



Deliverable 2.6 - Report on TCES upscaling



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Summary

The upscaling and industrialization of a Thermochemical Energy Storage (TCES) system with the RESTORE concept from the laboratory pilot plant to large-scale commercial plants represents one of the most critical steps in further integration of renewable energy technologies, as it encompasses critical engineering challenges to reach higher TRLs at the same time with a promising pathway toward achieving high-density, long-duration energy storage with minimal thermal losses. To fulfil this task components design has to be performed thoroughly concerning almost every part of the whole system. Special attention has to be paid to the design and scale up of:

- the reactor with the stirrer and heat exchanger surfaces
- the lines to prevent blockage by the suspension
- the storage vessels for the different components (suspension, oil, water, nitrogen)
- the coupling to the HP/ORC
- the control devices

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1. Introduction

The following subchapters give an overview about the most important reasons, why seasonal and therefore thermochemical energy storage will play a role in future, on renewable energy sources based energy supply systems. Scale up to different power and capacity classes will play an important role.

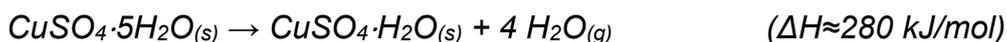
1.1. Background and importance of Energy Storage in the EU Energy Transition

The EU's commitment to climate neutrality by 2050 demands a radical transformation of its energy system. Further integration of renewable energy sources will not improve the critical shift between supply and demand unless reliable energy storage systems are incorporated more efficiently. With the significant imbalance between supply and demand, particularly in the heating sector, which accounts for nearly half of the EU's total energy consumption, the EU risks being locked into fossil fuel backup and facing significant renewable energy curtailment if a reliable cost-effective Seasonal Thermal Energy Storage does not have a role to play in the energy sector. Based on comprehensive research and analysis, the EU will need at least 600 GW of total energy storage capacity by 2050 [1], representing a dramatic increase from the current 89 GW installed across all technologies, requiring a massive ramp-up in deployment.

1.2. Overview of Thermochemical Energy Storage (TCES) and the RESTORE concept

Thermochemical Energy Storage is an innovative technology for long-duration and seasonal storage. It stores thermal energy through the enthalpy of some chemical reactions in reversible endothermic/exothermic reactions. Its primary advantages are **ultra-high energy density** and **zero loss during storage**, as thermal energy is stored as the enthalpy of reaction of the materials, not the temperature differential.

The fundamental working principle of TCES in RESTORE is based on driving a reversible chemical reaction using heat to dehydrate Copper Sulfate Pentahydrate ($\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$), which is considered charging.



The discharge mode, which is the exothermic direction of the reaction, takes place, giving back and the re-absorption of the water molecule. The volumetric energy density of the systems is 1.1 GJ/m³ for the 70% wt suspension.

Generally, TCES systems are capacity-based, not rate-based, making them ideal for Seasonal Thermal Energy Storage (STES), where long storage duration is required. Also, the total capacity of the systems becomes a matter of storage space and large areas the amount of

stored kWh can be exponentially augmented. Lastly, the cyclability and reversibility of the chemical system are proven to be stable for at least 30 cycles through the experiments performed, making it a suitable storage system for a 30-year lifetime. The following table presents some of the pros and cons of the RESTORE chemical system compared to sensible storage and a range of PCMs with similar output temperature.

Table 1: Storage densities of different thermal storage materials

TES Technology	CuSO ₄ Suspension (TCES)	PCM (Latent Heat Storage)	Sensible Heat (Water Tank)
Energy Density (ED)	1.1 GJ/m ³ (Very High)	~0.35–0.7 GJ/m ³ (High)	~0.05 GJ/m ³ (Low)
Storage Mechanism	Chemical Bond Energy (0% loss)	Latent Heat (Constant T)	Specific Heat (T decay)
Storage Duration	Seasonal (>6 months)	Days to Weeks (Encapsulation needed)	Hours to Days (High loss rate)
Handling Challenge	Medium to high concentrated Suspension (Erosion, Pumping, sedimentation)	Encapsulation (Cost, Heat Transfer)	Simple (Water/Steel)
Output Temperature	~90°C (Constant)	~90°C (Constant - PCM T _{melt})	Variable (Decays from T _{max})

1.3. Motivation for Scale-up: Industrial Applications, District Heating and Cooling, Integration of Renewables

The drive to scale the RESTORE TCES systems from the current 5 kW_{th} and 30 kW_{th} pilot plants to commercial targets is motivated by:

- **District Heating (DH):** Providing 90 °C supply water for the 4th and 5th generation DH networks, shifting cheap, abundant summer heat to winter demand
- **Industrial Process heat (IPH):** Utilizing medium-grade or even low-grade excess/waste heat, upgraded by a heat pump (working in rORC as the second core technology developed in RESTORE) and then providing flexible process heat
- **Renewable sources Integration:** Enabling Power-to-Heat strategies by using surplus wind/solar electricity to charge the TCES system, acting as a **Large-Scale Thermal Battery**.

1.4. The innovation offered by the RESTORE project in Thermochemical energy storage

The development of the first-of-a-kind TCES storage pilot plants within the RESTORE project by TU Wien addresses the main technological hurdle of traditional TCES: the **poor heat and mass transfer** in solid-gas systems. By suspending the reactive salt, copper sulfate pentahydrate (CuSO₄·5H₂O), in a hybrid thermal oil matrix, the system transforms the solid-

gas reaction into a high-performance suspension/slurry system, making it much efficient and simpler to be handled and processed by viable industrial systems.

1.5. Report Objectives and Structure

This report presents the technical framework for scaling up the TCES system, based on the RESTORE concept, for commercial applications. It proposes optimized reactant and product transport, separation, and storage strategies, alongside the most effective reactor stirring mechanisms, heat and mass transfer solutions, and reactor scale-up criteria. The report also identifies the optimal heat exchanger types for auxiliary processes to maximize dynamic energy storage efficiency and energy storage density. Furthermore, it addresses critical considerations such as corrosion, safety, and material recycling. Finally, the scale-up procedures for both small- and large-scale rORCs are examined.

2. Methods and strategies for scaling up

Scaling thermochemical energy storage systems from laboratory to pilot scale demands a holistic strategy that tackles technical, operational, and economic challenges while preserving performance and reliability. The RESTORE project exemplifies this progression, advancing from a 1 kW_{th} laboratory system to a 5 kW_{th} pilot plant, and subsequently to a 30 kW_{th} pilot installation. The conducted engineering studies so far have validated technical feasibility for MW-scale applications. However, scaling up such a process embodies intricate challenges that will be pointed out in the following.



Figure 1: Scale up steps in the RESTORE project from 1 kW_{th} Lab scale (Top left) to 5 kW_{th} (Top right) and to 30 kW_{th} Integrated with an rORC (bottom)

When addressing the scale-up of a TCES system as of RESTORE's concept, the fundamental challenge lies in understanding that **power rating** and **energy capacity** represent **independent design parameters** that can be optimized **separately** through strategic system architecture. This approach can fundamentally transform how we conceptualize TCES scaling from simplistic volume-based relationships to sophisticated modular and factor-based optimization strategies [2]. Factor-based optimization opens a broad perspective by introducing numerous variables that can influence the nominal power of a TCES stirred tank reactor and even the storage capacity. Some of these factors, namely, the process side heat transfer coefficient, solid concentration in the reactor, and kinetics of the reaction, affect the power rating of the plant. Some of these factors can be a function of several other factors, making the scale-up in this approach a very complicated issue.

A modular design philosophy, on the other hand, enables independent scaling by separating the thermochemical reactor from storage silos. Power optimization focuses on reaction kinetics, heat transfer coefficients, and mass flow rates within the reactor module, while capacity scaling addresses material quantity, storage vessel sizing, and thermal management in separate storage units.

All these being said, to relatively simplify the process of scale-up for a TCES system, two perspectives can be defined.

