FTI Initiative Energy Model Region

Publishable final report

Programme control:
Climate and Energy Fund

Programme management:
The Austrian Research Promotion Agency (FFG)

Final Report
created on
07/12/2021

Project title: HyStEPs

Hybrid Storage for Efficient Processes

Project number: 868842

Call	1. Call FTI Initiative Energy Model Region
Project Starting Date	01/09/2018
Project Ending Date	31/08/2021
Total duration of project (in months)	36 Months
Project holder (Institution)	AIT Austrian Institute of Technology GmbH
Contact person	Gerwin Drexler-Schmid
Postal address	Giefinggasse 4, 1210 Vienna
Telephone	+43 664 6207866
Fax	+43 50550-6679
E-mail	Gerwin.drexler-schmid@ait.ac.at
Website	www.ait.ac.at

HyStEPs

Hybrid Storage for Efficient Processes

Authors:
Gerwin Drexler-Schmid (AIT)
Sabrina Dusek (AIT)
Anton Beck (AIT)
Johannes Krämer (AIT)
Daniel Lager (AIT)
Stephan Kling (AIT)
Johannes Riedl (AIT)
Alexander Schirrer (TU-Wien)
Lukas Kasper (TU-Wien)
Dominik Pernsteiner (TU-Wien)
Benjamin Kerschbaum (TU-Wien)
Franz Rauscher (TU-Wien)
René Hofmann (TU-Wien)
Istvan Omasta (Edtmayer)
Tilman Schiebl (Edtmayer)
Andreas Kiedl (voestalpine)
Florian Javernik (voestalpine)

1 Table of content

2 Introduction

Motivation & starting point:

Two factors, i) the increase of the share of **renewable energy** sources in the grid and ii) the progressive **decarbonisation**, will **require** a drastic **capacity increase** of the **thermal energy storage** in existing industrial plants and processes in the future. A widespread and proven storage technology is the Ruths steam accumulator. It has been used for a long time in a variety of industries such as food, beverage, paper and metal industries. The motivation of the project is to increase the storage capacity of existing steam storage devices.

Consortium:

The consortium consisted of two industrial partners, i.e. voestalpine Stahl Donawitz GmbH, Edmayer Systemtechnik GmbH, three institutes of the Vienna University of Technology (Technische Universität Wien), i.e. Institute for Energiesystems and Thermodynamics, Institute for Mechanics und Mechatronics, Institute of Engineering Design and Product Development, and the AIT Austrian Institute of Technology GmbH

3 Content & Objectives:

The aim of **HyStEPs** was to **develop and** experimentally **test an innovative hybrid storage concept** in order to **increase** the storage **capacity** of Ruths steam storage in operation up to **40 %**. In the medium term, the **investment** costs required for this should only amount to **half** of an equivalent Ruths steam accumulator. In the project, a laboratory scale Ruths steam accumulator was encased in innovative latent heat storage elements. Heat conduction structures were developed and implemented and a state of charge measurement for the hybrid storage tank was developed to enable optimal interaction of the two thermal storage types over the entire charging and discharging cycle. This innovative solution approach, which was based on **AIT patent** applications, should exhibit nearly the same loading and unloading behaviour with **increased storage capacity** as a steam accumulator. In addition, a **techno-economic evaluation** was carried out on the basis of five industrial processes in various sectors and a detailed **needs analysis**.

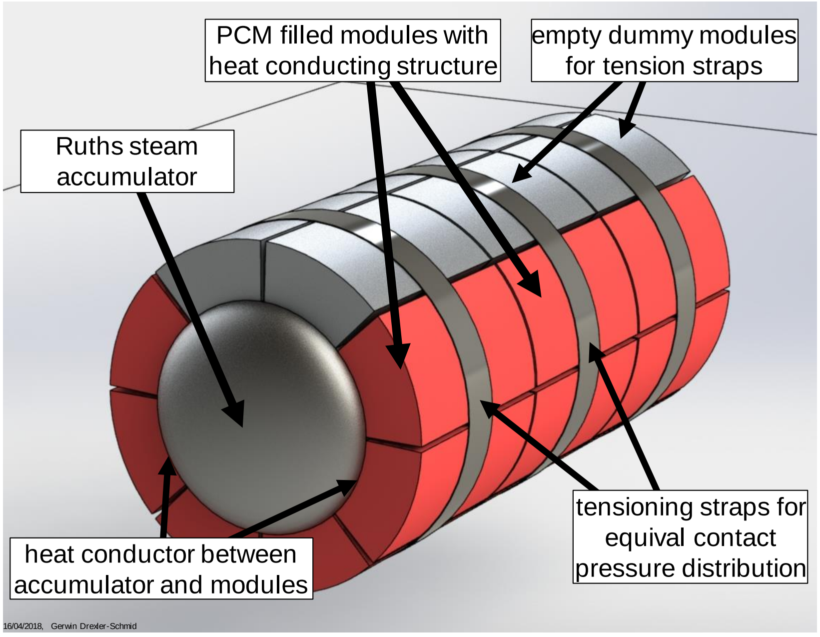


Figure 3.1: Initial concept to increase steam storage capacity of a Ruths steam storage device

Results & Insights: An innovative concept for hybrid storage consisting of steam and latent heat storage was developed in the consortium and experimentally tested at voestalpine Stahl Donawitz, whereby relevant findings for **future hybrid storage prototypes** were obtained. The developed **state of charge measurement** enables the control of future prototypes. Furthermore, knowledge about the industrial requirements and the economic efficiency of the storage concept was gained depending on additional and original storage capacity, performance, process dynamics and temperatures.

HyStEPs was part of the NEFI thematic model region that positions energy intensive and manufacturing industries and their decarbonization in the center of a long-term innovation process to boost technological development. **HyStEPs** contributed to the NEFI-innovation fields Energy Efficiency and New Processes, Renewable Energy, Storage and Demand Side Management through the development of a new and innovative thermal energy storage concept, which allows for increasing storage capacity of steam storage efficiently and cost-efficiently.
As a result, thermal storage capacities were increased by 30% by applying latent heat storage modules on a Ruths steam storage device.

The project was mainly structured in five parts:

1. Process Analysis and thermodynamic requirements
2. Design phase
3. Lab-scale investigation
4. Control strategies, and
5. Technoeconomic evaluation

In the following, these five parts will be presented.

4 Results and conclusions

4.1 Process Analysis and thermodynamic requirements

4.1.1 Storage requirements

The appropriate design of thermal energy systems strongly depends on the process requirements for steam supply. If the storage system is also to be used to exploit opportunities to participate in energy markets, requirements become even more complex. In Figure 4.1, parameters for steam supply and demand and their impact on the design of the hybrid storage are presented.

Variations of most of these parameters affect multiple aspects of the storage design. Similarly, exact process requirements and/or planned participation in energy markets need to be known to define concrete storage requirements. For this reason, the requirements for the storage are kept general and are not specific for the hybrid storage system.

Important design factors are capacity (stored energy), heat fluxes (energy flow) but also the duration of the charging and discharging periods. However, beside required storage energy flows and storage capacity, also pressure levels of steam supply and steam demand are crucial parameters for proper storage design. Large temperature differences between steam chamber and PCM are beneficial for the heat flow between these two storage components. However, high temperature in the storage correspond to high pressures and thus high stresses in the pressure vessel and subsequently limited admissible charging and discharging capacities.

For the design of hybrid storages distinct charging/discharging cycles are beneficial. If this is not the case, the use of multiple smaller storage units might be considered to obtain more regular charging/discharging cycles for the individual storages.

Rapid charging/discharging requires high heat flows between the steam chamber and the PCM, which in turn requires heat transfer enhancement methods such as the application of fins or the addition of materials with high thermal conductivity to the PCM.

Even though basic requirements for the hybrid storage can easily be identified, the implications for **storage design** are **not straightforward**. Certain thermodynamic requirements result in **complex trade-offs**. For example, higher maximum storage temperatures result in higher stresses in the pressure vessel, but higher driving temperature differences between the steam chamber and the PCM increase the heat transfer and thus increase effectiveness of the PCM part in the storage.

Process Parameters	Influences on hybrid storage: beneficial effects	Influences on hybrid storage: negative effects
higher supply/ demand temperatures	potentially higher temperature range; higher energy density	higher temperatures/ pressures in the steam storage; higher thermal stresses
larger diff. between supply/demand temperature	potentially higher temperature differences to PCM > higher heat flows > less heat transfer enhancement necessary	higher temperatures/ pressures in the steam storage; higher thermal stresses
Higher charging/ discharging rates	Higher temperature-differences between pressure vessel and PCM are realized	high heat transfer enhancement necessary; thermal stresses might become an issue
longer cycle duration	potentially more energy stored in PCM; less heat transfer enhancement necessary	less energy stored per storage-cycle

Figure 4.1: Thermal parameters and their impact on storage design

4.1.2 Phase change material selection

Depending on the **operating temperature** there are various possible phase change materials. A suitable PCM has to be chosen taking into account: **phase change temperature, phase enthalpy, density, corrosivity, toxicity, volumetric expansion, viscosity, flammability, long time stability and costs**.

Potential PCMs for the application at voestalpine for the temperature range of ~200-230°C are the salt mixtures **$LiNO_3$-NaCl**, **$LiNO_3$-$NaNO_3$** and **KNO_3-$NaNO_3$**. KNO_3-$NaNO_3$ is a common material for high temperature TES for solar power plants (also known as “solar salt”). Available material properties are summarized in Table 4.1.

$LiNO_3$-NaCl:

$LiNO_3$-NaCl has recently been studied to serve as phase change storage material [1]. Depending on the literature source, melting temperatures of 208 and ~220°C were reported, which lies within the appropriate range for the application at voestalpine. Compared to the other candidates, $LiNO_3$-NaCl has a high heat of fusion of ~360 or ~300 kJ/kg, depending on the literature source. In solid state, the reported thermal conductivity is also relatively high (1.35 W/mK) compared to the other PCM candidates. However, no information on volume expansion during melting has been reported. Also, corrosivity could be a problem for metal components in storage systems. Also, the high price for $LiNO_3$ (ca. 9-150 USD/kg) might exclude this material from economically feasible PCM selection.

$LiNO_3$-$NaNO_3$:

The mixture KNO_3-$NaNO_3$ is reported to have a melting temperature of ca. 195°C which was eventually used for lab-scale storage investigations at voestalpine. The heat of fusion was reported and measured was slightly lower compared to $LiNO_3$-NaCl (269 kJ/kg vs. ~334 kJ/kg). There are several research papers that considered this PCM for thermal energy storage.

[1] Dan Zhou, Philip Eames; A study of a eutectic salt of lithium nitrate and sodium chloride (87–13%) for latent heat storage, 2017

KNO_3-$NaNO_3$:

Amongst the selected PCM candidates KNO_3-$NaNO_3$ has been studied the most as it is often considered for thermal storage applications for solar power systems. The melting temperature is around 222°C which is on the upper tolerance level for application at voestalpine. KNO_3-$NaNO_3$ lies below $LiNO_3$-NaCl and $LiNO_3$-$NaNO_3$ when it comes to thermal properties but also costs are significantly lower when considering €/kg and €/m³.

Table 4.1: material properties for considered PCM materials (average values from literature sources)

average material properties	$LiNO_3$-NaCl	KNO_3-$NaNO_3$	$LiNO_3$-$NaNO_3$
phase change temperature (°C)	214.00	222.25	193.25
heat of fusion (kJ/kg)	334.50	106.25	269.00
density (kg/m³)	2125.00	1989.00	2283.50
thermal conductivity, solid (W/mK)	1.35	0.73	0.87
thermal conductivity, liquid (W/mK)	0.61	0.50	0.57
specific heat capacity, solid (kJ/kgK)	1.54	1.32	1.35
specific heat capacity, liquid (kJ/kgK)	1.56	1.49	1.72
volume expansion (%)	-	4.60	15,5±3
energy density, phase change (kWh/m³)	197.45	58.70	170.63
energy density, ΔT=+-10°C (kWh/m³)	215.75	74.26	190.10
relative energy density, ΔT=+-10°C	9.71	3.34	8.55
notes	salts are corrosive to metals		
Sources	[1,2]	[3,2,4]	[2,3,4,5]

Eventually $LiNO_3$-$NaNO_3$ was chosen because of the high heat of fusion and corrosivity was expected to be lower than of $LiNO_3$-NaCl. KNO_3-$NaNO_3$ was discarded because of the low heat of fusion, which would have resulted in approx. 16 times more heat transfer material in order to reach similar charging and discharging times, i.e. thermal conductivity material demand is inversely proportional to the third power of heat of fusion. As a result, $LiNO_3$-$NaNO_3$ is economically comparable to KNO_3-$NaNO_3$ even though raw material prices of $LiNO_3$-$NaNO_3$ are much higher.

