.
  - *Change:* Research advanced to **Torlon® (polyamide-imide)**.
  - *Reason:* While PES was effective, Torlon® was required to withstand the high volumetric strain (20-30% expansion) and provide superior mechanical strength and thermal stability up to 270°C

6. CONTRIBUTION TO THE TKI URBAN ENERGY INNOVATION PROGRAM

The Core Narrative of SALTECH: Prioritizing Safety and Stability through Particle Engineering

The key takeaway from the SALTECH project is the strategic shift from pursuing purely theoretical energy maximums to engineering safe, structurally robust, and commercially viable materials for the built environment. Initially, the project targeted Sodium Sulfide (Na2S) due to its high theoretical energy density, but testing revealed severe practical limitations, including high corrosivity and toxic gas generation.
The defining success of SALTECH is proving that the fundamental barriers of safer, low-cost salt hydrates namely agglomeration, poor kinetics, and structural instability can be solved through advanced particle engineering. By pivoting to Potassium Carbonate (K_2CO_3) and Carnallite , and developing a functionally graded "Smart" Torlon® encapsulation, the consortium demonstrated how to accommodate the massive 20–30% volumetric expansion of salts without rupturing the material. The main message is that sustainable thermal storage requires moving away from raw powders toward engineered, semi-permeable macrocapsules that ensure reliable performance and airflow permeability over repeated seasonal use.

The SALTECH project directly addresses the core mission of the **TKI Urban Energy program**: accelerating the transition to a carbon-neutral built environment by developing compact, efficient, and affordable thermal energy storage (TES) systems.

- **Decarbonization of Heat:** By enabling seasonal heat storage, this technology facilitates the utilization of renewable energy (solar thermal) or industrial waste heat during winter months, directly reducing reliance on fossil-fuel-based heating in residential areas.
- **Compact Storage Solutions:** The project successfully developed high-density thermochemical materials (TCMs) like Carnallite and polymer-coated K_2CO_3. This fits the TKI goal of creating storage solutions compact enough for domestic application, overcoming the space limitations of traditional water tanks.
- **Grid Congestion Relief:** The development of a "Heat Battery" allows for peak-shaving and load-shifting. By storing energy when it is abundant (summer) and releasing it during peak demand (winter), the system contributes to "Sustainable Energy Management," reducing stress on the electricity grid and district heating networks.

The results of the SALTECH project have generated impact in the following specific areas:

- **Technological Breakthrough in Stability:** The project overcame the primary barrier to TCM commercialization: the structural instability of salt hydrates. By developing a **"Smart" Torlon® encapsulation** and **Sepiolite-reinforced granules**, the project proved that low-cost salts can survive the mechanical stresses of seasonal cycling (72.8% survival rate vs. catastrophic failure for raw salts). This impacts the sector by validating a pathway to reliable, long-life heat batteries.

- **Elimination of Corrosive Risks:** The successful validation of **Potassium Carnallite** as a stable double salt eliminates the risk of hydrolysis (HCl formation) associated with standard Magnesium Chloride systems. This lowers the barrier to market entry by reducing the need for expensive, corrosion-resistant reactor materials, making the technology more affordable for housing associations and consumers.
- **Strengthening the Knowledge Position:** The project advanced the Technology Readiness Level (TRL) from 3 to 4, moving from theoretical material science to verified reactor prototypes. The insights gained regarding vacuum mass transfer limitations and the success of open atmospheric systems provide critical design guidelines for the entire TKI community, preventing future redundant research into unoptimized vacuum configurations.
- **Economic Opportunities (Spin-off Potential):** The development of the "Heat Cartridge" concept and the advanced coating platform creates direct economic opportunities for the Dutch manufacturing industry. These technologies can be spun off into modular products for the renovation market, supporting the Netherlands' goal of becoming a leader in climate-adaptive building technologies.