Rate-Oriented Scaling strategy

This approach focuses on maximizing reactor power density by optimizing key design parameters. The primary objective is to achieve high power-to-volume ratios (kW/m^3) through advanced heat exchanger placements and improved mass transfer architecture. Charging and discharging rates are largely determined by the design of the reaction zone, not the storage vessel size. Achieving optimal performance requires simultaneous enhancement of heat and mass transfer, reaction kinetics, material management, and careful sizing and sequencing of reactor modules—especially within modular system designs.

Capacity-Oriented Scaling Strategy

Here, the major concern is expanding energy capacity by increasing the quantity of storage material and improving overall thermal management, rather than modifying reactor size. In this scenario, storage capacity typically grows linearly with the available material volume, and there are only very limited technical barriers as long as adequate storage space is available. This makes the approach flexible and straightforward to implement, as the system's energy reserve can be increased by simply adding more material.

Comparative Evaluation

While capacity-oriented scaling offers clear advantages in terms of economic flexibility, environmental impact, and system reliability, rate-oriented scaling is typically more restrictive. Once a facility is constructed with power-density optimization as the main design focus, subsequent modifications or upgrades become significantly more difficult, locking in certain operational parameters. Therefore, rate-oriented scaling deserves extra attention during the

initial design phase, as its constraints are less easily adjusted compared to strategies emphasizing storage capacity.

2.1. Scale-up Path Definition

With the insight from the previous arguments, critical scale-up considerations, according to the importance, include design of heat transfer mechanism, reactor design and its volume calculations, material transportation and handling systems configuration, separation, process control architecture, and finally, material storage. Laboratory systems typically operate with simplified heat exchange and limited material handling requirements, while pilot systems require continuous operation, sophisticated thermal management, and automated material handling systems. Thus, the transition to higher scales requires special attention in reactor design philosophy from the current proof-of-concept demonstrations to industrial operation scales.

To be more clear about this, in small-scale laboratory systems, a high surface-to-volume ratio facilitates efficient and uniform heat distribution, allowing for simplified thermal design and rapid response. However, as systems are scaled up, achieving temperature uniformity becomes more complex; pilot and commercial units require engineered heat exchanger configurations and advanced thermal management strategies to ensure consistent performance.

RESTORE pilot systems have demonstrated heat transfer coefficients in the range of 500– 700 W/(m²K) by leveraging optimized impeller designs and improved coil geometries. For practical scale-up calculations, it is advisable to use the lower end of this range, as larger systems generally experience increased inefficiencies due to a lower power-to-volume ratio and higher internal thermal gradients. This conservative approach helps account for unavoidable losses and ensures the scalability and reliability of system performance on a commercial scale.

To define the pathway for scale-up steps that **minimize technical and financial risk** while **providing sufficient complexity** to validate all critical system components, a proper method of progression is based on a framework that relates the Technology Readiness Level (TRL) to the power output of the systems.

- **TRL 4–5** typically aligns with small pilot units (10–50 kW), where integrated component validation occurs under representative conditions. The 30 kW TCES plant developed at TU Wien can be well positioned in this range, which has successfully demonstrated system capacity to integrate and its operability.
- **TRL 6** is associated with larger pilot or demonstration plants (50– kW)
- **TRL 7** moves toward pre-commercial deployments in the range of 0.5–2 MW,
- **TRL 8–9** represents commercial deployment, typically in the multi-MW scale, Scaling-up Bottlenecks and Mitigation

In this part of the report, three further steps for scaling up by increasing size and complexity are proposed for engineering based on this guideline. These steps are the TCES plant with nominal power ratings of **500 kW_{th}** and **1 MW_{th}**, and **10 MW_{th}**.

2.2. System Architecture

The system, fundamentally, is based on a closed loop circulation of a suspension of $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$ and $\text{CuSO}_4 \cdot \text{H}_2\text{O}$ in a thermal oil matrix within several equipment.

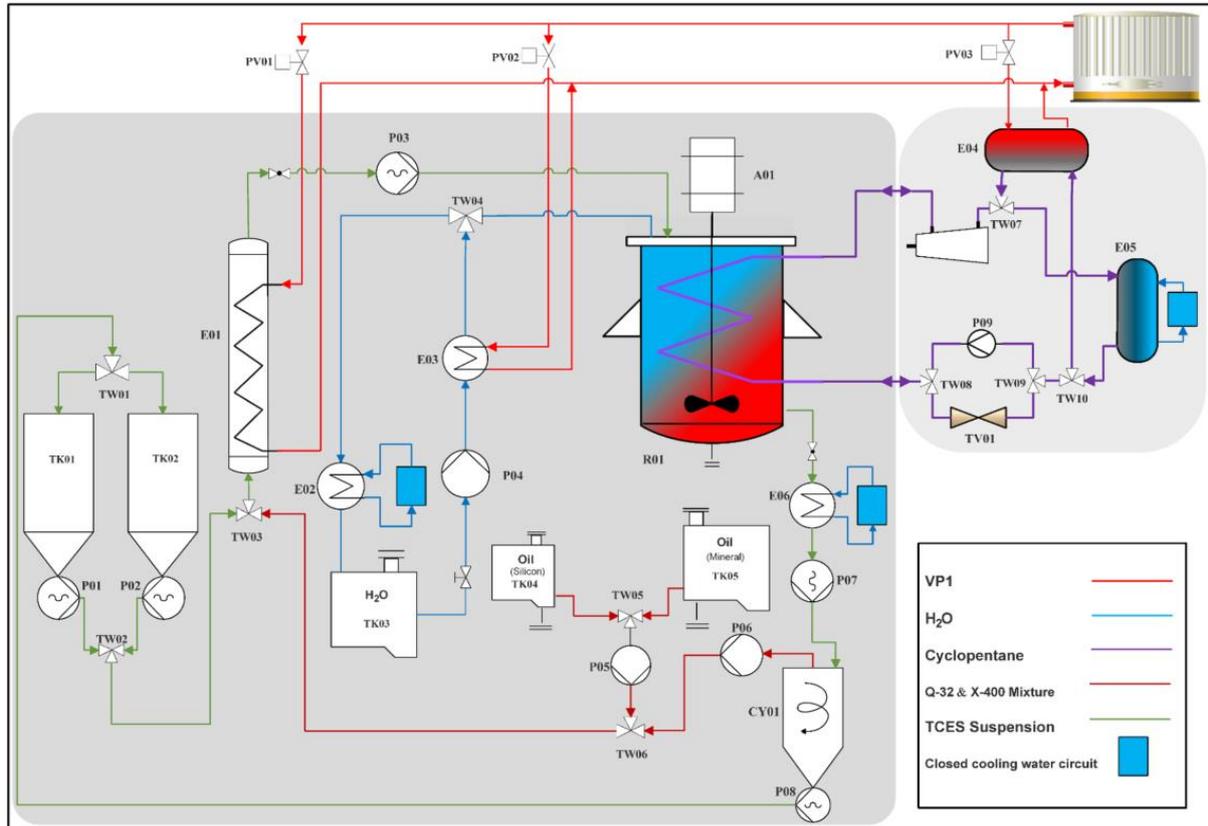


Figure 2: Scheme of the TCES-suspension storage system with an integrated rORC

The Key units will be:

- **Storage Tanks for:**
 - TCES Material
 - Thermal Oil
 - Water
 - N_2
- **Pumps**
 - Slurry pumps (capable of pumping copper sulfate suspension in concentrations from 30% wf up to 70% wf)
 - Oil pumps for heat transfer fluids
 - Water pumps for the rehydration step
- **Heat exchangers**
 - Preheaters

- Recuperators
- Condensers
- **Reactor** (Main zone for dehydration/rehydration equipped with a proper agitation system)
- **Separator**
 - solid-liquid
 - liquid-liquid
- **Measurement instruments**

2.2.1. Reactor design

The design of a TCES reactor for copper sulfate pentahydrate requires specialized engineering addressing the unique characteristics of TCES multiphase systems, ensuring well-dispersed operating temperatures in the vessel, and continuous operation requirements for industrial applications. Based on the RESTORE project demonstrations and scaling analysis, reactor design encompasses vessel sizing, agitation system specification, heat transfer optimization, and material handling integration.