[2] Jose Pereira da Cunha, Philip Eames; Thermal energy storage for low and medium temperature applications using phase change materials – A review; 2016

[3] Huili Zhang, et al.; Thermal energy storage: Recent developments and practical aspects; 2016

[4] Rainer Tamme, et al.; Latent heat storage above 1208C for applications in the industrial process heat sector and solar power generation; 2008

[5] Jose Cunha; Medium Temperature Latent Heat Storage with Phase Change Materials

4.2 Design phase

4.2.1 Thermal design

For the investigations regarding the thermal design of the hybrid storage a Modelica/Dymola model was used that consisted of following parts: liquid water / steam in the pressurized vessel, surrounding phase change material, insulation and three heat resistances between each layer (see Figure 4.2).

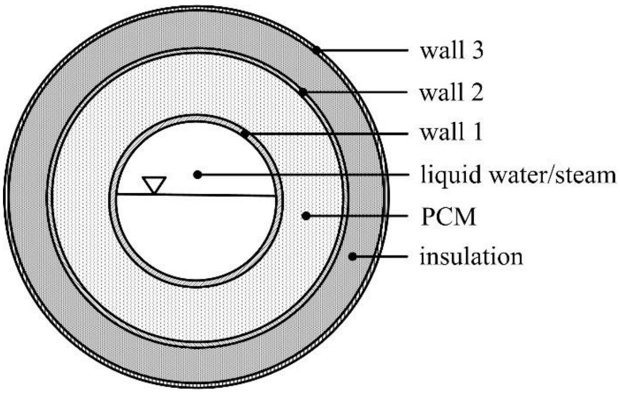


Figure 4.2 Schematic representation of the individual hybrid storage parts (sub-models)[6]

It was decided to fix the maximum pressure for charging the lab-scale device at a **maximum of 23 bar$_a$**. This results in a maximum temperature of **220°C** for the lab-scale device. **$LiNO_3$-$NaNO_3$** was chosen as PCM for the lab-scale hybrid storage. The PCM material properties used for thermal designing are summarized in Table 4.2.

Table 4.2 PCM material properties, measured values

Phase Change Temperature	192 °C
Heat of Fusion	307 kJ/kg
Density	2317 kg/m³
Specific Heat Capacity	1350 J/(kgK)
Thermal Conductivity	0,59 W/(mK)

A **minimum storage temperature of 165 °C or a minimum pressure of 7 bar$_a$** was selected for the lab-scale investigations so that the temperature difference between the maximum storage device temperature and the phase change temperature and the temperature difference between the phase change temperature and the minimum storage device temperature are approximately the same.

[6] S. Dusek, R. Hofmann. A Hybrid Storage Concept for Improving Classical Ruth's Type Steam Accumulators. *In Proceedings of the12th Conference on Sustainable Development of Energy, Water and Environment Systems*, Dubrovnik, Croatia, October 4.-8., 2017.

Table 4.3 Aluminum hole plates properties[7,8]

Thickness	0,8 mm / 1 mm
Aluminum Content (A_C)	49 %
Hole diameter (w)	3 mm
Hole distance (t)	4 mm
Density	2800 kg/m³
Specific Heat Capacity	896 J/(kgK)
Thermal Conductivity	205 W/(mK)

In order to improve heat transfer between the liquid/steam storage medium and the PCM, aluminum hole plates will be used in the lab-scale hybrid storage. Two different thicknesses of hole plates (0.8 mm and 1 mm) were investigated for the thermal design. The properties of the hole plates are shown in Table 4.3.

For a Ruths steam storage with an outer diameter of 700 mm and a length of 2.1 m, an increase in storage capacity of 50% was calculated by encasing 2/3 of the shell surface with PCM. For this example, a discharge time of 1.5 hours was achieved by using aluminum hole plates with 1 mm thickness. A full encasing was ruled out due to low heat transfer coefficients in the upper part of the storage. Decreasing the discharge time to 1 hour yields significantly higher expenses in terms of costs and production for additional aluminum plates. Since the hybrid storage model has not been validated yet, the simulation results can deviate greatly from reality, so it makes sense to adhere to the results for a discharge time of 1.5 hours. The calculated storage capacity is at least 10% higher than formulated in the project goals.

4.2.2 Construction Concepts

When it came to construction concepts there were three main issues:

- Sever corrosion effects: it was found that corrosion occurs especially when the PCM is in contact with water, i.e. air humidity. In this regard, also the purity of the used phase change materials is of importance, since small amounts of other elements and chemical compounds strongly influence corrosion behavior.
- Thermal expansion: the thermal expansion was determined in experiments and resulted to 14 to 17% from 25 to 220°C for $LiNO_3$-$NaNO_3$
- Thermal conductivity: thermal conductivity inside the PCM had to be enhanced by relatively expansive sheets of aluminum. Furthermore, the thermal heat transfer between the steam vessel and the PCM-modules had to be ensured.

In the following some of the many discussed concepts will be briefly described.

4.2.2.1 Closed Aluminum models filled with PCM

A concept with closed aluminum models filled with PCM were discussed. In this concept closed shells filled with PCM were attached to the steam storage, a sketch of one shell is shown in Figure 4.3. The

[7] Material Archiv. Aluminiumknetleg., rein EN AW-1050A. http://www.materialarchiv.ch/app-tablet/#detail/772 (accessed on 19 September 2019).

[8] Anton Schweizer. Stoffwerte. https://www.schweizer-fn.de/stoff/start_stoff.php (accessed on 22 October 2019).

elements are very small so there is no need for heat structures inside the shells. The problem with this concept is that the shell must be filled with liquid PCM and had to be closed after filling. The thermal expansion of the PCM must be compensated by the case.

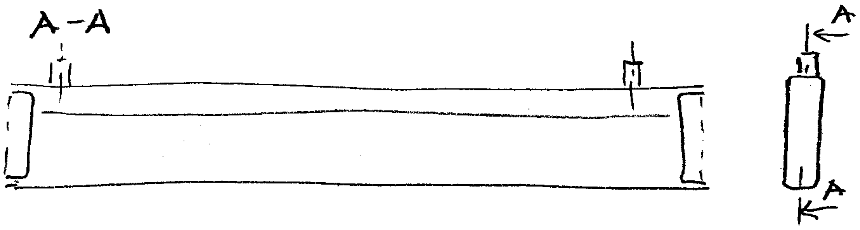


Figure 4.3 concept of hybrid storage with closed aluminum shells

4.2.2.2 Double shell

In this concept a double shell (3) will be implemented around the steam storage (1). The space between the two shells is filled with heat transfer structure (2) and PCM, the level of the PCM is at about 75% of the free space, see Figure 4.4.

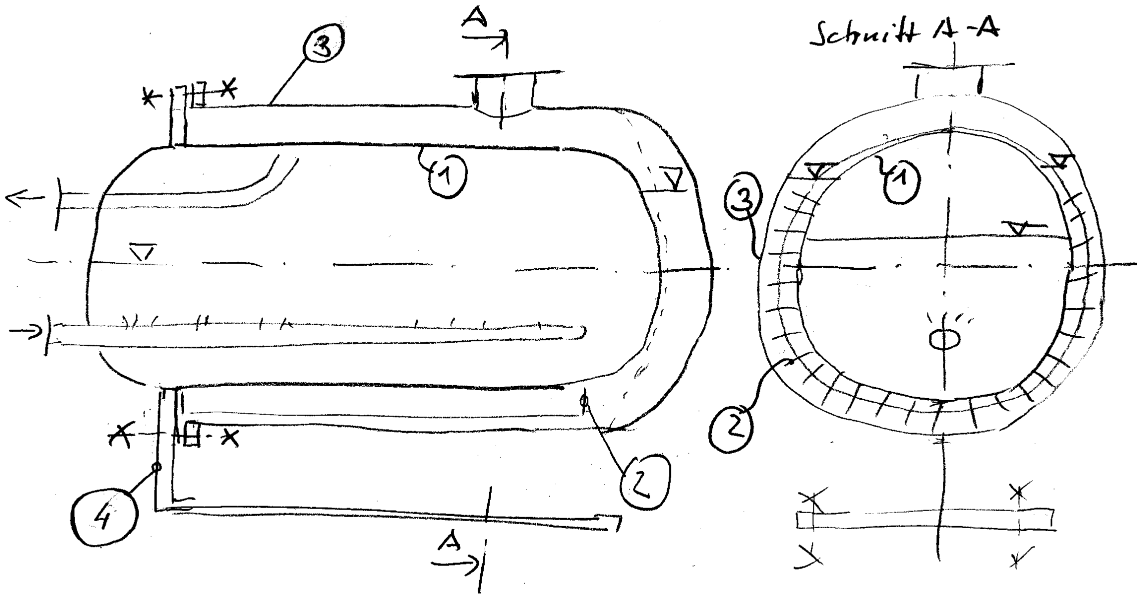


Figure 4.4 concept of hybrid storage with a double shell

The PCM device can be filled with granulated PCM, after heating up the system to a temperature over the melting temperature of the system the level of PCM will decrease (because of the difference in density), a few refills would be necessary. The volumetric expansion of the PCM between liquid and solid will be compensated by the level inside the PCM space (solid PCM is filled about 75% of the max level, liquid PCM at about 90%). In this concept unknown corrosion behavior was found to be a safety issue. Additionally, integration of the piping to the vessel and the vessel supporting would have been very difficult.

4.2.2.3 Open Modul

In this concept open modules were attached to the steam storage, these modules are filled with heat structures, see Figure 4.5. The maximum level of solid PCM in the modules are at about 75% of the storage high. The volumetric expansion is compensated by the level of PCM (like the double shell concept). The modules can be pre-filled with PCM granulate (heated up and refilling) and installed directly to the steam storage. The PCM is not directly in contact with the steam storage, which is a drawback for the thermal contact. Still, corrosion and thermal expansion could be tackled with this approach.

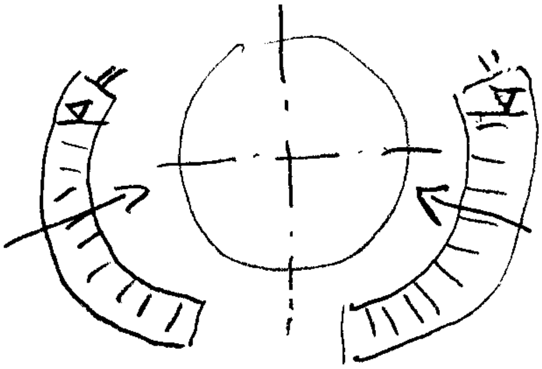


Figure 4.5 concept of hybrid storage with open modules

4.2.3 Stress analysis

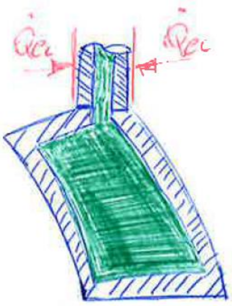
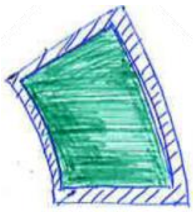
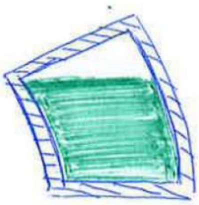
A stress analysis was carried out for several different module variants. For the stress analysis of PCM modules, the expansion of the PCM caused by heating and cooling is the most important load. According to the compensation of these expansions, the solutions are categorised by two criteria (Tab. 1):

- Open or closed module
- Modules which are 100% filled with PCM, and ones which are partially filled (filling<100%).