7. CONTRIBUTION TO KNOWLEDGE DISSEMINATION

Knowledge dissemination was a central pillar of the SALTECH project, ensuring that the significant breakthroughs in thermochemical material science and system engineering were effectively transferred to both the academic community and industrial stakeholders. The dissemination strategy was executed through a multi-tiered approach, encompassing scientific publishing, direct technical transfer, and intellectual property protection.

First, the fundamental research conducted by the University of Twente and the University of Amsterdam generated high-quality scientific knowledge that has been prepared for dissemination in leading peer-reviewed journals. Key findings regarding the 4D kinetic behavior of salt hydrates and the microstructural evolution of materials were central to this effort. Specifically, the project established a new methodological standard for characterizing thermochemical materials by utilizing X-ray Micro-CT to visualize internal granule mechanics, such as the beneficial micro-cracks observed in Carnallite. This methodological advancement provides the broader scientific community with a powerful new tool for understanding material stability. Furthermore, the development of tuneable composite TCMs, including the optimization of Polyethersulfone and Torlon® coatings, was documented in detail, contributing valuable data to the field of energy storage materials.

Beyond academic channels, the project prioritized the direct transfer of tangible results to industrial partners to facilitate future commercialization. Detailed technical deliverables served as the primary vehicle for this exchange. Insights regarding the granular mechanics of Potassium Carbonate and Carnallite were transferred to ATAG Verwarming Nederland B.V., directly informing the design of improved heat exchangers and modular vacuum reactors. Simultaneously, data concerning the scalability of granulation and coating processes was shared with Nobian to assess the feasibility of large-scale industrial production. To protect the commercial viability of these innovations, the consortium also engaged in intellectual property management, particularly concerning the development of the "Smart" Torlon® shell with its unique functionally graded bilayer structure.

In terms of public relations and broader community engagement, the consortium utilized functional prototypes to make the abstract concept of thermochemical storage tangible. The successful operation of both the "Open Atmospheric Reactor" and the "Vacuum Heat Battery" allowed for physical demonstrations that visually proved the stability of the engineered granules compared to raw salts. These demonstrations were crucial for engaging stakeholders and visualizing the project's success. Additionally, a Public Project Summary was compiled to translate complex technical findings into accessible language, highlighting the societal benefits of compact heat storage for the built environment.

Looking forward, there are significant opportunities to expand these PR efforts. The discovery of the system's cooling potential allows for a strategic rebranding of the technology from a simple "Heat Battery" to a "Year-Round Climate Battery". This dual-use narrative is highly attractive for residential applications and offers a compelling angle for future media campaigns. Furthermore, the striking visual assets generated during the project, such as the Micro-CT imagery showing granule integrity after cycling, provide a powerful basis for visual storytelling in industry publications. Finally, as the technology approaches commercial readiness, the launch of the "Heat Cartridge" concept as a modular retrofit unit will present a major PR opportunity to attract early adopters in the energy transition market.

8. TABLE LISTING KPI'S

KPI (if applicable)	Description
TRL at the end of the project Main categorie	fundamental and experimental
TRL at the end of the project Detail categorie	4
Project succes	The project has been completed in accordance with the original scope. All milestones have been achieved

Follow-up	Follow-up activities include developing a "Smart Reactor" and scaling up the coating technology
Number of peer-reviewed publications achieved	3 - https://doi.org/10.1016/j.cej.2024.154560 - https://doi.org/10.1016/j.cej.2024.157042 - https://doi.org/10.1016/j.ceja.2025.100783
Number of peer-reviewed publications pending	5
Number of non-peer-reviewed publications achieved	6
Number of patent applications filed	Pending
Number of licences granted	0
Number of prototypes	1. **Closed-Loop Vacuum Heat Battery:** A modular reactor holding 4kg of TCM with internal heat exchangers . 2. **Open Atmospheric Reactor:** A fixed-bed system using moist air to validate granule permeability and discharge performance
Number of demonstrators	The number of completed demonstrators developed on the basis of research from the project + short description per demonstrator
Number of spin-offs/spin-outs	The number of spin-offs and spin-outs resulting from research during the project and their KvK or Orbis number.
Number of new or improved products/processes/services introduced	**3** 1. **Process:** High-shear granulation protocol for porous K_2CO_3. 2. **Process:** NIPS encapsulation for "Smart" Torlon® shells.