Best Practice Engineering Recommendations:

- **Vessel**

The optimum aspect ratio (H/D) for the CSTR type in this application would have a range between 1.2 to 1.4; however, a deviation from the optimized value, for commercial-scale systems with certain precautions, up to H/D=1.8 is tolerable.

Vessel construction utilizes stainless steel for corrosion resistance with copper sulfate and thermal oil, with wall thickness calculations based on pressure vessel standards for 6 bar design pressure. In multi-MW reactors, the construction material can be opted for Carbon Steel with a high-performance built polymer lining (e.g., Epoxy) certified for 130° C to reduce the CAPEX.

- **Coils**

The heating coils inside are recommended to have a helical geometry due to their higher surface-to-volume ratio and can be stacked up to three bundles that are fixed with proper spacers and supports. Implementation of an engineered internal baffle-coil system to create favorable flow conditions is of utmost importance. The range for the pitch of the coils needs proper engineering to gain maximum surface density, but avoid disturbances in the macro flow structure within the reactor vessel.

- **Agitation system**

The goals for the agitation system of such a multiphase TCES reactor are: 1) Maintain uniform suspension (prevent settling of 300 µm particles at reaction temperatures and oil viscosity), 2) facilitate necessary heat transfer to the particle surfaces in hydration and from the particle to the oil in rehydration, while creating excellent mass transfer conditions. 3) Avoid excessive shear that could damage TCES particulates, which will result in challenging particle management for future cycles.

Such an agitation system for such the TCES reactor incorporates at least two pitched blade impellers (PBT) configurations with axial flow direction for bulk mixing and radial flow component for heat transfer enhancement. Variable frequency drives are essential to make speed optimization possible for different operating conditions and load requirements. The best shaft sealing utilizes mechanical seals specifically designed for high-temperature thermal oil service with external flush systems and temperature monitoring.

Lastly, for multi-Megawatt plants, it is recommended to design modular reactors to obtain optimized flow conditions without the necessity of designing very big agitation systems and more reliability of the plant in case of need for maintenance.

2.2.2. Material Handling

2.2.2.1. Objectives & constraints

- **Suspended particle mean size:** 300 μm at 30% wt during process lines and up to 70% wt in storage vessels
- **Minimum velocity** to avoid sedimentation:

This parameter requires calculations depending on the density difference of the suspending medium, the hybrid oil, however at some zones we are not really dealing with a dilute suspension of TCES particles but more with a paste like medium. As an empirical value for the minimum velocity in the pipes a range between **0.6-0.8 m/s** was set in the 5 kW and 30 kW plants.

- **Temperature & viscosity:** viscosity will be lower at 130 °C (~35 mPa·s) for 30 %wt suspension and exponentially higher at ambient operations; it is recommended to settle for worst-case during shutdown (much higher viscosity at lower temp).
- **Erosion & abrasion:** solids are hard and sharp-edged; choose materials and geometries to minimize wear.

2.2.2.2. Pipe sizing & routing

Baseline rule: It is recommended to design pipes to maintain the critical velocity **when operating**. For the TCES suspension with low required volumetric flows, pipe diameters can be small, but flows should be sized to maintain both the minimum velocity and acceptable pressure drop, having in mind that sometimes the TCES material contains lumps up to 10 mm.

Routing best practices

- Keep slope $\geq 1-2\%$ toward pumps/drains to avoid pooling.
- Avoid long horizontal runs with low velocity; use vertical rises and loops when practical.
- Minimize the number of elbows and use long-radius elbows (3D sweep) to reduce dead zones.
- Include **flush and blowdown ports** every 2–4 m and accessible wash headers.
- Insulate all hot piping and provide trace heating, where freezing or viscosity increase is possible.

2.2.2.3. Pump selection & sizing

Pump types suitable for 30% wt to 70% wt TCES particle content, with mean particle size of up to 300 μm :

- **Progressive cavity (PC / eccentric screw) pumps:** good at handling abrasive slurries, constant flow at low shear, tolerant of entrained gas. Seal/drive life and sensitivity to temperature must be managed.



Figure 3: A progressive cavity pump connected to a storage tank (highly concentrated TCES suspension) on the 5 kW_{th} pilot plant

- **Peristaltic (hose) pumps:** excellent for abrasive/high concentrated solid suspensions and easy maintenance (hose replacement), but for larger flows and continuous duty, their power and hose lifetime are limiting.
- **Diaphragm pumps (hydraulically actuated):** robust, fair solids handling (our tests with a pneumatically actuated diaphragm pump revealed that they were not successful in handling concentrations above 20% wt), and they show higher capital cost for hydraulic actuation and higher operational cost for pneumatic actuation.

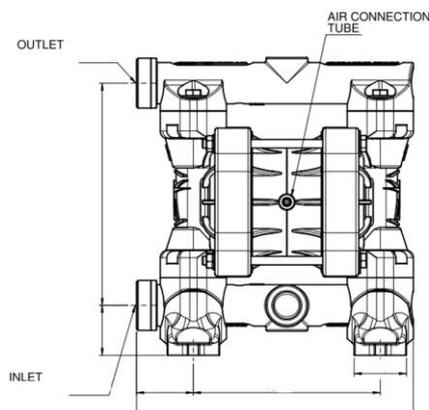


Figure 4: A double diaphragm pump in the 5 kW_{th} pilot plant for low concentration TCES suspension

- **Recessed impeller centrifugal pumps** with hard alloy internals can be used if particle size and solids fraction allow; they offer higher speeds with lower maintenance but may be less tolerant for higher concentration of solids (towards 30% wt).

Best recommendation: Use **progressive cavity pumps** for the suspension circulation duties (suction lift, moderate heads). For smaller, precision metering or dosing, peristaltic pumps could also be a good choice;

2.2.2.4. Erosion, wear & material selection (wetted parts)

- Use **hardened alloys** for impellers/rotors (e.g., stainless 316L with wear sleeves, or ceramic coatings for critical wear surfaces).
- Internal linings for elbows, tees, and pump suction must be abrasion-resistant (even replaceable sleeves can be considered)
- Avoid soft elastomers in contact zones except where peristaltic hoses are intended.

2.2.2.5. Valves & control to minimize clogging

- Use **full-bore ball valves** or **butterfly valves** (lug style) with a large opening to avoid blockage.
- It is strongly recommended to avoid globe valves or small-port throttling valves in slurry lines.
- Using **bleed ports** where necessary and provide flush bypass around closed valves.
- Instrumentation: insert-type sensors have been avoided in the construction of the 5 kW and the 30 kW plants, and instead, clamp-on PT100 for temperature measurement, and ultrasound flowmeters, for flow verification were a successful practice. For critical measurements Coriolis flowmeters are recommended.

2.2.2.6. Maintenance & anti-clog strategies

- Define a well-planned start-up and shut-down procedure based on the lower-scale plants' experiences to protect the pipelines
- Provide **periodic high-velocity flush loops** using clean oil or solvent to flush lines.
- **Purge ports** and pigging capability for larger bore lines.
- **Bypass and redundancy** for all critical pumps.
- Inline strainers (mesh 0.05-0.2 mm) before the oil pumps to protect internals, with blowdown capability.
- Scheduled inspection and replacement cycles for wear parts (pump stators, hoses).

2.2.3. Material Separation

1. Gravitational clarifier/lamella settler

- Low shear, low CAPEX for large flows.
- Needs a large footprint at high throughput. Effective if particles aggregate and hindered settling is manageable.
- Can be configured with sloped plates (lamella) to increase effective area and reduce footprint.

2. Centrifugal decanter / solid bowl centrifuge

- Compact and fast separation, suitable for continuous operation and higher solids.
- Higher CAPEX and energy, but small footprint and better performance for small particles or when oil viscosity is high.
- Better integrated in continuous large systems (10 MWh target).

3. Filtration (belt filter or pressure filter)

- Produces dry cakes and clean oil but fouling and cleaning are maintenance-intensive.
- Good if solids must be isolated or when product dry product is needed.

4. Cyclonic separator

- Useful where density difference is high and particle sizes $>50 \mu\text{m}$; smaller footprint but depends strongly on flow and particle size, thus not very reliable outside of nominal flow conditions.