The following solutions are excluded:
Open System 100%-filled: In this case, the volume expansion of the PCM is compensated by liquid PCM from a compensation system consisting of pipes and tanks. The problem is that this system does not work if the PCM solidifies there. Therefore, the compensation system had to be heated, which is too complicated for the storage systems considered within this project.
Closed system partially filled with gas: The volume expansion is compensated by compressing the gas volume. If the gas volume is within an acceptable range, pressures due to expansion of the PCM are too large for thin-walled casings.
The following solutions are further considered:
Closed System 100%-filled: In this case, the expansion of the PCM, has to be compensated by elastic and eventually plastic deformation of the casing. To check if this is possible, structural analysis was done for a simple configuration of this type.
Open System partially filled: In such a system, the expansion of the PCM has to be compensated by flowing of liquid PCM to the gas volume during melting. In the gas volume, atmospheric pressure is assured by ventilation. Here a design has to be chosen in a way that this flow is possible.
The following analyses were carried out for the design given in 4.2.2.1:

- Thermomechanical analysis
- Gross plastic deformation design checks
- Stability design checks
- Fatigue calculations

Table 4.4 Possible encapsulation design approaches

	100%-filled	Partially filled
Open (ventilated) system	**Volume compensation by liquid PCM** Compensation pipe and vessel have to be heated (eg. electrical heating) to prevent solidification in the compensation system. 	**Volume compensation by ventilation** There is a gas volume over the PCM. The gas volume is connected to the atmosphere to prevent overpressure or vacuum (**eventually chosen design**). 
closed system	**Volume compensation by stretching of the casing** The module is completely filled with PCM. The case of the module has to be flexible to compensate the expansion 	**Volume compensation by compression of gas** The compressibility of gas volume over the PCM is used for volume compensation 

Strength analysis of closed PCM-modules made of aluminium was performed to consider the severe stresses due to volumetric expansion of the PCM during warming up and melting.
Within the structural model, it was possible to model elasto-plastic behaviour of the shell and PCM. Phase change of the PCM was modelled by changing material parameters with temperature. The connection of shell and PCM was modelled by contact elements and therefore, gliding and forming of gapes at the interface of the shell and the solid PCM is included.
Due to the structural mesh only very limited flow can be included. Investigation of convection and flow within small gaps is not possible with this model. Another limitation of the model is the formation of bubbles, which results in cavities in the crystallised PCM. In the current stat, the results can be checked for vacuum, which is a precondition for building bubbles.
According to the evaluation, the considered module can withstand a small number of cycles. The limited factor is damage due to cyclic deformation caused by expansion and shrinkage of PCM during melting and crystallisation. The fatigue Design Check itself had to be done with rough estimated design curves, because no design curves are available for aluminium within this high temperature range. According to these design curves, the fatigue life is too small for steam storage.

This small fatigue life and other problems, where the reason to choose alternative designs, which avoid this damage due to cyclic deformation. When it turns out, that the expansion of PCM cannot fully be compensated, the developed procedures can be used for further analysis.

The analyses were done within a preliminary design, which used eutectic KNO_3-$NaNO_3$, for which a minimum of material parameter, including strength parameters, are available. When using less frequently used PCMs, like the eutectic $LiNO_3$-$NaNO_3$, which was eventually considered within the project, it was necessary to evaluate the necessary parameters before such analyses can be performed.

At least for the pressure vessel in the test setup, stresses due to temperature differences introduced due to the PCM-modules, are negligible. In the case of real steam storage, the effect of temperature differences in the shell of the pressure vessel can be evaluated within fatigue analyses. The temperature differences due to the configurations, which are considered at the moment, are small, therefore no problems are expected due these thermal stresses.

4.2.4 Design of lab-scale devices

In order to be able to integrate the steam accumulator into the existing system, it was decided to build a base frame. This base frame is constructed in such a way that the possible thermal expansions can be absorbed. For this purpose, the storage was mounted in a floating and a fixed bearing.

Furthermore, I-beams were attached for easy disassembly of the PCM containers, which can be dismantled for transport. These I-beams offer the possibility of accommodating trolleys so that the PCM modules can be dismantled without much effort.

In order to mount the PCM modules as precisely as possible on the steam storage, a clamping device was constructed.

The PCM modules are each made of 2 rolled half-shells, which were adapted to the curvature of the steam storage by means of a gauge during production. The containers are equipped with aluminium lamellas on the inside, which should help to distribute the PCM optimally in the interior, so that a good heat transfer can be guaranteed (see Figure 4.6).

Furthermore, each PCM module has an inlet and outlet nozzle so that the containers can be filled accordingly. For monitoring the temperature, sleeves are welded in at various points, which make it possible to attach temperature sensors.

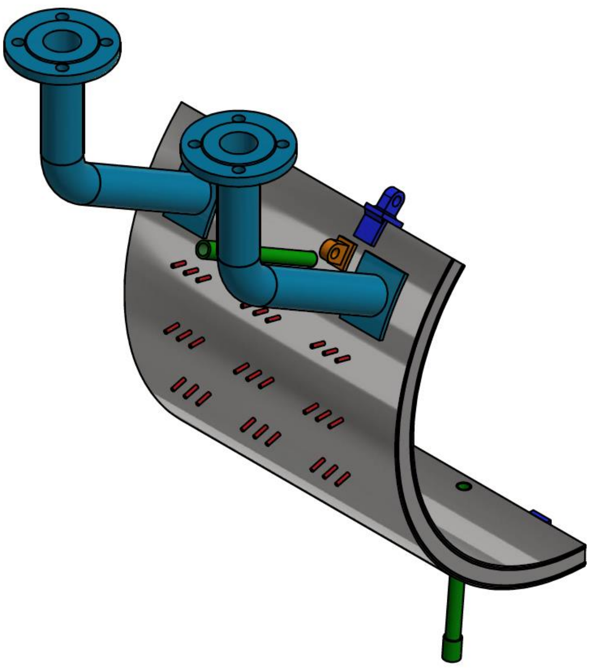


Figure 4.6: Final design of the PCM-modules

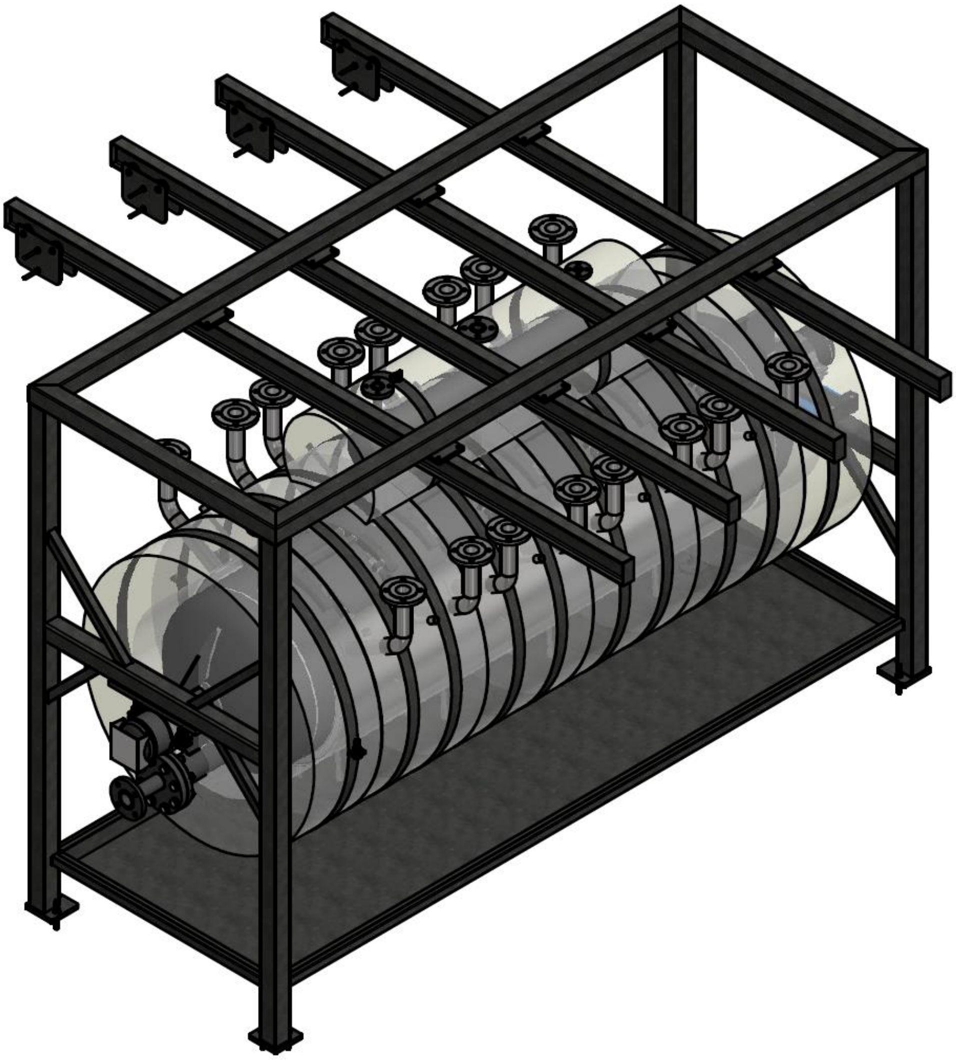


Figure 4.7: Final design of the overall setup: steam storage device with 8 PCM-modules and insulations

4.3 Lab-scale investigation

4.3.1 Construction of lab-scale devices

4.3.1.1 Construction of steam vessel

The steam vessel constructed by the company Reisenauer under supervision of Edtmayer Systemtechnik. In following figures, the different components of the steam vessel are shown.

Figure 4.8: Vessel base body under construction

Figure 4.9: Collector under construction

Figure 4.10: Vessel end with basket arch base and connection

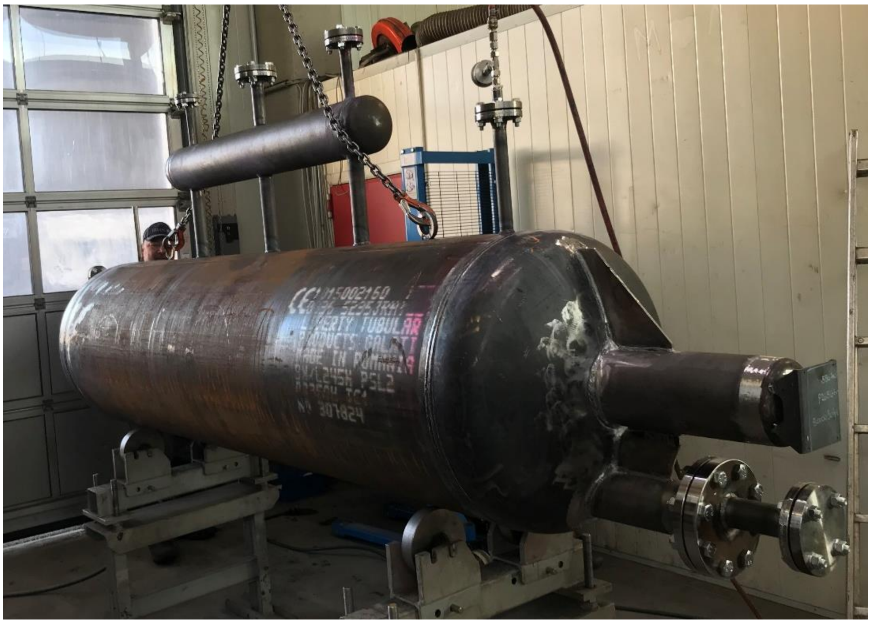


Figure 4.11: Vessel complete 2

4.3.1.2 Setup steam vessel

The lab scale Ruths steam storage (~ 1 m³ volume) was installed at voestalpine in Donawitz right next to the existing storage devices, which have a volume of 55 to 80 m³.

Figure 4.12: Lab scale Ruths steam storage device insulated and ready for experiments in May 2021

4.3.1.3 PCM Modules

At this point the PCM modules were under construction and planned for delivery in February. Due to a COVID incident at the manufacturing companies, the modules were not delivered until the mid of March.

4.3.1.4 Filling of the PCM-Modules

The following procedure describes all the activities and steps that were necessary to fill the modules with the intended PCM.

