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FlexModul *Final Report*

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FlexModul

Demonstration of a Modular Solid Sorption Heat Storage System

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2 Introduction

The volatility (fluctuations) of renewable energy sources creates a high demand for energy storage systems, which is essential to ensure a secure supply even during periods of low energy production. According to Statistics Austria (n.d.), Austrian households consumed 207 473 TJ of energy for space heating in 2023/2024, accounting for 70.3 % of total energy consumption in the household sector. Due to this large share, heat storage systems will therefore play a crucial role in the future integration of renewables and waste heat into energy systems in the future. Their high flexibility and balancing capacity make them particularly well suited for this purpose. This ensures that the storage system can absorb surplus energy from renewable heat and electricity sources and release it when heat demand is high. In this way, they help to smooth out fluctuations in renewable energy production and consumption, thereby reducing peak loads and relieving both electricity and heating networks.

2.1 Task

The aim of the FlexModul project was to develop and demonstrate an innovative, modular and compact sorption storage system – a so-called thermochemical storage system. This technology is characterised above all by its high energy storage density and flexibility, as well as low thermal losses. Investment and operating costs were to be reduced to a minimum and the applicability of the concept was to be tested in other areas of application in the heating and electricity sector, starting with classic buildings. Furthermore, good technical and economic scalability of the heat storage concept based on a modular design was sought.

2.2 Focal points of the project

The project focused on the further development of sorption storage systems at both the component and system level, with particular emphasis on modularity, compactness, scalability and mass production capability to reduce investment costs to a minimum and maximise the applicability of the concept. During the course of the project, it became evident that there is substantial added value in viewing the "FlexModul" not only as an efficient and compact heat storage device, but also as a complete heat preparation system. To explore the full application potential of the technology, targeted analyses were carried out to examine various business case options, considering the technical and economic performance of the modular storage concept.

2.3 Placement in the programme

The "FlexModul" project was submitted in the third call for proposals of the „Vorzeigeregion Energie“. The aim of the FTI initiative "Vorzeigeregion Energie" was to build on existing knowledge, developed technologies and solutions, and implemented pilot projects in order to foster further development, enable system integration and support market introduction. The initiative aimed to maintain and further

strengthen Austria's leading position in the heat storage sector while creating new opportunities for Austrian stakeholders.
The "FlexModul" project directly addressed these objectives. The consortium's long-standing expertise in the field of sorption storage technologies proved highly beneficial, as the underlying technology had already been successfully demonstrated in previous projects at TRL 5/6. To make the big leap from TRL 6 to TRL 8, the project combined numerous technological improvements at multiple levels.

2.4 Fundamentals

To introduce the topic and provide a basic understanding of sorption technology, the underlying principles are outlined below.

Heat storage using sorption technology is relies on a reversible physical process in which heat is stored and released according to the formula ***A + B*** ↔ ***AB + Heat***.
When the storage system is charged, heat is added to substance ***AB***, which dissociates into components ***A*** and ***B***. If both components are stored separately, no reaction can take place. To recover the heat, the two components ***A*** and ***B*** are allowed to react with each other. In this way, heat can in principle be stored at any temperature for any length of time. To simplify the separation of ***A*** and ***B***, one of the reactants is usually in a gaseous state and can be recondensed after separation. The choice of substances ***A*** and ***B*** depends on the temperature range in which the reaction outlined in Figure1 takes place. (Wagner et al., 2006)

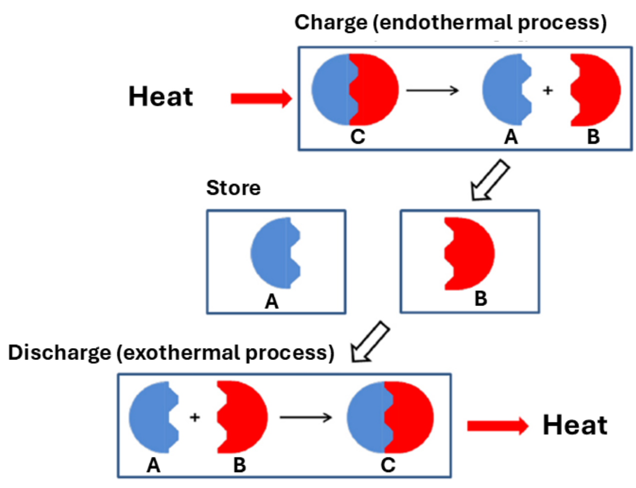


Figure1 : Basic principle of the sorption process (Pfeiffer, 2015)

Short- and long-term heat storage was realized in this project through water vapour adsorption in the microporous structure of zeolite.