Recommendation: For modular, robust operation:

- **Use a two-stage separator** for 1–10 MWh:
 - **Stage 1:** coarse centrifugal decanter to remove bulk solids and speed up separation (reduces oil carryover).
 - **Stage 2:** lamella settler or pressure filter polishing stage to meet oil clarity and solids removal specs.
- For pilot and <1 MWh systems, a **lamella clarifier** paired with a batch centrifuge for solids handling will be cost-effective.

2.2.4. Storage Strategies:

Thermochemical energy storage systems need, besides the storage vessels for the charged and uncharged material, in case of using a suspension system, storage devices for oil and water, see **¡Error! No se encuentra el origen de la referencia..**

As mentioned above in **¡Error! No se encuentra el origen de la referencia.** the required storage vessels are shown: TK01 and TK02 are the storage tanks for the uncharged and

charged material. The two types of oil (silicon and mineral oil) are stored in TK05 and TK04. The use of a minor quantity of silicon oil ($\approx 10\%$) – added to the mineral oil - helps to prevent foaming during the charging process. Due to the remarkable difference in price the required silicon oil part should be tried to be kept as low as possible. The water tank TK03 collects the condensed steam after dehydration and supplies liquid water to the reactor for hydration→discharging. So, compared to sensible and phase change storage systems, thermochemical storage devices need considerably more devices, like the reactor itself, the mentioned tanks, pumps, and separation devices.

2.2.4.1. Oil storage

The oil storage tank is provided to separate the oil from the suspension in case of (long-term) storage. Whereas the highest solid concentration tested under operating conditions in the reactor was at 30% wt for sole storage, this value can be enhanced up to 70% wt if the oil is separated from the solid material for the storage process. The advantage is, that sedimentation inside the solids storage tanks is rather prevented and therefore suspension distribution remains more uniform inside TK1 and TK2. Otherwise, a two phase region inside TK1 and TK2 would be formed, with the oil in the upper region and the concentrated suspension in the lower part. The resulting disadvantages would be that:

- before unloading the vessels, the suspension has to be homogenized by using stirrers, which in turn won't be effective, guaranteeing constant solids concentration at the extraction point,
- the big volume of the storage vessels containing oil and solids

2.2.4.2. Suspension storage:

The suspension is stored at the 5 kW_{th} as well as at the 30 kW_{th} reactor in stainless steel vessels. As already mentioned, the vessels are equipped with stirrers to equalize uneven suspension distribution, especially when the system is started after longer storage periods. For larger applications, even tanks made of HDPE (high-density polyethylene) can be used.

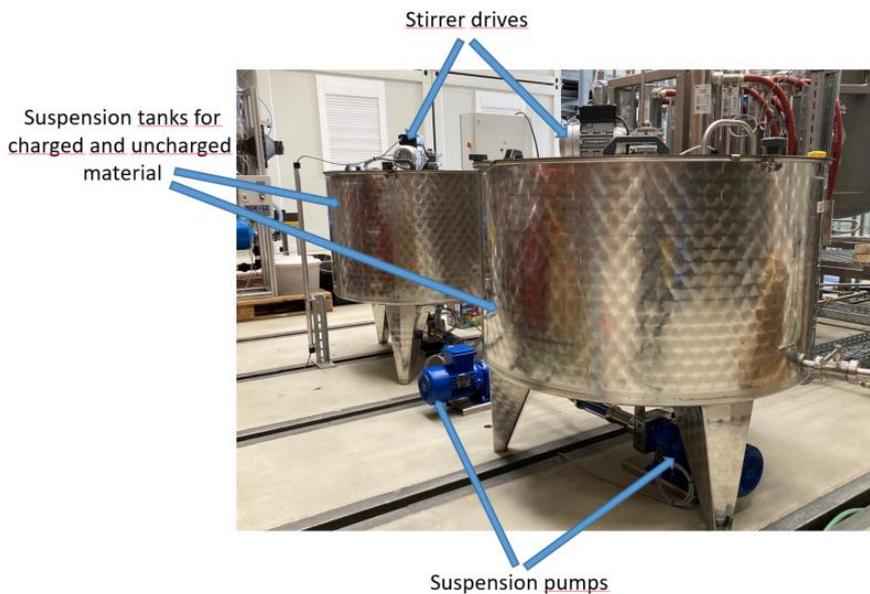


Figure 5: Stainless steel storage tanks of the 30 kW_{th} reactor

In Figure 5 the TCS-storage tanks for the 30 kW thermal reactor are shown. They have a capacity of 500 l per tank and enable an operating time of 5 h. At the top of the tanks the stirrer devices are shown. For suspension transport the cavity pumps, see also Figure 3 are used.

In a large-scale TCES plant, the storage tanks design addresses thermal management, atmospheric protection, and material quality preservation during extended storage periods. Thus, a proper design for the storage tanks not only prevents challenges in the initial stages of material handling in the process but also contributes to the overall thermal capacity of the plant. For instance, the prevention of freezing during winter in cold climates by proper insulation on the storage vessels, or even utilizing heat tracers, ensures smooth process operations as well as having a meaningful influence on the overall efficiency of the plant both by thermal management and the fact that lower temperatures in the tanks means higher viscosity of the TCES suspension and higher required pumping power by the pumps for a certain mass flow rate.

Best Practice Engineering recommendations for design and scale-up:

- **Material compatibility:** Storage Vessels out of mild steel with protective coating or high-density polyethylene for cost efficiency to resist CuSO₄ corrosion would be a proper choice.
- **Geometry:** Vertical tanks are favored for a smaller footprint and better mixing. Also, a conical base with 30-45 degree angle will facilitate the material extraction.

- **Maintenance & Scale-Up:** Access hatches for periodic cleaning are recommended. Also Modular tanks that allow phased scaling are recommended.

3. Corrosion, safety and recycling

This chapter focuses on additional considerations that need to be included in the discussion about the upscaling of the thermochemical energy storage (TCES) technology. Since salts are known for their corrosive properties, especially in contact with steel, the corrosion potential is assessed. Additionally, safety concerns tied to the used chemicals are addressed and the recycling of said materials is discussed.

3.1. Corrosive properties

The corrosive properties of the salt hydrates were previously mentioned in Deliverable 2.4, in which the theoretical chemical compatibility of different stainless steel types with the salt hydrates was introduced.

An excerpt of these theoretical compatibilities, as given by the steel manufacturer ThyssenKrupp [3] are listed in Table 2, and the corrosive properties are described according to this terminology:

- 0 = resistant to abrasive surface corrosion
- 1 = low attack by abrasive surface corrosion
- 2 = hardly resistant to abrasive surface corrosion
- 3 = not resistant to abrasive surface corrosion
- L = Risk of pitting, crevice, or stress corrosion cracking

The steels listed in Table 2 (1.4301, 1.4044 and 1.4571) are commonly used steels which were also used in the construction of the TCES prototypes (5 kW_{th} and 30 kW_{th}).

Table 2: Chemical compatibility of the investigated TCM with different stainless-steel types [3]

TCM	Temperature	1.4301	1.4404/1.4571
H_3BO_3	20 °C/boiling	0/0	0/0
$\text{MgSO}_4 \cdot 7 \text{H}_2\text{O}$	20 °C/boiling	0/0	0/0
$\text{CaCl}_2 \cdot 6 \text{H}_2\text{O}$	20 °C/boiling	0L/1L	0L/1L
K_2CO_3	20 °C/boiling	0/0	0/0
$\text{CuSO}_4 \cdot 5 \text{H}_2\text{O}$	20 °C/boiling	0/0	0/0

The chemical compatibilities as reported by the manufacturer suggest that no corrosion of the steel is expected when it comes into contact with H_3BO_3 , $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$, $\text{K}_2\text{CO}_3 \cdot 1.5\text{H}_2\text{O}$ or $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$, but $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$ could pose some problems with pitting corrosion, which is typical in stainless steels that are exposed to a chloride environment [4].

ThyssenKrupp's tests were performed at 20°C or in boiling saturated brine, probably around 100 °C. These temperatures are lower than those the material must withstand in the RESTORE application. Also, unlike in the TCES prototypes, the material was not suspended in oil. Therefore, experimental investigations were conducted at higher temperatures and with several charging and discharging cycles in an oil suspension to better judge the corrosion potential.