4.3.1.5 Preparation of the PCM

The PCM consists of a eutectic of sodium nitrate ($NaNO_3$) and lithium nitrate ($LiNO_3$). The two powdery substances were each weighed into 31.25kg batches and mixed. The ratio is 15.938 kg $NaNO_3$ to 15.313 kg $LiNO_3$. When mixing the PCM, noticeably coarse lumps were crushed to reduce the melting time.

4.3.1.6 Preparation of the Modules

The modules were covered with custom-made heating and insulating mats which were operated with external temperature controllers (Figure 4.13). As the upper operating limit of the heating mats is 250°C, the controllers were set to 240°C. The heating process of the empty module required between 30 and 60 minutes, depending on the ambient temperature inside the laboratory.

Figure 4.13: Mounting frame front view

The original variant of injecting the PCM in powder form into the pre-heated module failed. The heating elements did not have enough heating power to cause the phase change at the filling location (nozzle). Therefore, the PCM had to be externally heated to a liquid state and then filled into the module. The PCM was heated in batches of 2 kg to approx. 300-350°C in order to keep it liquid for as long as possible during the filling process. Larger quantities would not have been useful, as the PCM needs a certain amount of time to infiltrate through the lamellae in the module. In addition, handling larger containers poses an increased safety risk. To speed up the process, several pots were used.

Figure 4.14: Heating process of PCM

Figure 4.14 shows schematically the minimum and maximum filling level that was achieved. The check was carried out with a measuring rod that was inserted into the nozzle. The PCM was filled until a level was visible on the measuring rod. This guaranteed that the level was at least at the lower edge of the nozzle. Care was taken to leave the upper part of the nozzle free to allow air exchange during actual operation.

After reaching the required level, waited at least 10 minutes and checked again. The PCM needs time to distribute and vent evenly in the internal lamellas. After ensuring that the level no longer changes, the heating elements were deactivated, and the module was unpacked from the heating mats. The cool down time took several hours, which made it impossible to change the module immediately afterwards. On the one hand because the PCM could leak during handling and on the other hand because of the high temperature. In order to reduce or eliminate residual air inclusions and possible irregular distribution of the PCM, the module was heated up one more time and the filling level was checked again. Through this process, an average of 0.8 kg more PCM per module could be filled.

4.3.1.7 PCM vapour extraction system

A concept was developed to exhaust any vapours that may be generated by the hot PCM from the installation hall. It consists of a 32mm reinforced PUR hose which connects each of the 16 flanges. The two sides of the PCM modules are brought together like a common rail and routed to the outside. The exact hose lengths required were determined and installed directly on site.

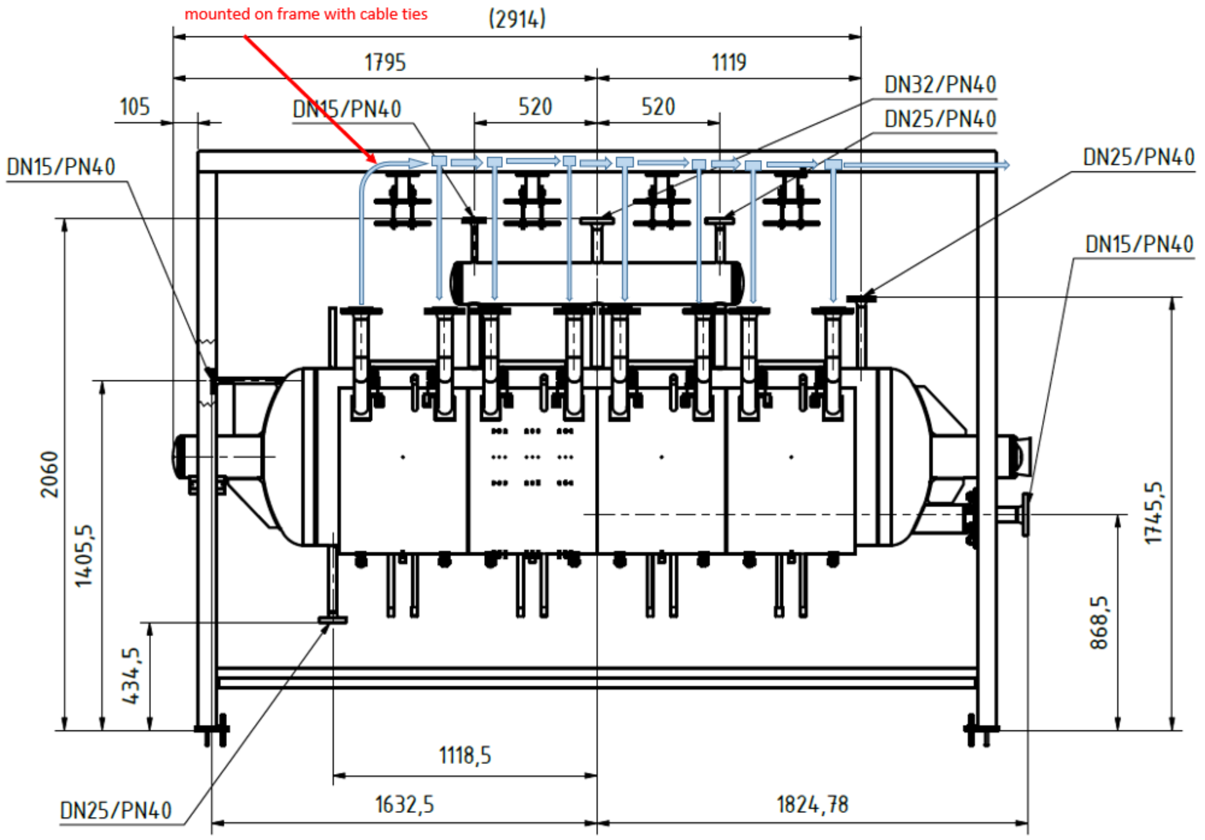


Figure 4.15: Schematic of the vapor extraction system

4.3.1.8 Assembling of steam vessel with PCM-Modules

After the experiments without the PCM were finished the insulation was dismantled and the PCM-modules were applied. Figure 4.16 shows the experimental setup without (left) and with (right) PCM modules after the insulation was already applied to the whole setup. The required additional volume to increase the storage capacity is marginal. Figure 4.17 shows the setup without insulations in the construction phase.

Figure 4.16: Lab scale Ruths steam storage, comparison without modules (left) and with PCM-modules (right)

Figure 4.17: Module assembling onto the Lab scale Ruths steam storage device, in the background a 80 m³ Ruths steam storage device

4.3.2 Experimental investigation and results

Higher heat loss than anticipated was observed in both RSS and hybrid storage experiments. It should also be noted that, presumably due to the constructional design, the initial condition before the start of the experiment has an influence on the measured heat losses.

The comparison between the measured and simulated results of the RSS experiments showed that the Dymola RSS model, in which the charging and discharging mass flows were determined on the basis of the pressure measurement, delivered a significantly more accurate result than the MATLAB RSS model, in which the liquid filling level measurement was mainly used.

Comparison between measured and simulated temperature trajectories in the PCM modules of the HyStEPs storage showed that the MATLAB PCM model could describe the physical behavior adequately. Still, despite of a thorough parameter identification and optimization procedure deviations remain. Deviations between individual PCM modules also indicate different contact conditions (e.g. different size of air gaps) between RSS and PCM modules (see Figure 4.19). Additionally, it was observed that heat is not evenly distribution within the modules (see Figure 4.20). Again, not the whole intended surface of the PCM-module was in contact with the steam storage surface, which resulted in a decreased heat transfer.

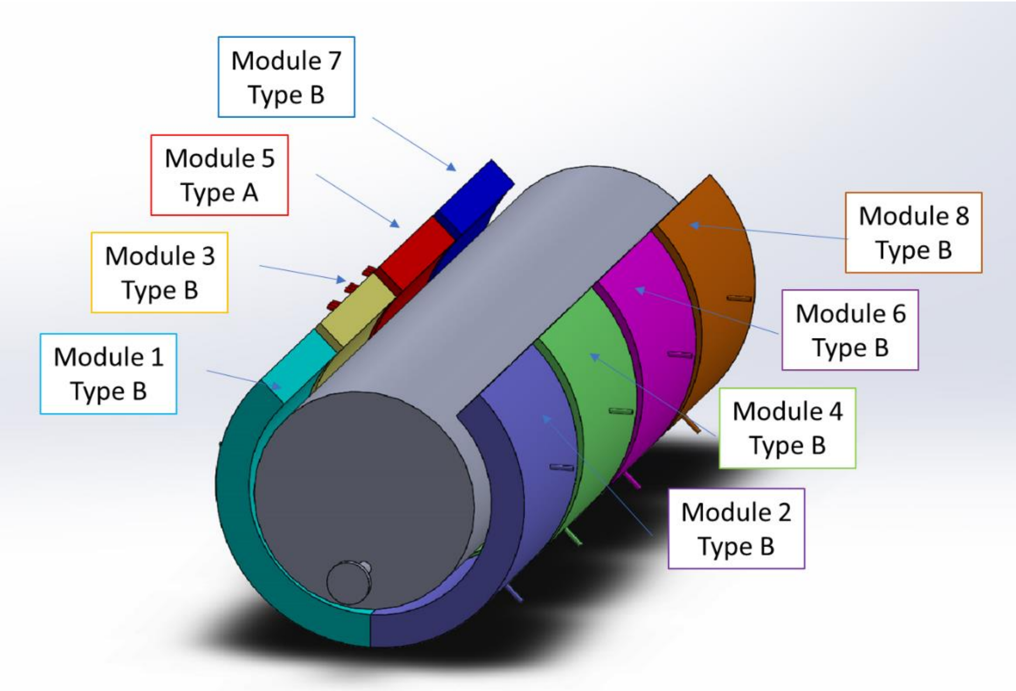


Figure 4.18: PCM-module position on the Ruth steam storage device

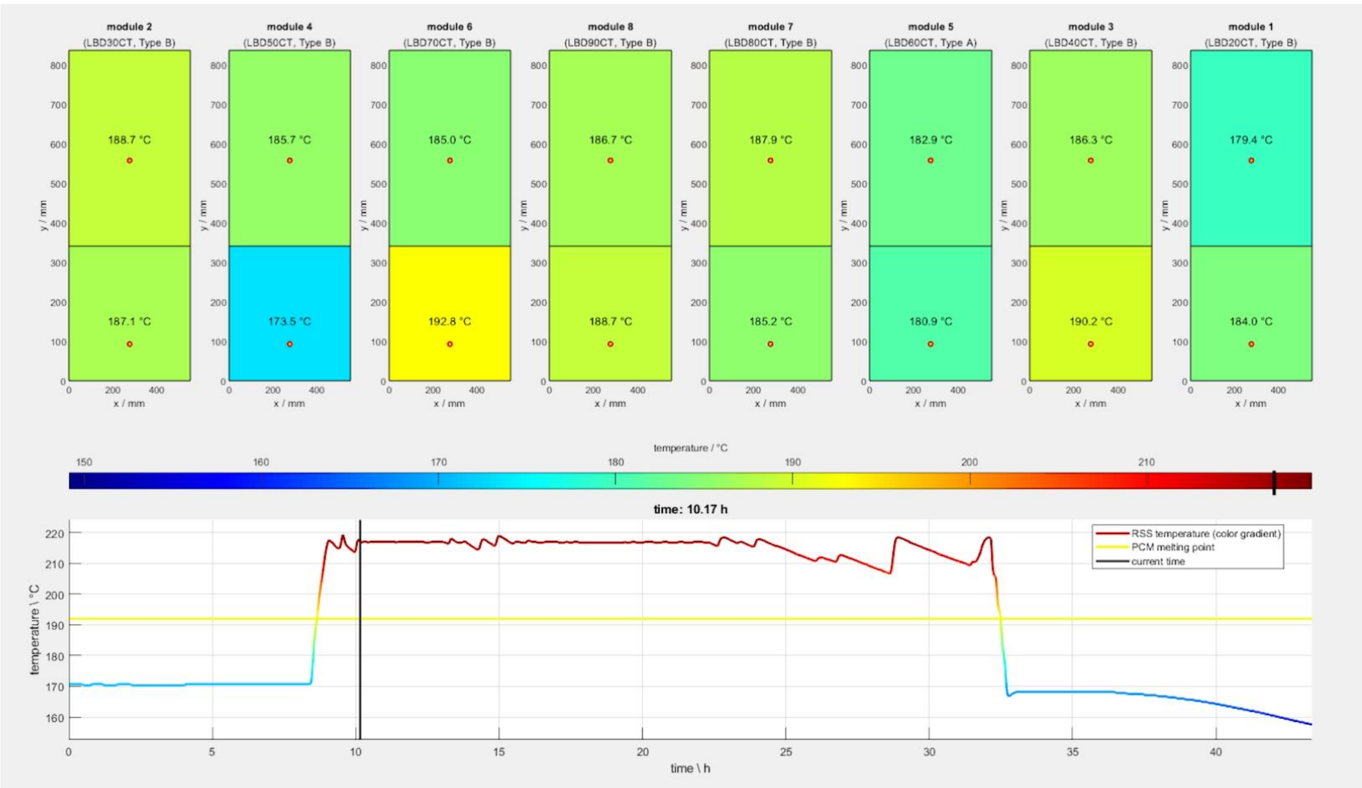


Figure 4.19: PCM-modules have different charging/discharging behavior due to different thermal contact quality wth the steam storage device