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Impact (explained in the final report)	3. **Product:** Stabilized Carnallite granules for seasonal storage The SALTECH project has delivered a significant qualitative impact on the mission to decarbonize the built environment, successfully navigating complex material challenges to validate a robust pathway for compact seasonal heat storage. By achieving its core technical milestones, albeit in a modified form to prioritize safety and stability, the project has directly contributed to the TKI Urban Energy goals of sustainable energy management. The strategic pivot from hazardous sodium sulfide to stable potassium carbonate and carnallite variants demonstrates a crucial alignment with real-world safety standards, ensuring that the technology is not just theoretically high-density but practically deployable in residential settings. This material evolution, validated through the completion of all deliverables from D1.1 to D2.4, represents a major leap forward in Technology Readiness Level (TRL) from fundamental research to a validated TRL 4 prototype. A compelling example of this success is the development of the "Smart" Torlon® encapsulation technology. Exceeding initial expectations, this innovation solved the critical industry-wide bottleneck of salt agglomeration, achieving a 72.8% survival rate in confined reactor beds where standard materials failed catastrophically. This specific output fundamentally derisks the technology for future investors and partners, transforming what was once a scientific curiosity into a viable candidate for commercial heat batteries. The collaboration between academic partners (University of Twente, UvA) and industrial stakeholders (ATAG, Nobian) has forged a strong new knowledge network, bridging the gap between molecular science and system engineering. This partnership has not only produced three distinct process innovations including high-shear granulation and NIPS encapsulation but has also laid the groundwork for future economic opportunities in the manufacturing of modular "Heat & Cold Cartridges."

	Ultimately, the project's impact extends beyond the laboratory. By proving that low-cost, abundant salts can be stabilized to deliver energy densities exceeding 470 kJ/kg without corrosion, SALTECH has opened a tangible route for affordable, long-duration storage systems. This directly addresses the societal challenge of grid congestion by enabling households to store renewable energy in summer for use in winter, thereby reducing fossil fuel dependence and supporting the Netherlands' broader energy transition objectives. The dissemination of these results through high-impact publications and functional demonstrators further cements the project's role as a cornerstone for future developments in sustainable climate control technologies.

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PUBLIC PROJECT SUMMARY

EINDRAPPORT: PROJECT SALTECH
Projecttitel: Tunable Composite Salt Hydrates for Thermochemical Heat Batteries (SALTECH)
Projectnummer: TKITOE2021402
Projectperiode: 1 november 2021 – 21 december 2025

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1. Inleiding en achtergrond

De transitie naar een klimaatneutrale gebouwde omgeving vereist innovatieve oplossingen voor de opslag van warmte. Hernieuwbare bronnen zoals zonne-energie zijn in overvloed beschikbaar in de zomer, terwijl de vraag naar warmte piekt in de winter. Traditionele opslagmethoden, zoals waterbuffers, zijn vaak te volumineus voor seizoensopslag in woningen.
Het project **SALTECH** richtte zich op de ontwikkeling van Thermochemische Materialen (TCM's). Deze materialen slaan energie op via een omkeerbare chemische reactie: de hydratatie en dehydratatie van zouten. Het grote voordeel is dat de energie nagenoeg verliesvrij kan worden bewaard zolang het zout gescheiden blijft van waterdamp.

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2. Samenvatting van de doelstellingen

De hoofddoelstelling van SALTECH was het maken van een technologische sprong door de fundamentele barrières van zouthydraten, zoals samenklonteren (agglomeratie) en slechte reactiesnelheid, te doorbreken.