3.1.1. Corrosion tests: setup and procedures

To test the corrosive properties of the thermochemical materials (TCM) during the charging-discharging process in the reactor and the storage period in the tanks, two types of tests were performed using steel samples (1.4301, 1.4404 and 1.4571):

- Reactor tests
 - Steel samples tied to the stirrer (see Figure 6 (a))
 - Cycling performed in the batch reactor (see Figure 6 (b))
 - TCM: $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$, $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$
 - Suspension composition: 30 wt% salt and 70 wt% oil
 - Conditions in the reactor:
 - $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$: charging (~6 h, 200 °C), discharging (~30 min, 50 °C)
 - $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$: charging (~2 h, 130 °C), discharging (~30 min, 50 °C)
 - Sampling after 10/20/25 charging-discharging cycles
- Storage tests
 - Steel samples stored in Schott flasks (see Figure 6 (c)) at room temperature
 - TCM: $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$, $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$, $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$, H_3BO_3 , $\text{K}_2\text{CO}_3 \cdot 1.5\text{H}_2\text{O}$
 - Suspension composition: 70 wt% salt and 30 wt% oil
 - Sampling after 1/2/5 months

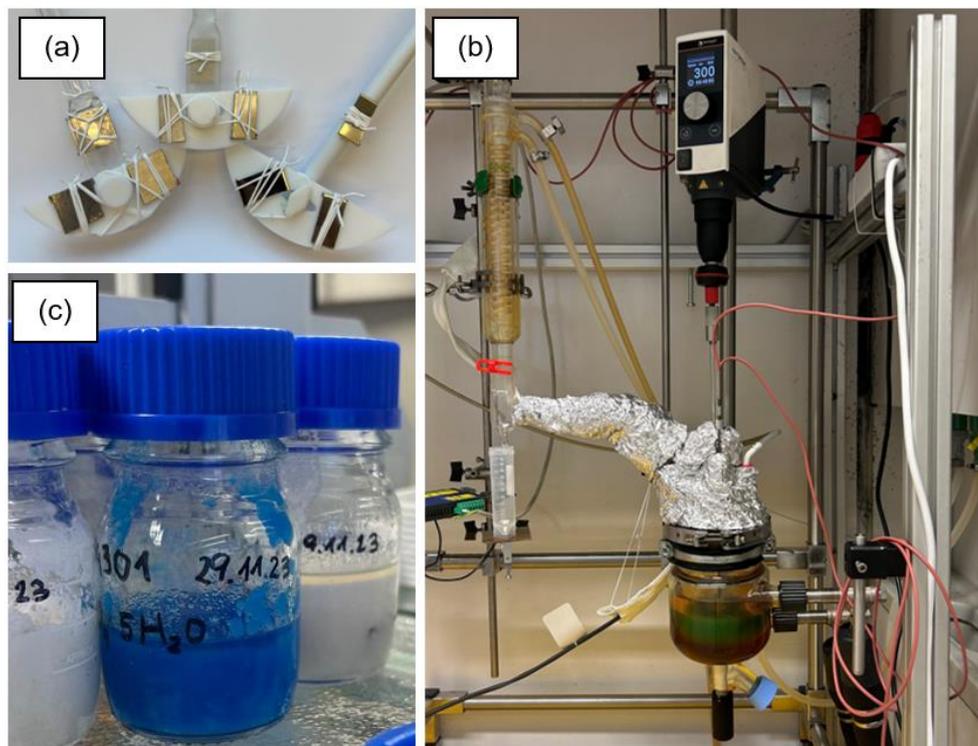


Figure 6: Steel samples tied to the stirrer (a) which underwent 25 charging-discharging cycles in the batch reactor (b) and Schott flasks (c) in which the samples were stored for 5 months

After sampling, the corrosion potential was evaluated by examining the surface of the steel samples using a digital microscope (VHX S660E, KEYENCE) with a resolution of 0.1-1 μm . Additionally, X-ray diffraction measurements of the salts after the cycles/the storage period were conducted. However, no crystalline products of the corrosion reaction were found in the salts, which is why the following paragraphs only discuss the results of the microscopic analysis of the steel samples.

3.1.1. Corrosion tests: results

Figure 7 shows what the steel samples looked like after 10 charging-discharging cycles in the $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$ suspension. These samples were cleaned and dried, and looked at under the microscope to judge possible changes on the surface of the steel sample.

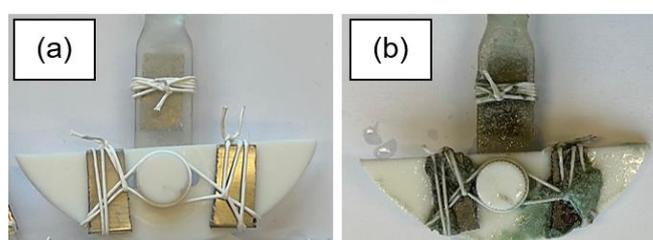


Figure 7: Steel samples before (a) and after (b) 10 charging-discharging cycles in $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$

The evaluation results in 9-18 pictures for each investigated TCM. Therefore, the ones from the tests with $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$, the main TCM used in the RESTORE solution, are given as an example in Figure 8 and Figure 9, but the results for all materials are discussed below.

Figure 8 shows the microscopic images of the steel samples in the $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$ suspension over the course of the 5-month storage period. All three steel samples exhibit a colour change (staining) after 5 months of storage, but the effect is most pronounced in the “cheapest” steel 1.4301 whereas the titanium alloyed steel 1.4571 only shows beginning staining in the last sample. Furthermore, no signs of beginning pitting corrosion are detected.

5 months storage, room temperature

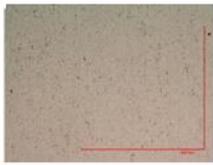
Steel type	Before	After 1 month	After 2 months	After 5 months
1.4301				
1.4404				
1.4571				

Figure 8: Microscopic images of the steel samples in the $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$ suspension over the course of the 5 months storage period (at room temperature in the Schott flask)

Figure 9 shows the steel samples over the course of the 25 charging-discharging cycles in the $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$ suspension. Compared to the storage effects seen in Figure 8, the colour change is even more pronounced, especially in the 1.4404 sample.

25 cycles in the reactor, reaction temperature

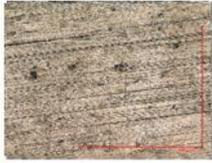
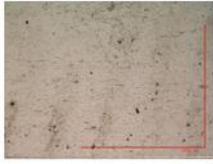
Steel type	Before	After 10 cycles	After 20 cycles	After 25 cycles
1.4301				
1.4404				
1.4571				

Figure 9: Microscopic images of the steel samples in the $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$ suspension over the course of the 25 charging-discharging cycles (at reaction temperature in the batch reactor)

Additionally, the 1.4301 sample shows many small pits, which could indicate beginning pitting corrosion. The depth analysis of one of these pits is shown in Figure 10, revealing that it is around 5 μm deep.

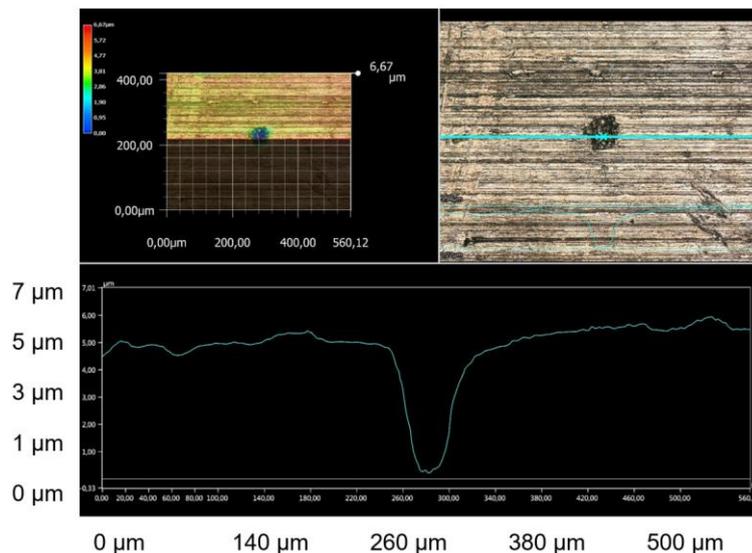


Figure 10: Small pit (depth $\sim 5 \mu\text{m}$) on the 1.4301 sample after 25 charging-discharging cycles in the $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$ suspension

The same analysis of the 1.4301 sample that was tested in 25 charging-discharging cycles in the $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$ suspension reveals pits up to $\sim 15 \mu\text{m}$ deep (see Figure 11) indicating the onset of pitting corrosion, which is typical of chlorides.