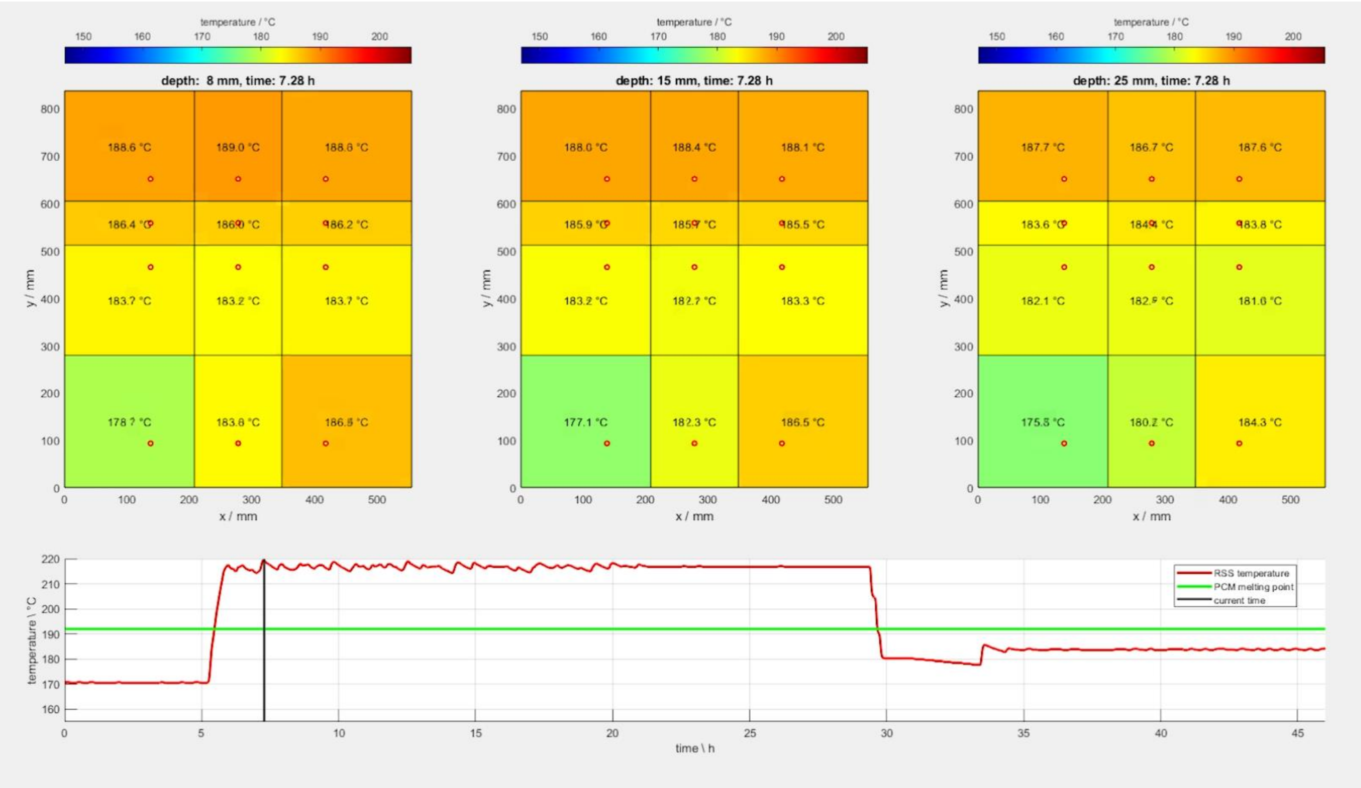


Figure 4.20: Inhomogeneous temperature distribution inside one module (module 5)

Within the Ruths steam storage reference unit, a maximum energy of 200MJ could be stored. Within the PCM storage modules, a maximum energy of approximately 60MJ could be stored. The hybrid storage, including PCM modules, can thus store about 30% more energy. However, full latent heat activation is only achieved after 10 to 20 hours of charging at 21 bar Ruths steam storage pressure. The long charging time is presumably due to the air gap between the PCM module and the pressure vessel. Approximately 28% of the stored energy in the PCM containers could be recovered to the steam system during a discharging period of 10 hours, as consequence of high heat losses and unsatisfactory heat transfer between PCM modules and RSS.

Simulation results attest to plausible energy recovery rates of up to 70% if the behaviour of the “best-performing” modules is assumed for the whole PCM storage unit. This demonstrates promising potential for future development, but also stresses the importance of engineering high heat transfer rates between Ruths steam storage and PCM modules.

4.4 Control strategies

4.4.1 Definition of operating strategy

The advantage that high loading and unloading rates are possible with steam storage is already highlighted in the literature. In contrast, the performance of the latent heat thermal energy storage is strongly limited due to the poor thermal conductivity of the PCM. In hybrid storage, the two storage technologies are interconnected. Therefore, with regard to operation strategy of the hybrid storage, care should be taken to ensure that the hybrid storage is charged or discharged as long as possible at a high temperature difference. Short-term high charging and discharging rates should be taken over by the steam storage part.

A typical implementation of RSS systems in a process is shown in Figure 4.21. The RSS storage system react very fast and therefore is used as a buffer between steam generators and consumers. For the hybrid storage system, a new operating strategy has to be developed, because of the different dynamic behavior compared to a pure steam storage device. To exploit the full potential of the additional storage capacity obtained by the attached PCM containers, the fast and slow dynamics present in the hybrid storage system need to be optimally utilized via model-based optimal/predictive control concepts. To load/unload the PCM segments a significant temperature difference between the RSS temperature and the temperature of the PCM melting point over a longer period of time is needed. Therefore, it is necessary to control the hybrid storage system (RSS 3 in Figure 4.21.) and remaining RSS units (RSS 1 and 2 in Figure 4.21.) in a multi-input, multi-output fashion. In doing so, appropriate multivariable control can exploit the advantages of fast RSS capabilities and slow but additionally available heat storage capacity from the PCM simultaneously and dynamically. The new operating strategy is developed and tested on the experimental hybrid storage system. Assuming that the steam generator provides steam whenever it is produced in the generating process, the storage operating strategy chooses which (if any) of the storage units are being charged via controlled valves. In turn, the operating strategy also dynamically decides upon which (combination of) storage units satisfy the consumers steam demand via actuating respective valves. It is expected that the RSS efficiently provides for the fast dynamic storage demands while the hybrid/PCM storage systems are consequently operated on a slower time scale to successfully activate the additional storage capacity.

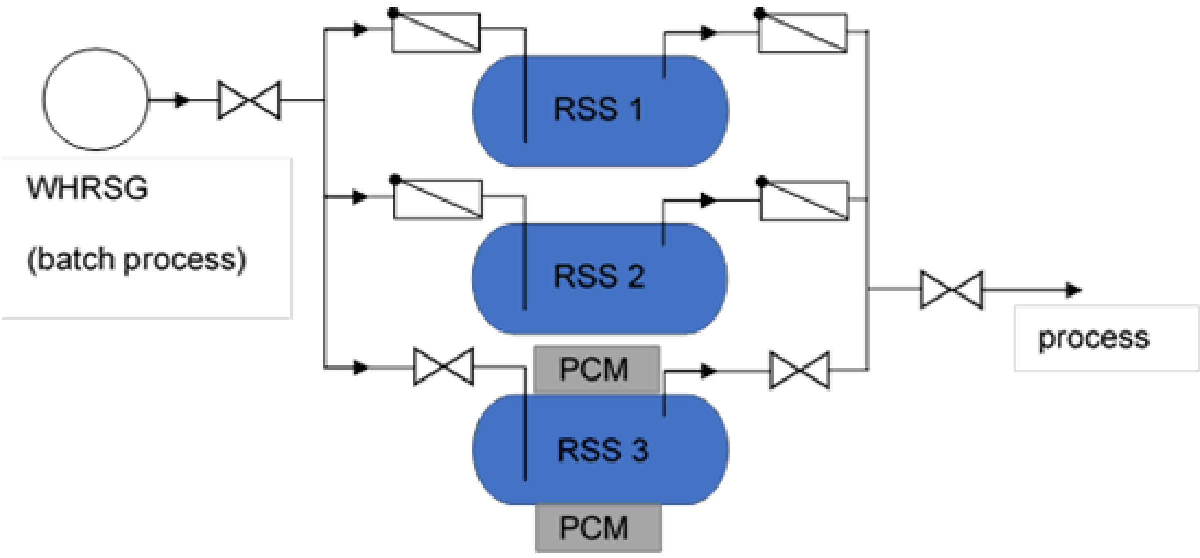


Figure 4.21: Typical system configuration of real RSS/PCM hybrid storage implementation with a waste heat recovery steam generator (WHRSG) in batch operating mode

The resulting control scheme is depicted in Figure 4.22 with Table 4.5 Signal specification for control/estimation schemegiving the signal specifications.

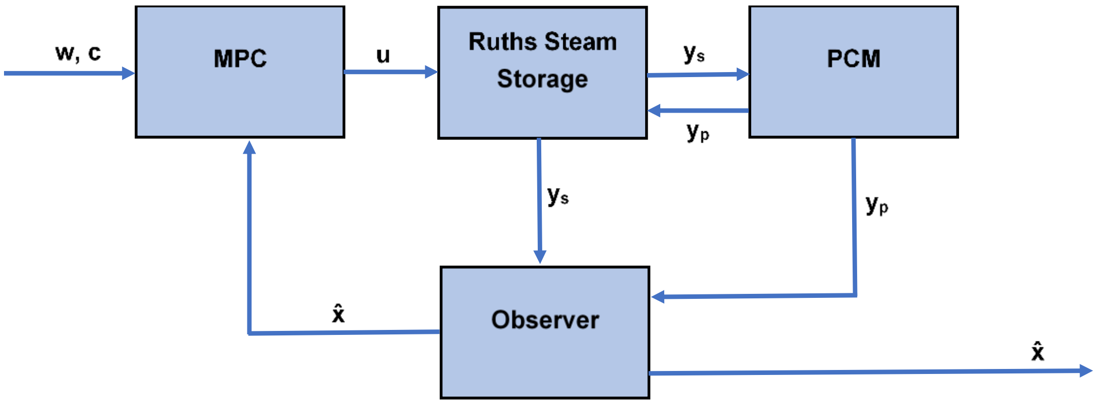


Figure 4.22: Block diagram of the control and estimation scheme

Table 4.5 Signal specification for control/estimation scheme

Signal	Symbol	Components
Control Variable Reference	**w**	RSS filling level reference
		RSS pressure reference
		mass flow steam out reference
Constraints	**c**	inputs (amplitude and rate of change)
		outputs (amplitude)
		filling level limits
Control Input to Steam Storage	**u**	mass flow steam in
		mass flow steam out
		mass flow feedwater in/out
Disturbances		steam quality in (water load, pressure, temperature)
		Coupling heat flow RSS <=> PCM
Output Steam Storage	$\mathbf{y_s}$	mass flow steam in
		mass flow steam out
		RSS temperature
		steam quality in (water load, pressure, temperature)
		RSS pressure
		RSS filling level
Output PCM Storage	$\mathbf{y_p}$	PCM temperature
		PCM pressure
Estimated States	$\hat{\mathbf{x}}$	temperature field
		location of the melting front
		liquid phase fraction field
		specific enthalpy

4.4.2 State estimation

The Ruths steam storage (RSS) contains water in liquid as well as vapor state and can be considered to be in thermal equilibrium. In thermal equilibrium, aggregated measurements such as temperature and mass (e.g. via the filling level) describe the overall system state, and the state of charge can be determined.