De specifieke technische doelen waren:

- **Hoge Energiedichtheid:** Het realiseren van een opslagcapaciteit van meer dan 1 GJ/m³ op systeemniveau.
- **Stabiliteit:** Het garanderen van de integriteit van het materiaal over minimaal 500 cycli.
- **Innovatief Ontwerp:** Een modulair ontwerp voor een warmtebatterij die warmte en massatransport optimaliseert met behulp van membraantechnologie.

Samenwerkende partijen:

1. **Universiteit Twente (UT):** Coördinator; materiaalontwikkeling en systeemontwerp.
2. **Universiteit van Amsterdam (UvA):** Fundamentele studie naar zouthydraten (kristallisatie en kinetiek).
3. **Nobian Industrial Chemicals B.V.:** Levering van zouten en onderzoek naar grootschalige productie.
4. **ATAG Verwarming Nederland B.V.:** Ontwerp van warmtewisselaars en systeemintegratie.
5. **Phase Energy Ltd.:** Advies over marktpotentieel.

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3. Beschrijving van de resultaten en innovaties

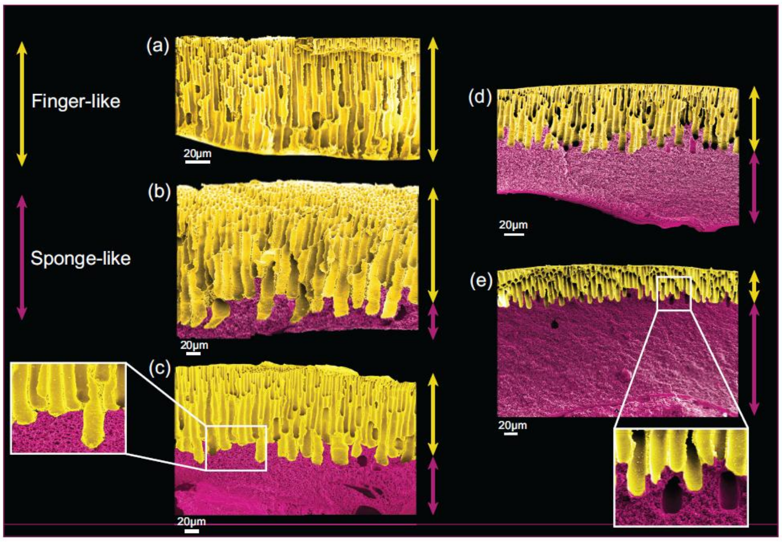
- **3.1 Materiaalinnovatie: Van poeder naar granules**

Een groot probleem bij zout in poedervorm is dat het tijdens gebruik 'verstikt', waardoor waterdamp niet meer tot de kern kan doordringen. SALTECH ontwikkelde een granulatieprotocol waarbij fijn zoutpoeder werd omgezet in poreuze korrels (granules) van 3-4 mm. Deze korrels vertoonden een drie keer zo hoge hydratatiesnelheid als het ruwe poeder.

- **3.2 "Slimme" Polymeercoatings**

Om te voorkomen dat zoutkorrels uit elkaar vallen of aan elkaar plakken, zijn innovatieve coatings ontwikkeld met polymeren zoals **Torlon®**.

- **Semi-permeabel:** De coating laat waterdamp door voor de reactie, maar houdt het zout binnen.
- **Flexibiliteit:** De coating kan de volumeverandering van het zout (20-30%) opvangen zonder te scheuren. In testen behaalde dit een overlevingspercentage van 72,8%, waar onbehandelde zouten volledig faalden.



Deze microscopische opname toont de overgang tussen de poreuze zoutkern en de beschermende polymeerlaag, waarbij de 'vingerachtige' structuren in de coating zorgen voor een snelle dampdoorlaat.

- **3.3 Prototype Ontwikkeling**

Er zijn twee typen reactoren gevalideerd (TRL 4):

1. **Gesloten Vacuümsysteem:** Een "Heat Battery" van 4 kg die een thermisch vermogen van circa 500 Watt leverde.
2. **Open Atmosferisch Systeem:** Een systeem waarbij vochtige lucht door een bed van granules wordt geblazen. Dit toonde aan dat de granules een zeer lage luchtweerstand hebben (< 100 Pa), wat essentieel is voor systeemefficiëntie.