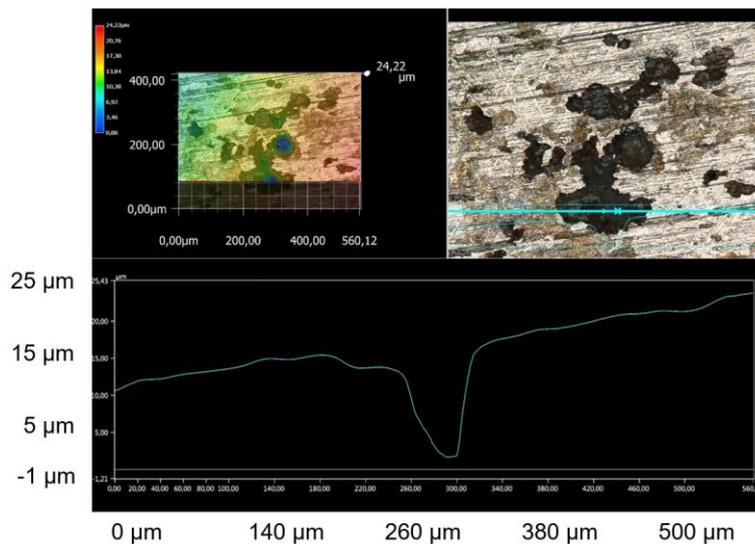


Figure 11: Beginning pitting corrosion (depth ~15 μm) on the 1.4301 sample after 25 charging-discharging cycles in the $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$ suspension

Table 3 sums up the results of the reactor and storage tests for all the tested TCMs. T_{room} refers to the room temperature during the storage tests, and T_{reaction} refers to the reaction temperature in the reactor during the charging-discharging cycles, which are mentioned in Chapter 3.1.1.

For some TCM, the results align with those expected based on the chemical compatibility sheets provided by the steel manufacturer, ThyssenKrupp, but for others, they differ. The observed pitting corrosion in the $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$ tests was expected, as the aggressive Cl^- ions weakened or damaged the passive layers of the steels. As expected, the samples in the H_3BO_3 and $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$ suspensions remained mostly unaffected. However, the higher salt concentrations and/or elevated temperatures in the $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$ and $\text{K}_2\text{CO}_3 \cdot 1.5\text{H}_2\text{O}$ tests, compared to those performed by the manufacturer, resulted in a higher corrosion potential of the TCM. Additionally, impurities in the salts (e.g. Cl in $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$) and surface defects on the steel samples could have amplified the effect.

- $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$
 - beginning pitting corrosion on the 1.4301 and 1.4571 samples (storage + cycling)
 - small pits on the 1.4404 sample after cycling
 - cause for corrosion: chlorides
- $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$
 - colour change of all steel samples (storage + cycling)
 - small pits on the 1.4301 sample after cycling
 - cause for corrosion: elevated temperatures, impurities (e.g. Cl), steel surface quality
- $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$ and H_3BO_3
 - only colour change on the 1.4301 sample (storage)
- $\text{K}_2\text{CO}_3 \cdot 1.5\text{H}_2\text{O}$
 - only colour change on the 1.4301 sample (storage)
 - beginning pitting corrosion on the 1.4571 sample (storage)
 - cause for corrosion: steel surface quality

Table 3: Summary of the results of the corrosion tests

Alloy	TCM	Compatibility ¹	Corrosive effects (storage, T _{room})	Corrosive effects (25 cycles, T _{reaction})
1.4301 (304)	CaCl ₂ ·2H ₂ O	1L	- beginning pitting corrosion, colour change	- beginning pitting corrosion
	CuSO ₄ ·5H ₂ O	0	- colour change	- many small pits, colour change
	MgSO ₄ ·7H ₂ O	0	- beginning colour change	n.a.
	H ₃ BO ₃	0	- beginning colour change	n.a.
	K ₂ CO ₃ ·1.5H ₂ O	0	- beginning colour change	n.a.
1.4404 (316L)	CaCl ₂ ·2H ₂ O	0L	- colour change	- many small pits
	CuSO ₄ ·5H ₂ O	0	- colour change	- colour change
	MgSO ₄ ·7H ₂ O	0	- no detectable change	n.a.
	H ₃ BO ₃	0	- no detectable change	n.a.
	K ₂ CO ₃ ·1.5H ₂ O	0	- no detectable change	n.a.
1.4571 (316Ti)	CaCl ₂ ·2H ₂ O	0L	- beginning pitting corrosion	- few pits, undercutting pitting corrosion
	CuSO ₄ ·5H ₂ O	0	- beginning colour change	- colour change
	MgSO ₄ ·7H ₂ O	0	- no detectable change	n.a.
	H ₃ BO ₃	0	- no detectable change	n.a.
	K ₂ CO ₃ ·1.5H ₂ O	0	- beginning pitting corrosion	n.a.

¹ According to the steel manufacturer ThyssenKrupp [3]

3.1.2. Corrosion tests: conclusion and outlook

Table 3 also shows that out of the tested steel samples, the 1.4044 alloy performed the best, which is also caused by the better surface quality of the sample in comparison to the 1.4301 and 1.4571 alloys. In general, 1.4404 and 1.4571 performed better than 1.4301 due to higher amounts of corrosion-resistant alloying elements (molybdenum and titanium). Still, for reactor use, a combination of the more affordable 1.4301 and 1.4404 with electropolished surfaces is recommended to balance cost efficiency and long-term durability. Overall corrosion should be manageable in the steel vessels when $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$, $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$, H_3BO_3 and $\text{K}_2\text{CO}_3 \cdot 1.5\text{H}_2\text{O}$ are used, but the chloride-induced pitting corrosion when working with $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$ needs further investigation.

Future reactor design should explore classical corrosion protection methods (e.g., cathodic protection, inhibitors, protective coatings) alongside optimised steel surface quality and corrosion-conscious construction (e.g. optimised flow to avoid agglomeration) [5], [6]. Also, the storage tanks could be made from high-density polyethylene (HDPE) as a more cost-efficient option if the suspension is cooled down to below 60 °C before entering the storage tank [7].

3.2. Safety

Safety aspects of the TCES technology have already been discussed in Deliverables 2.1 and 2.2 in the form of the safety concept for the 1kW_{th} TCES unit (D2.2) and the safety questions in the conceptual design (D2.1). Since the dissemination level of those previous deliverables is not public, the safety concerns regarding handling of the chemicals and the reactor will be discussed here again.

3.2.1. CLP Hazard classes and categories of investigated materials

The CLP (EU Regulation No 1272/2008/EC on Classification, Labelling and Packaging of Substances and Mixtures), hazard classes and categories of the components of the investigated chemical systems are taken from the website of ECHA (European Chemicals Agency) [8]. These CLP hazard classes and their possible categories are:

- **Acute Tox.** Acute toxicity (Categories 1 - 4)
- **Reprod.** Reproductive toxicity (Categories 1A, 1B, and 2)
- **Eye Irrit.** Serious eye irritation (Categories 1, 2)
- **Eye Dam.** Serious eye damage (Categories 1, 2)
- **Aqua. Chron.** Hazardous to the aquatic environment (Cat. Chronic 1 - 4)
- **Aqua. Acute** Hazardous to the aquatic environment (Category Acute 1)
- **Carc.** Carcinogenicity (Categories 1A, 1B, and 2)

For the classes with more than one category it says the lower the category number, the higher the hazard.