The modules surrounding the RSS are filled phase change material (PCM). The PCM stores energy during phase transition at almost constant temperature. Due to the complex energy-temperature dependency and low thermal conductivity of PCM, the state of charge cannot be measured directly, thus a suitable model-based observer is necessary [9].

The proposed observer framework is able to handle nonlinear distributed-parameter systems, such as those encountered in the present phase change problem. The method is based on a high-order but real-time capable finite element model for the PCM, which is used to predict future states [10]. This prediction model is linearized around the current trajectory and then efficiently reduced via balanced truncation to obtain an observer model with dominant modes only. The low-order observer model's states are augmented by selected parameters that should be estimated along with the states in order to deal with parameter mismatch or uncertainty. The observer model system matrices serve as Jacobians in an extended Kalman filter, and a state update of the prediction model is computed according to the difference between the measurements and the predicted model outputs. Thereby the observer combines temperature and volume measurements.

It is seen that an observer of this form converges well and is insensitive against model errors. The reduction of states restricts the intervention options of the observer. The observer computes the correction of the nonlinear prediction model based on the reduced states and thus can only correct the system according to its dominant behavior. The temperature sensor placement is optimized using a proposed mode-shape-based selection criterion.

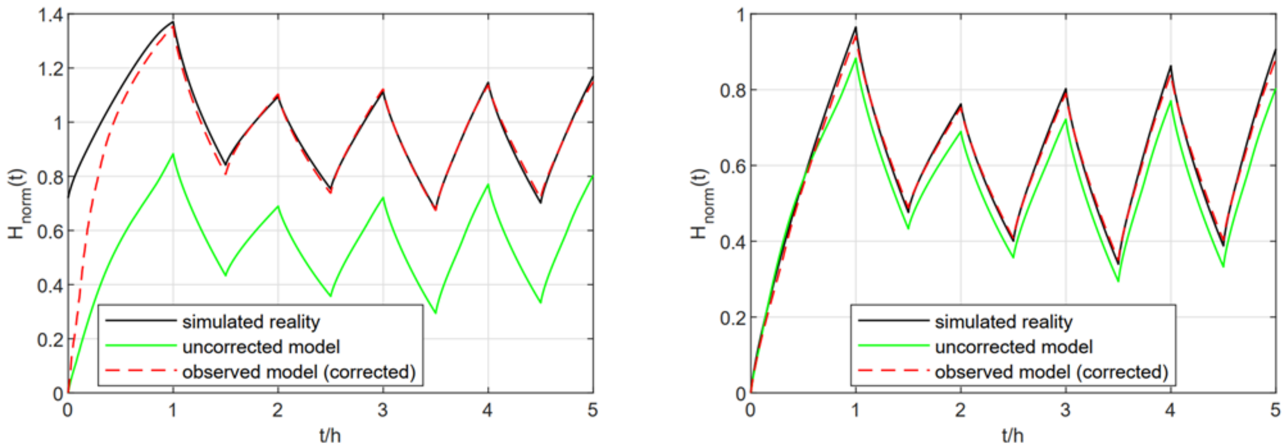
The observer can be computed in real-time and its performance is demonstrated in simulation studies of two scenarios: a wrong-initialization and a wrong-parametrization case. It is tested with simulated measurements generated by a detailed (but not real-time-capable) high-fidelity reference model, which exhibits a slightly different temperature distribution. The results are satisfactory, especially considering the large initialization error of the first test scenario and the modelling error of the temperature distribution between the prediction model and the simulated reality. The total enthalpy and thus the state of charge can be estimated with high accuracy, see Figure 4.23. Also, the location and shape of the melting front is estimated correctly, see Figure 4.24.

The developed observer method is capable for reliable state of charge estimation and thus serves as foundation to fully exploit the high energy density of PCM.

---

[9] Pernsteiner, D., Schirrer, A., Kasper, L., Hofmann, R., Jakubek, S., 2021. State of charge estimation in a nonlinear melting/solidification problem of a latent heat thermal energy storage using a novel extended Kalman filter framework. Computers & Chemical Engineering, doi: 10.1016/j.compchemeng.2021.107444

[10] Pernsteiner, D., Schirrer, A., Kasper, L., Hofmann, R., Jakubek, S., 2021. Data-based model reduction for phase change problems with convective heat transfer. Applied Thermal Engineering, doi:10.1016/j.applthermaleng.2020.116228



(a) wrong-initialization scenario (b) wrong-parametrization scenario

Figure 4.23: The normalized enthalpy content $H_{norm}(t)$ of the observed model shows an excellent convergence over time t in both test scenarios of wrong-initialization (a) and wrong-parameterization (b), even despite model errors.

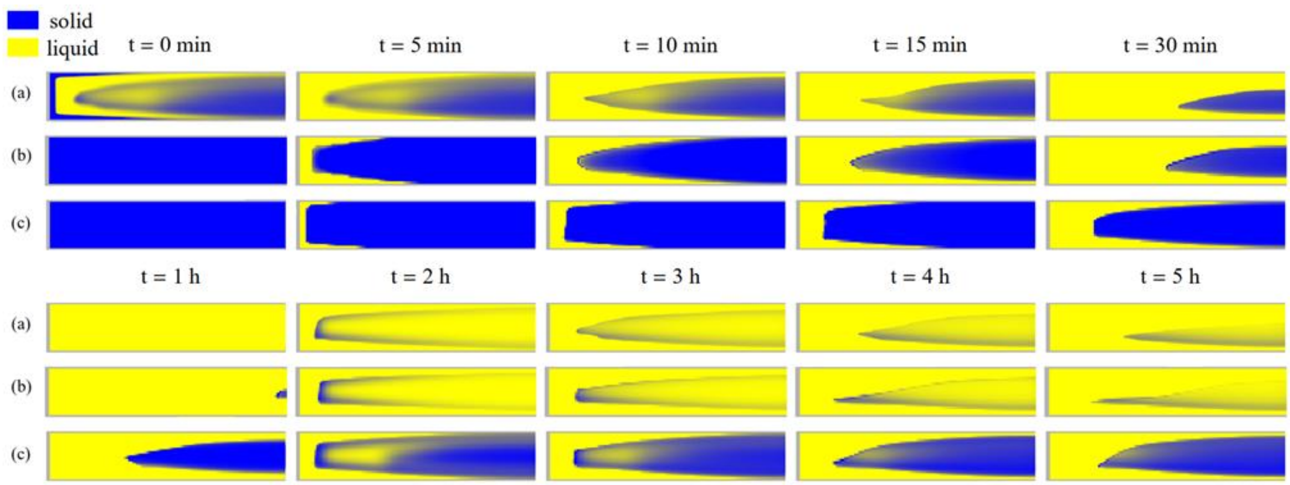


Figure 4.24: In the wrong-initialization scenario, the observed model (b) estimates accurately the melting front location and shape of the simulated reality (a) compared to the uncorrected model (c).

4.5 Technoeconomic evaluation

4.5.1 Process analysis

Four steam driven processes are analyzed regarding future steam generation scenarios coupled to electricity prices. Process dynamics are analyzed using Fast Fourier Transformation which yields information on required storage cycle durations. The storages that would be necessary in the considered future energy system were also evaluated regarding their effectivity. Data for the considered processes was provided from partners within the project consortium.

4.5.1.1 Introduction and Assumptions

Application scenario was defined as 2030-2050:

- Steam generation is purely from renewable sources
- This means natural gas, blast furnace gas is replaced by mainly electricity or sometimes biomass.

- Only steam generation from electricity is taken into account, as strong price fluctuations between day and night are to be expected here in the future.
- Steam production using a heat pump is conceivable here, but is not considered in detail.

Initial estimates and application scenario:

- Storage tanks can be charged during the day when electricity is cheap.
- Electricity storage vs. steam storage: battery 300-600 €/kWh, steam storage ~40 €/kWh
- Storage serves as a current collector for smoothing overcapacity.
- All processes in which electricity or gas is required to generate steam today

4.5.1.2 Process Analysis

Three different price scenarios are considered for steam supply. In the first scenario steam is supplied at a constant heat load. In the second and third scenario steam supply is assumed to be electricity driven and production rates are linked to electricity prices (Figure 4.25). These scenarios target future decarbonized energy systems with fluctuating energy prices.

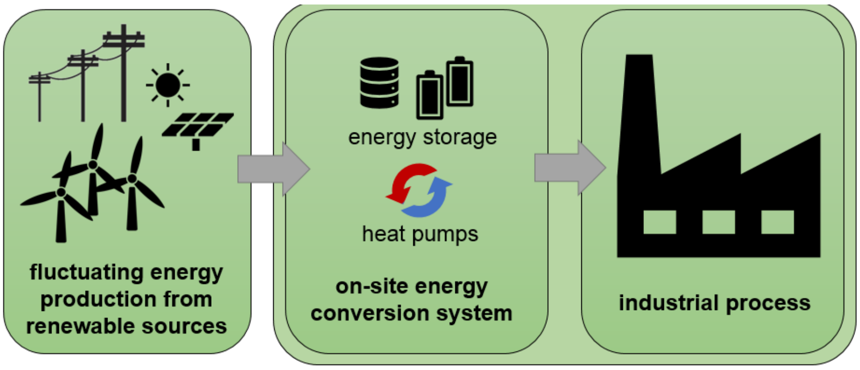


Figure 4.25: Scenario for future energy systems

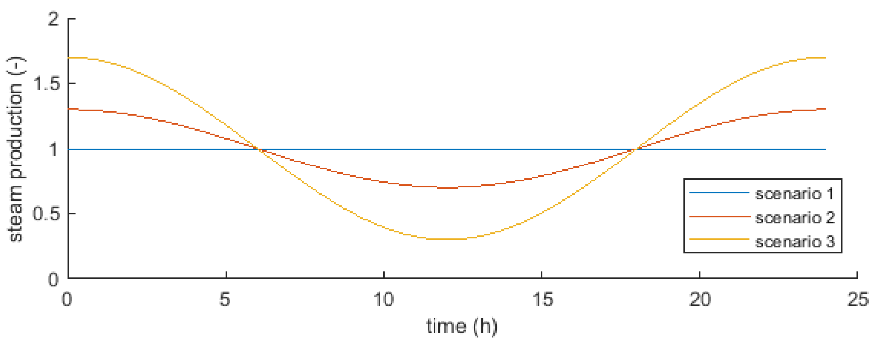


Figure 4.26: Considered scenarios for daily steam production

Steam demand from four different processes is analyzed regarding cyclic charging patterns using **Fast Fourier Transformation**, required storage capacities and charging/discharging rates. Then, the processes are evaluated regarding suitability for storage integration. The data was either provided by industrial partners (Process 1, Process 4), from previous projects (Process 2) and from voestalpine

(Process 3). Except for voestalpine the data presented stems from food and beverage processes. Temperature requirements for those processes can be considered to be in the range of 110-250°C.

In Figure 4.27 cumulated energy that needs to be stored and the corresponding residual storage power are shown for the individual processes and scenarios. It is apparent, that the required storage capacities strongly depend on the time frame considered.