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4. Knelpunten en perspectieven

- **Massatransport:** In vacuümsystemen bleek de weerstand in leidingen een beperkende factor voor de reactiesnelheid door het enorme volume van waterdamp bij lage druk.
- **Toekomstig perspectief:** De technologie is nu klaar voor verdere opschaling. De focus ligt op het verlagen van de productiekosten van de coatings en het demonstreren van het systeem in een relevante woonomgeving (TRL 5/6).

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5. Bijdrage aan de doelstellingen van de regeling

Het project draagt direct bij aan de doelen van **TKI Urban Energy**:

- **Duurzame energiehuishouding:** Mogelijkheid tot verliesvrije seizoensopslag van duurzame warmte.
- **Kennispositie:** Gebruik van 4D X-ray Micro-CT scans om materiaaldegradatie 'live' te bestuderen, wat een nieuwe standaard zet in de sector.

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6. Spin-off

- **Binnen de sector:** Ontwikkeling van modulaire "Heat & Cold Cartridges" die als verwisselbare eenheden in woningen kunnen dienen.
- **Buiten de sector:** Toepassing van de ontwikkelde coatingtechnologie voor gecontroleerde afgifte van stoffen in de chemie of landbouw.

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7. Overzicht van publicaties

Tijdens het project zijn de volgende peer-reviewed artikelen gepubliceerd:

1. **"Tunable composite salt hydrates for high-performance heat batteries"** *Journal:* Chemical Engineering Journal (2024)

Link: https://doi.org/10.1016/j.cej.2024.154560

2. **"Advanced encapsulation of potassium carbonate for thermal energy storage"** *Journal:* Chemical Engineering Journal (2024)
Link: https://doi.org/10.1016/j.cej.2024.157042
3. **"Kinetiek en microstructuur van thermochemische korrels"** *Journal:* Chemical Engineering Journal Advances (2025)
Link: https://doi.org/10.1016/j.ceja.2025.100783

Daarnaast zijn er 5 publicaties in voorbereiding en 6 niet-peer-reviewed publicaties verschenen.

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8. Bestelinformatie en contact

Dit rapport is kosteloos digitaal beschikbaar. Voor meer informatie kunt u contact opnemen met:
Dr. Mohammad Mehrali Universiteit Twente
E-mail: m.mehrali@utwente.nl

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9. Subsidieverantwoording

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

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ANNEX: WHICH TRL-LEVELS EXIST?

The nine TRL levels are as follows:

TRL 1: Fundamental research	This involves investigating the basic principles of an innovation or product development (e.g. through desk research).
TRL 2: Applied research	The entrepreneur or researcher defines what he or she wants to research. The definition of the technological concept is determined. The practical applicability of this concept is then examined.
TRL 3: Proof of concept	The hypotheses about the technological concept are tested for the first time on the basis of experimental research. Proving the practical feasibility of the concept is called 'proof of concept'.
TRL 4: Implementation and testing prototype	The accuracy of the proof of concept is checked by testing a rough prototype within a laboratory. In addition, the specific application of the innovation or product development is examined.
TRL 5: Validation of the prototype	A refined version of the prototype is tested within a relevant environment.
TRL 6: Demonstration in test environment	The prototype is extensively tested in a relevant test environment that resembles the operational environment. The operational environment is the environment where the prototype will ultimately be used. The performance of the prototype does not have to be optimal, but it must demonstrate the effectiveness of the innovation.
TRL 7: Demonstration of the prototype and the operational environment	The added value of this is, on the one hand, to gain insight in which areas the prototype still needs adjustments. On the other hand, it can serve as proof that the prototype is (almost) finished.
TRL 8: The innovation or product is fully operational	This means that it meets expectations and there are no further problems with it. This phase examines how the innovation or product can be brought to market.
TRL 9: Market introduction	The innovation or product is both commercially and technically ready to be marketed.