Table 4 shows the harmonised² classification of the components of the investigated chemical systems as well as their CAS (Chemical Abstracts Service) number and the corresponding safety labels. Both the educt and product of the reversible reactions are listed.

Table 4: CLP hazard classes and categories of investigated TCM [8]

TCM (charged and discharged)	CAS (Chemical Abstracts Service) Number	Label	Harmonised CLP classification						
			Acute Tox.	Reprod.	Eye Irrit.	Eye Dam.	Aqua. Chron.	Aqua. Acute	Carc.
H ₃ BO ₃	11113-50-1		-	1B*	-	-	-	-	-
HBO ₂	13460-50-9		-	-	-	-	-	-	-
B ₂ O ₃	1303-86-2		-	1B*	-	-	-	-	-
MgSO ₄ ·H ₂ O	14168-73-1	-	-	-	-	-	-	-	-
MgSO ₄ ·7H ₂ O	10034-99-8	-	-	-	-	-	-	-	-
CaCl ₂	10043-52-4		-	-	2	-	-	-	-
CaCl ₂ ·2H ₂ O	10035-04-8		-	-	-	-	-	-	-
K ₂ CO ₃	584-08-7	-	-	-	-	-	-	-	-
K ₂ CO ₃ ·1.5H ₂ O	6381-79-9		-	-	-	-	-	-	-
CuSO ₄ ·H ₂ O	10257-54-2	 	-	-	-	-	-	-	-
CuSO ₄ ·5H ₂ O	7758-99-8	  	4	-	-	1	1	1	-
Mineral oil	64742-54-7		-	-	-	-	-	-	1B*
Silicone oil	63148-62-9		-	-	-	-	-	-	-

* 1B = presumed human reproductive toxicant; assessment based primarily on animal evidence

The most notable hazard classifications in the used TCM are copper sulphate mono- and pentahydrate, being hazardous to the aquatic environment, and boric acid and boron oxide, being presumed human reproductive toxicants.

Concerning the used suspension media, the producers of the mineral oil (Fragoltherm Q-32-N) and the silicone oil (Fragoltherm X-400-A) used in the lab, states in the safety data sheets of both oils, that they do "not meet the criteria for classification in accordance with Regulation No 1272/2008/EC" and that no hazard classes are to be assigned to the oils.

² Substances for which an agreed set of classification and labelling data has been agreed at EU level by Member States.

Table 4 shows the hazard classes of the CAS number taken from the safety data sheet of Fragoltherm Q-32-N according to ECHA. The company provides no CAS number for Fragoltherm X-400-A so the one for Polydimethylsiloxane (silicone oil) is chosen.

3.2.2. Required personal protective equipment (PPE)

Especially when mixing the suspension and filling up/emptying the reactor or the transport system, PPE (Personal Protective Equipment) is required. The following items should be worn while doing these tasks:



protective gloves



eye protection



protective clothes



respiratory protection

3.2.3. Safety concept for TCES suspension reactors

Table 5 shows possible hazards in a pressurised suspension reactor used for TCES. These hazards can be minimised with optimised reactor design, safety valves, close monitoring and periodic inspections. Recommendations to prevent failure are also given in Table 5.

Table 5: Safety considerations for a pressurised suspension reactor used for TCES

Component	Deviation	Possible Causes	Consequences	Safeguards / Recommendations
Reactor vessel (pressure)	Overpressure	Blocked vent, pressure relieve valve failure, closed outlet	Vessel rupture, suspension release	Safe design (e.g. pressure safety valves (PRV), burst disc), pressure alarm/trend monitoring
Reactor vessel (pressure)	Slow pressure rise	Minor leak, poor venting	Fatigue, unnoticed stress	Pressure alarm/trend monitoring, automated vent, leak tests
Reactor vessel (pressure)	Loss of pressure	Rupture, open valve, seal failure	Air ingress, increased reaction rate → foam formation during dehydration/ flashing during hydration	Pressure alarm/trend monitoring, check valves

Component	Deviation	Possible Causes	Consequences	Safeguards / Recommendations
Flanges, manways	Leak/failure under pressure	Thermal cycling, wrong torque, corrosion	Spray of suspension, loss of pressure	Personnel training, monitoring, PPE secondary containment
Heating coils (internal)	Coil rupture/leak	Thermal fatigue, erosion, corrosion	Thermal fluid ingress, sudden pressure rise	Leak detection, isolation valves, backflow prevention
Heating coils (external side)	Overpressure of thermal fluid	Pump malfunction	Spray of hot thermal fluid	Relief on coil feed, burst discs, interlocks
Stirrer	Seal failure (mechanical)	Abrasion by salt, vibration, incompatible seal	Leak of pressurised suspension	Seal monitoring, robust design, maintenance
Stirrer	Shaft or impeller failure	Fatigue, imbalance	Loss of mixing, agglomeration, vessel damage	Vibration monitoring, automatic shutdown on imbalance
Pumps (circulation/transfer)	Blockage/overpressure	Blocked line, closed valve, cavitation	Pump rupture, overpressure transmitted to system	Relief, bypass line, sensors & interlocks
Relief system/vents	PRV/burst disc fails	Fouling, corrosion, stuck valve, undersized	Vessel overpressure → failure	Design redundancies, routine testing
Relief system/vents	Vent blocked	Salt deposition	Relief ineffective → overpressure	Routine inspections, flow monitoring
Water addition	Overdose	Control valve fault, operator error	Agglomeration, sudden pressure increase	Dosing interlock, safe design (PRV)
Oil (suspension medium)	Vapour formation/boiling	Overheating, low pressure	Pressure increase, flammable vapour	Choose oil with high flame point, pressure/temperature monitoring, fire detection

Component	Deviation	Possible Causes	Consequences	Safeguards / Recommendations
Oil (suspension medium)	Aging/ decomposition	Hotspot, heater fault, poor mixing, high oil age	Agglomeration	Stirrer monitoring
Corrosion/ materials	Pitting/Stress corrosion cracking	Chlorides, high temperatures	Sudden rupture, leak	Use alloyed steel with electropolished surface, corrosion prevention, inspection
Instrumentation and control	Sensor drift/failure	Corrosion, thermal stress	Wrong control actions, missed overpressure	Redundant sensors, regular calibration, protective housings
Secondary containment (tray/tub)	Containment failure during leak	Large rupture, tray overflow	Hot suspension leak	PPE, showers, detection and evacuation plan

3.3. Recycling

This chapter lists recycling considerations for the used materials (TCM and thermal oils). The goal is to maximise reuse of oils and salts, minimise waste, and comply with safety/environmental rules. The considered materials, which are used in the TCES technology, are as follows:

- Thermal oils: Mineral oil, silicone oil, vegetable oils (rapeseed and sunflower oil)
- TCM: $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$, $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$, $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$, H_3BO_3 and $\text{K}_2\text{CO}_3 \cdot 1.5\text{H}_2\text{O}$

3.3.1. Thermal oils

To keep track of the ageing of the oils over time, continuous monitoring of their properties (e.g. viscosity, acid number, water content) is recommended. Once the performance drops, the first measures are to regenerate the oil according to the following steps:

- Filtration and settling/centrifugation to remove salt particles
- Water removal (thermal treating, demulsification)
- Adsorption (e.g. activated carbon) to reduce degradation products
- Additives (e.g. antioxidants, anti-foaming agents) to extend life

At the end of the life of the oils for the TCES application, they could be cleaned and recycled as follows:

- Re-refining for mineral and silicone oils [9]
- Biodiesel conversion for the vegetable oils [10]
- Energy recovery via controlled incineration as a last resort

3.3.1. Thermochemical materials

Same as for the thermal oils, the first approach is to reuse/revive the TCM if their performance drops (most probably due to agglomeration or fouling). Since all the used TCMs are highly soluble in water, the most practical regeneration route is to dissolve and recrystallise them, with optional salt washing to improve purity [11]

In the unlikely case that the TCM cannot be used for the TCES application (or other applications) after regeneration, they should be treated as follows:

- $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$, $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$ and $\text{K}_2\text{CO}_3 \cdot 1.5\text{H}_2\text{O}$
 - Not classified as hazardous (see Table 4)
 - If clean enough, they can be downgraded to non-critical uses (e.g. de-icing, dust control, neutralisation)
 - Otherwise, dissolve and discharge via a permitted wastewater treatment system
- $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$
 - Aquatic toxic (see Table 4)
 - Must be collected as hazardous waste
 - Disposal routes: recovery of copper (preferred), or transfer to an authorised hazardous waste facility (stabilisation + secure landfill or high-temp treatment)
- H_3BO_3
 - Reprotoxic (see Table 4)
 - Must be collected as hazardous waste
 - Disposal routes: transfer to an authorised hazardous waste facility (stabilisation + secure landfill or high-temp treatment)

4. Scale-Up in smaller and larger systems

Smaller and larger systems in this case refer to the system to which this energy storage is embedded. Whereas smaller systems benefit from the equipment needed for a reversible organic rankine cycle (rORC), larger systems are more favourable for a separate heat pump (HP) and an organic rankine cycle (ORC).