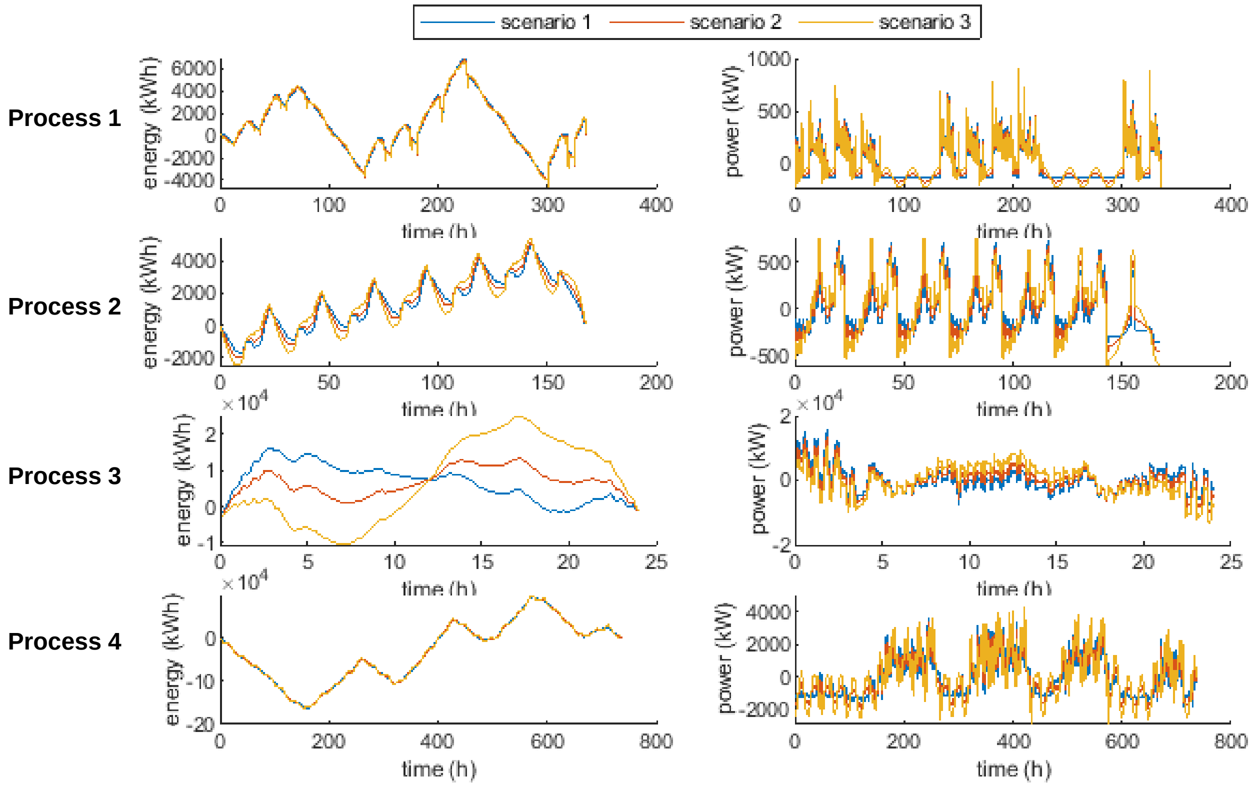


Figure 4.27: Cumulated energy and residual storage power for the considered processes

Processes 1 and 2 show periodic fluctuations of residual storage power requirements with approximately weekly fluctuations in cumulated energy. In contrast, Process 4 shows a period behavior with a period duration of about 1 week. *Fast Fourier Transform* analysis (Figure 4.28) highlights the fact, that process 1 has two main periodic charging and discharging patterns with a period length of one week and 24 hours respectively. Process 2 shows to have its main period durations for charging/discharging of 24,12 and 8 hours respectively. Process 3 does not seem to have significant contributions of individual charging/discharging frequencies, however a lot of relatively large amplitudes within a narrow period duration range around ½ hours exists. For Process 4 the main contributions stem from period durations of rd. 1 week. The weekly patterns mostly occur due to altered production plans during weekends. If only weekdays would be considered, the contributions from weekly patterns would be much less.

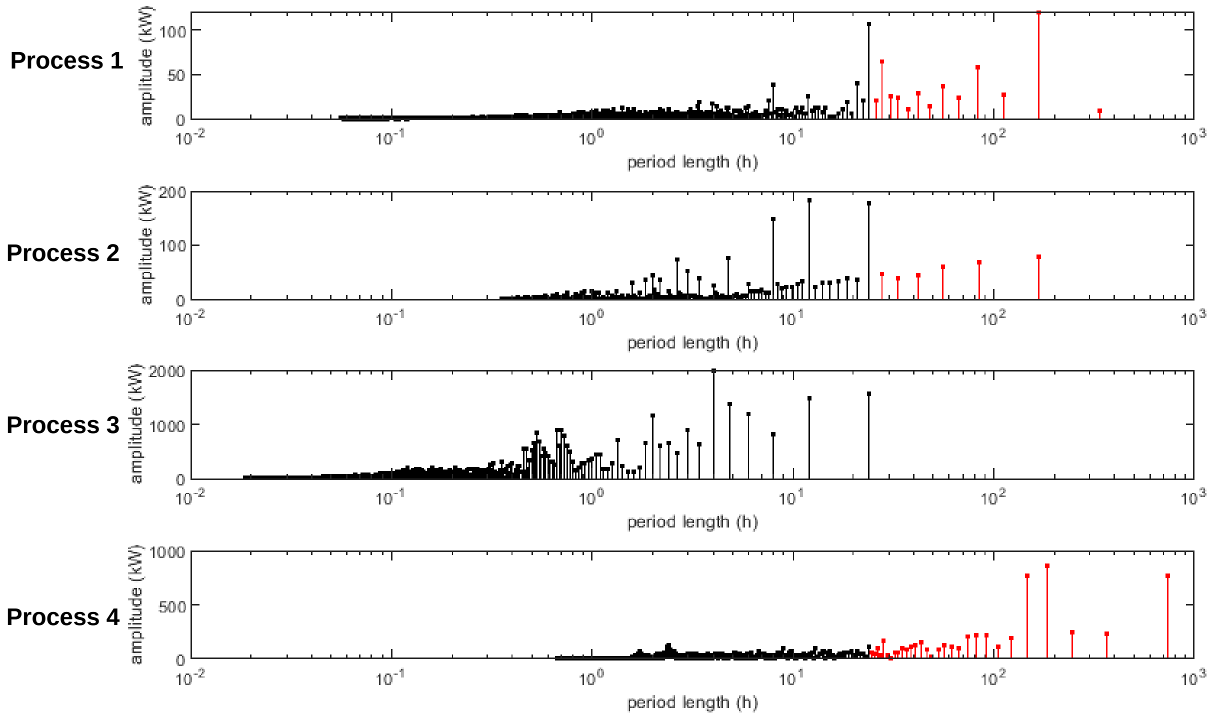


Figure 4.28: Results from FFT for the considered processes; period durations below 24h are shown in black

To quantify the effectiveness in terms of full charging cycles per day the following formula was used:

$$effectiveness = \frac{stored\ energy * \frac{charging\ time}{days}}{storage\ capacity}$$

The results for storage effectiveness in Figure 4.29 show that for process 3 steam storages can be most most effectively used, for all three scenarios. The results also show that for certain processes (i.e. process 3) varying steam production can increase storage effectivity (scenario 2).

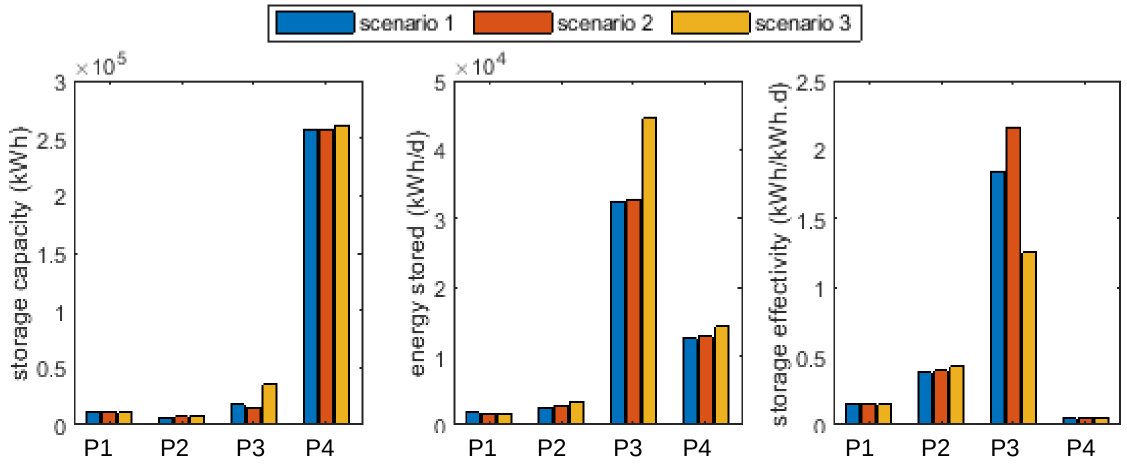


Figure 4.29: Total required storage capacity, daily stored energy and storage effectiveness (cycles per day)

4.5.2 Techno-economic analysis

In this analysis to approaches to increase the storage capacity will be compared, i.e. adding an additional Ruths steam storage device or retrofit an existing Ruths steam storage device to a hybrid storage device by applying PCM-filled modules.

4.5.2.1 Theoretical approach

In Figure 4.30 the theoretical cost savings for the retrofit measure compared with additional Ruths storage systems, are presented. It can be seen that the greatest cost savings can be achieved in the dairy process and the lowest cost savings occur for the brewery process. A reason for the low cost savings in the brewery process is that the PCM for this process is very expensive. On the other hand, the PCM is the most favorable for the voestalpine process. The PCM for the dairy process is also less expensive. Despite the low PCM costs in the voestalpine process, the cost savings are significantly lower compared to the dairy process. One reason is the low phase change enthalpy of this particular PCM. Another reason for the high cost savings in the dairy process is the high density of the PCM and thus the lower number of modules. Furthermore, the temperature difference between the phase change temperature and the maximum temperature in the pressure vessel influences the cost savings of the retrofitting measure.
Moreover, in Figure 4.30 on the diary process and bauxite process curve, points for the corresponding characteristic time span according to **Fehler! Verweisquelle konnte nicht gefunden werden.** are marked. For the paper mill and the voestalpine process the characteristic time span cannot be reached. On the contrary, for the brewery process the characteristic time span of 350 hours can be reached without aluminum. Already, a charging/discharging time of 14h can be reached without aluminum in the hybrid storage system of the brewery process.

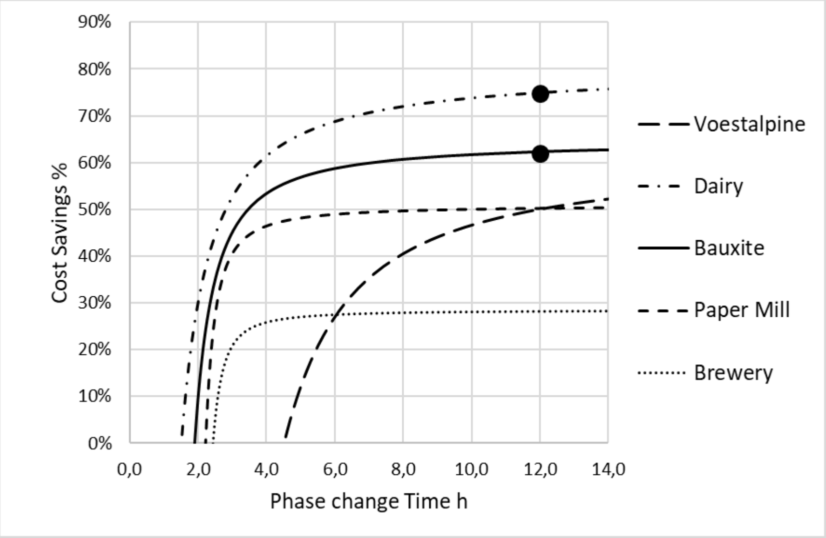


Figure 4.30: Cost savings when retrofitting the Ruths storage systems to the hybrid storage systems

4.5.2.2 Cost Calculation and sensitivity analysis based on prototype

In this chapter, the costs of different storage module capacities are calculated for a 55 m³ storage device with a max. pressure of 23 bar_as and a min. pressure of 7 bar_as. For a sensitivity analysis costs of PCM and modules are varied in the range of ± 30%. Additionally, costs of a Ruths steam storage device of equivalent capacity are estimated.