This chapter aims to elucidate from different point of views the interface between the TCES, more specifically the reactor, and rORC, HP, or ORC. This should make the interests of certain systems clear, to realize the best system, when following the design guidelines of section 2.

Figure 13 displays the most relevant options for combining the TCES reactor with subsequent machines. The top left picture describes the simple layout with a single reactor interacting with a fully reversible ORC. In this configuration, the reactor's internal heat exchanger is the hot side heat exchanger (HX) of the rORC.

In split systems with an HP and an ORC, three main configurations come in hand. The first approach would be to have one reactor for each machine, thereby tailoring each reactor to the needs of its subsequent machine, and system demand. With the aim of only one reactor two approaches can be thought of. One utilizes the same internal HX of the reactor for both the HP and ORC. Another one tries to fit two separate internal HX into the reactor, one for each machine.

Choosing the configuration is not only influenced by pure equipment cost. Additionally, efficiency, space requirements, and foremost, heat demand, as well as excess heat supply, will play a role. Especially the ratio of heat flow in the consecutive periods, so during charging and discharging, will have a big influence on the decision about the configuration.

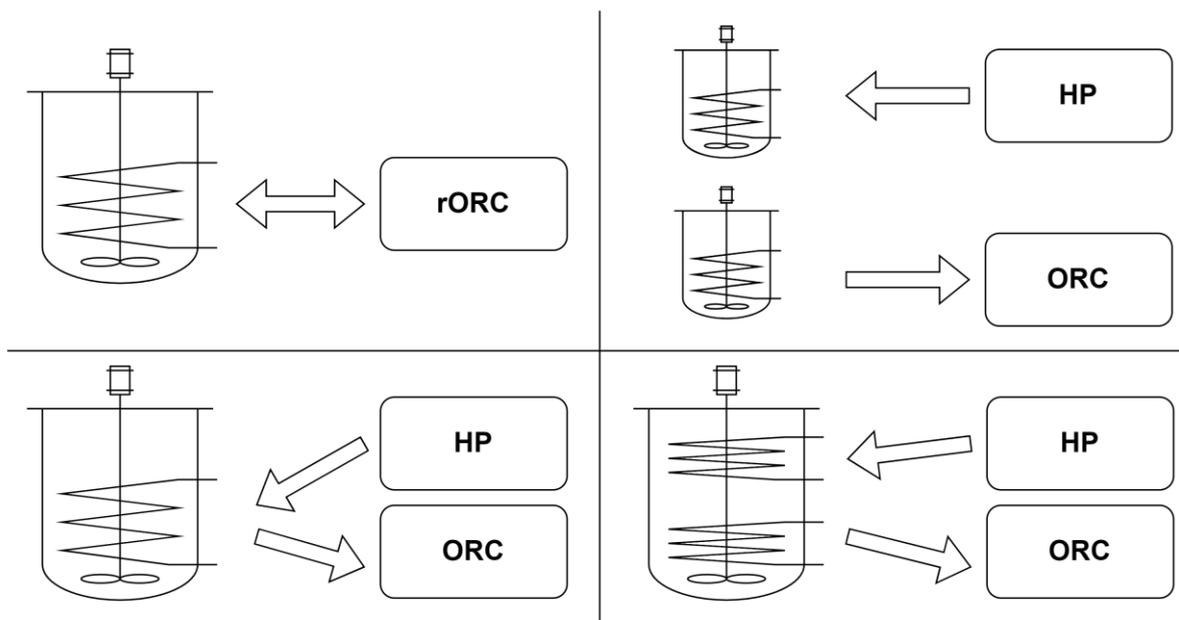


Figure 12: Possible system configurations in small and large systems.

4.1. Smaller Systems – TCES coupled to rORC/HP

If less equipment-intensive systems are decided to be used the more the demand for high level engineering will rise. Following ideas have to be kept in mind:

- If a rORC/HP has been fixed, the same HXs for both operating modes have to be used.
- A rORC always uses the same process fluid.
- A rORC works best close to the temperature level of the reactor

These eventually lead to the top left configuration in Figure 12, with a single dual purpose reactor.

This is in many ways challenging from an engineering perspective, not because of the complexity of the system, but the multipurpose nature of each equipment. Considering HXs in the easiest way each one has two design points, or in other words, each HX has a very important off-design point to be considered. As the interfacing HX of the rORC are condensing and evaporating in different states, the geometrical location has to be chosen thoroughly.

From a reactor's point of view, also two modes have to be facilitated with the same internal geometry. This narrows the field of operation of the reactor to certain mass flows and reaction volumes, therefore dictating the possible heat flows to and from the internal HX, which again has an impact on the rORC.

4.2. Larger Systems – TCES coupled to HP and ORC

With completely separate systems, as pictured on the top right in Figure 13, each machine can have its own designed components for its own purpose and with just one design point. This simplifies engineering, but enhances the costs of the most components.

With just a single dual purpose reactor, two approaches, one with a shared internal HX, and one with two internal HX can be realized.

Both have non-negligible constraints. A single internal HX which is shared by the HP and the ORC means, that either a heat transfer loop is implemented to service both high temperature HXs, or the process fluid of each machine is the same, to have an interconnected loop for the ORC and the HP.

With the limits of reactor design on heat transfer rather than on reaction kinetics, two internal HX could make this fact worse and increase the reactor size.

5. Conclusions

The RESTORE project provides comprehensive lessons for thermochemical energy storage technology development, demonstrating successful advancement from laboratory concept to pilot-scale validations while revealing and establishing pathways for commercial deployment of TCES technology. Key technical achievements during this projects include validation of the stirred tank reactor configuration accomodating TCES material suspended in thermal oil for thermal storage as a viable alternative to conventional fluidized bed systems, achievement of energy densities reaching 1.11 GJ/m^3 for suspension systems, investigation of various chemical systems to find the most suitable candidate that aligns perfectly with the RESTORE's set boundary conditions, successful operation of TCES over multiple charging-discharging cycles, creation of innovative equipment for TCES process, utilization of digital simulation tools to enable optimal system design and coordination while managing complex multi-component process, and finally manufacturing two 5 kW_{th} and $30 \text{ kW}_{\text{th}}$ pilot plants with unique features demonstrating validation under controlled conditions (TRL4), which can be considered an indication of RESTORE's potential for broader applications. Last but not least, system integration lessons from RESTORE demonstrated the successful coupling of thermochemical storage with a reversible Organic Rankine Cycle (rORC) technology, which was a witness to prove that such a TCES system can provide flexibility in operation with other energy systems.

In this report, structured technical guidelines and strategic considerations that support a feasible and scalable development pathway for future projects have been discussed. A comprehensive set of optimized strategies for the architecture of the process is provided. The PFD and the systems components and best engineering practices for the transport, separation, and storage of reactants and products are presented as well. Also, it details the most effective reactor engineering solutions, covering stirring for the best heat/mass transfer, and successful scale-up criteria. A good part of the report discusses the investigations on the corrosion and safety practices for the materials used in scale-up plants. Finally, it outlined the specific scale-up procedures for both small- and large-scale rORCs.

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