4.5.2.3 Total module costs

The total module costs obtained by summing up PCM and module costs are given in the following table:

Additional storage capacity	PCM cost	Module costs	Total Module costs	Module cost ratio %
10%	27 728 €	259 200 €	283 928 €	91,3 %
20%	55 372 €	285 120 €	340 492 €	83,7 %
30%	82 736 €	313 632 €	396 368 €	79,1 %

Table 4.6: Total module costs

4.5.2.4 Steam storage costs

As a benchmark the costs of a Ruths steam storage device of equivalent additional storage capacity were calculated, i.e. for +10%, +20%, and +30%. Costs of steam storage devices vary a lot. As a new steam storage device must be integrated into the existing steam system, additional costs of about 100% were considered. Estimated costs and their variations are given in the following table:

		additional capacity		
		10% ~ 5.5 m^3	20% ~ 11 m^3	30% ~ 16.5 m^3
Cost variation	-67%	12 650 €	25 300 €	37 950 €
	-50%	18 975 €	37 950 €	56 925 €
	-33%	25 300 €	50 600 €	75 900 €
	-17%	31 625 €	63 250 €	94 875 €
	0%	37 950 €	75 900 €	113 850 €
	17%	44 275 €	88 550 €	132 825 €
	33%	50 600 €	101 200 €	151 800 €
	50%	56 925 €	113 850 €	170 775 €
	67%	63 250 €	126 500 €	189 750 €

Table 4.7: Ruths steam storage costs

4.5.2.5 Sensitivity analysis of total module costs and benchmarking

In the following, costs of modules and PCM are varied by ± 30% in order to determine the influence on the total module cost price. This is done for all investigated additional capacities, i.e. +10%, +20%, +30%.

For 10% additional capacity the costs for the modules vary between 198 750 € and 369 107 €. The costs of the modules have the largest impact on the total costs. The difference is approx. 54 k€. The PCM price has a much lower impact, with a cost difference of only 17 k€. As mentioned before a cost decrease of 10% due to series productions seems feasible. As the PCM is a raw material prices are assumed to remain stable. Even larger quantities would not make a large difference according to vendors. It is a similar picture for 20% and 30% additional capacities. Here the costs range from 238 344 € to 442 640 € for 20% and 277 457 € to 515 278 € for 30% additional storage capacity.

The module costs have a larger cost impact than PCM costs.

Comparing with Ruths steam storage costs it becomes clear that all displayed total module costs exceed the costs of an Ruths steam storage device, which range from 12 650 € to 63 250 €. This is shown in **Figure** 4.31, where cost ranges of Ruths are compared with the expected costs of the hybrid concept. At this point, it must be concluded that the current hybrid concept is far from economic feasibility. However, it can be observed that the gap of Ruths costs and hybrid costs decreases with increasing additional storage capacity.

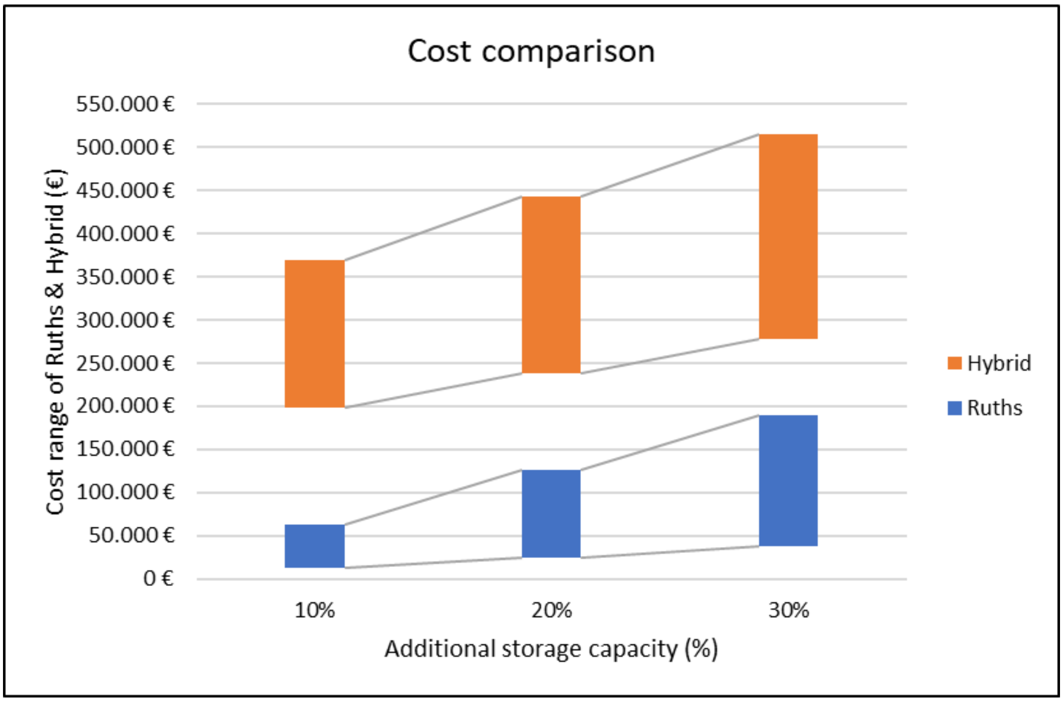


Figure 4.31: Cost comparison of adding storage capacity via additional Ruths steam storage and applying steel cased PCM modules (hybrid)

4.5.2.6 How it may work

As the cost gap is smallest at 30% additional capacity, we will take a look on how far costs need to be decreased in order to be compatible with state-of-the-art Ruth steam storage technology. For that the module costs will be decreased as they are the main cost driving factor. Furthermore, the costs of the modules are far more likely to be decreased than PCM costs.

A cost decrease of the modules of 90% would be needed to yield similar prices as the Ruths storages, 89 k€ to 139 k€ for hybrid vs. 38 k€ to 190 k€ for Ruths. Now a module would cost between 6 000 € and 8 000 €. This cost needs to be reduced by 90%, i.e., 600 € to 800 € per module.

There are some ideas how the costs could be decreased, e.g., by using completely new material combinations. However, at this point it is not clear if the drastic cost decrease of 90% can be realized.

4.5.3 Conclusion

In summary, the studies have shown that the cost savings using the hybrid storage retrofit approach, depend on many factors. The most important factor is the charging/discharging time. The longer the time, the more beneficial the retrofitting measure to the hybrid storage system can be. Moreover, the temperature difference in the pressure vessel, the PCM properties of the available PCMs and the PCM costs are important factors.

Neglecting encasing costs (module): For the dairy and the bauxite process cost savings higher than 60% could be reached while meeting the process requirements. For the voestalpine and the paper mill process the process requirement could not be fulfilled with the retrofitting measure. Additional Ruths steam storage systems are the better option. Cost savings higher that 20% could be reached with the retrofitting measure in the brewery process.

Including encasing costs (module): A capacity enhancement for a **55 m³ Ruths steam storage** device was discussed. It was found that the current hybrid concept would cost much more than an additional Ruths steam storage device of equivalent capacity, i.e. +10%, +20%, and +30%. The costs of the hybrid concept consist of module costs and PCM costs, where the former has the major impact on costs. Thus, a decrease of costs of the modules by 90% would be necessary to be in the same costs range as the Ruths steam storage. That means, that module prices need to decrease from 6 000-8 000 € to 600-800 €.
The Ruths storage device would then still bear the benefit of small charge and discharge time, i.e. ~ 30 minutes, whereas the hybrid concept has several hours. To choose the hybrid concept over the Ruths concept, the costs of the hybrid concept need to decrease even further. This would be possible, if PCM prices and module costs could be lowered. Since the PCM contains Lithium, it is very unlikely that its price will go down soon. Another PCM ($NaNO_3$-KNO_3) that was taken into account, would have cost much less, but only has a third of the melting enthalpy.

5 Outlook and recommendations

In the project HyStEPs a lab scale steam storage device was built and implemented into a steam network to carry out experiments with attached phase change material modules. These modules allowed an increase of the steam storage capacity of 30 %. Technical issues that were addressed in course of the project were: corrosion and thermal conductivity of the phase change material, heat transfer between the modules and the steam storage vessel, the control strategy of the resulting hybrid storage device, and techno-economic aspects.
The working principle of enhancing existing steam storage devices with latent heat storage material, i.e. PCM, was successfully demonstrated. However, this very first project in this field also showed currently existing challenges to make this technology market ready:

i) for mass production a new approach for the encasing of PCM is necessary, which is less expensive
ii) the heat transfer between the steam vessel and the module must be increased to increase performance
iii) heat transfer within the PCM has to be increased in a clever way

To sum up, better performance and cheaper productibility are main goals for a follow-up project. This basically means back to square one, since material selection and the overall concept have to be reimagined. There are already some promising concepts within the consortium, that shall be investigated in a follow-up project in the near future.
The goal: to increase steam storage capacity without interfering into the existing steam infrastructure.

6 Selected Publications

Design Optimization of a Hybrid Steam-PCM Thermal Energy Storage for Industrial Applications
Rene Hofmann, Sabrina Dusek, Stephan Gruber, Gerwin Drexler-Schmid
Energies 2019, **12**(5), 898
https://doi.org/10.3390/en12050898

Eine Eiswürfelhülle für heißen Wasserdampf
Veronika Schmidt
Die Presse, Print-Ausgabe, 19.09.2020
Eine Eiswürfelhülle für heißen Wasserdampf | DiePresse.com

Co-simulation methodology of a hybrid latent-heat thermal energy storage unit
Dominik Pernsteiner, Lukas Kasper, Alexander Schirrer, René Hofmann, Stefan Jakubek
Applied Thermal Engineering, Volume 178, September 2020, 115495,
https://doi.org/10.1016/j.applthermaleng.2020.115495

Data-based model reduction for phase change problems with convective heat transfer
Dominik Pernsteiner, Alexander Schirrer, Lukas Kasper, René Hofmann, Stefan Jakubek
Applied Thermal Engineering, Volume 184, 5 February 2021, 116228
doi:10.1016/j.applthermaleng.2020.116228

State of charge estimation in a nonlinear melting/solidification problem of a latent heat thermal energy storage using a novel extended Kalman filter framework
Dominik Pernsteiner, Alexander Schirrer, Lukas Kasper, René Hofmann, Stefan Jakubek
2021, *Computers & Chemical Engineering*, Volume 153, October 2021, 107444,
https://doi.org/10.1016/j.compchemeng.2021.107444

Numerical studies on the influence of natural convection under inclination on optimal aluminium proportions and fin spacings in a rectangular aluminium finned latent-heat thermal energy storage Lukas Kasper, Dominik Pernsteiner, Martin Koller, Alexander Schirrer, Stefan Jakubek, René Hofmann
Applied Thermal Engineering 190 (2021) 116448
https://doi.org/10.1016/j.applthermaleng.2020.116448

7 Contact Details

Project Lead

AIT Austrian Institute of Technology GmbH
Gerwin Drexler-Schmid
Giefinggasse 2, 1210 Wien
+43 664 6207866
gerwin.drexler-schmid@ait.ac.at
www.ait.ac.at

Project Partners

voestalpine Stahl Donawitz GmbH
Florian Javernik
Kerpelystraße 199, 8700 Leoben
+43 50304252142
florian.javernik@voestalpine.com
www.voestalpine.com

Edtmayer Systemtechnik GmbH
Michael Wallner
Talpagasse 6, 1230 Wien
+43 1 7896340
michael.wallner@edtmayer.at
www.edtmayer.at

TU-Wien, Institut für Energietechnik und Thermodynamik
René Hofmann
Getreidemarkt 9/BA, 1060 Wien
+43 1 58801 302327
rene.hofmann@tuwien.ac.at
www.iet.tuwien.ac.at

TU-Wien, Institut für Mechanik und Mechatronik
Alexander Schirrer
Getreidemarkt 9/325, 1060 Wien
+43 1 58801 325521
alexander.schirrer@tuwien.ac.at
www.mec.tuwien.ac.at

TU-Wien, Institut für Konstruktionswissenschaften und Produktentwicklung
Franz Rauscher
Getreidemarkt 9, 1060 Wien
+43 1 58801 32910
franz.rauscher@tuwien.ac.at
www.ikp.tuwien.ac.at