Zeolites are aluminosilicates whose lattice structure consists of SiO_4 and AlO_4 tetrahedra. There are natural and synthetic zeolites. Synthetic zeolites are predominantly used for technical applications, as the purity of the more than 40 naturally occurring zeolites is usually not satisfactory. Synthetic zeolites,

on the other hand, can be produced in high purity and with reproducible composition and structure. Depending on the ratio of silicon to aluminium, different crystal structures and correspondingly different physical properties result. The respective pore size depends on this crystal structure and also on the incorporated cations. (Hauer, 2002)
The zeolite used for the storage system in the present project is called type 13X, which features a lattice structure with a 12-membered ring.
Beyond their common use in drying processes, air purification and decomposition processes, and hydrocarbon separation, zeolites are also applied in storage applications. According to Storch (2010), the type X zeolites are particularly suitable for this purpose due to their low silicon content, which ensures a sufficiently hydrophilic character.

Advantages of zeolites are their high mechanical strength and excellent thermal stability. In addition, they achieve comparatively high storage densities. Also, some drawbacks must also be considered. Zeolites require relatively high charging (desorption) temperatures and, according to Meitner (2016), are more expensive compared to alternative materials such as silica gel.

In the diagram shown in Figure1, component ***A*** corresponds to dry zeolite, component ***B*** to free water vapour and substance ***AB*** to zeolite saturated with adsorbed water. The components were selected for the following reasons: In addition to its wide availability and physiological safety, water offers a very high evaporation enthalpy, which leads to high energy storage densities. For example, the condensation of water vapour at 50 °C releases a heat quantity of approximately 0.65 kWh/kg. Since the adsorption of water vapour on the surface of the zeolite involves a phase transition between the gaseous and liquid phases, during which the molecules become sorptively bound to the solid surface. The adsorption enthalpy released in this process therefore consists of the condensation enthalpy combined with the contribution from the binding forces of the zeolite surface. As the adsorbent becomes increasingly loaded (i.e. as more water molecules are already adsorbed on the surface), the binding energy and thus the released reaction heat decreases, since the binding forces act only over short ranges.

The task of the material is to adsorb as much water as possible. This requirement can be met by a variety of technical adsorbents such as silica gels, zeolites and activated carbons, all of which are available on an industrial scale.

Open and closed systems

When water vapour is used as the working gas, the storage system can be designed as either open or closed system. In an open system, desorption is achieved by flushing the zeolite with dry air, whereby the water vapour is released into the atmosphere. For discharge (adsorption) moist air must then be supplied.

For the development of the sorption storage system in this project, a closed system was preferred in which the released water vapour condenses and is stored separately as liquid water. Before discharge (adsorption) it can be re-evaporated at low temperatures, allowing efficient reuse within the system..

This process was chosen for the following reasons:

• No electrical energy is required for water vapour transport.
• Omitting air as a carrier medium makes it possible to use finer, irregular granulate and thus denser and more cost-effective material packings.
• The decoupling of heat and mass transport leads to better utilisation of the adsorption capacity with suitable heat transfer in the adsorber.
• In open systems, moist air must be available for discharge. The provision of moist air usually requires additional energy consumption and the achievable level of air humidity determines the amount of heat that can be generated in the storage tank.

Water is particularly well suited as a working fluid in a sorption system due to its high specific evaporation enthalpy and polarity. Compared with other adsorbents such as ammonia or methanol, it achieves the highest energy densities.

Beyond its high evaporation enthalpy, water offers the following advantages:

• it is chemically stable
• it is ecologically and physiologically harmless
• it is available in almost unlimited quantities
• it is relatively inexpensive

When applying the sorption principle as an energy storage medium for a heating system, the storage material in the actual project is charged using a power-to-heat unit supplied by PV modules. In this charging process, the adsorbent is dried (desorption), while the released water vapour is condensed and the water collected in a separate container.
During discharge, the water is evaporated at a low temperature. The resulting water vapour is adsorbed by the zeolite and releasing heat at a higher temperature, which can then be transferred to the heating system via a heat exchanger. Even during the winter month, periods of high radiation can be utilised to desorb parts of the water vapour, enabling repeated adsorption-desorption cycles. This significantly reduces the required storage size. (Wagner et al., 2006)
The following figure shows the basic principle of a closed sorption storage system.

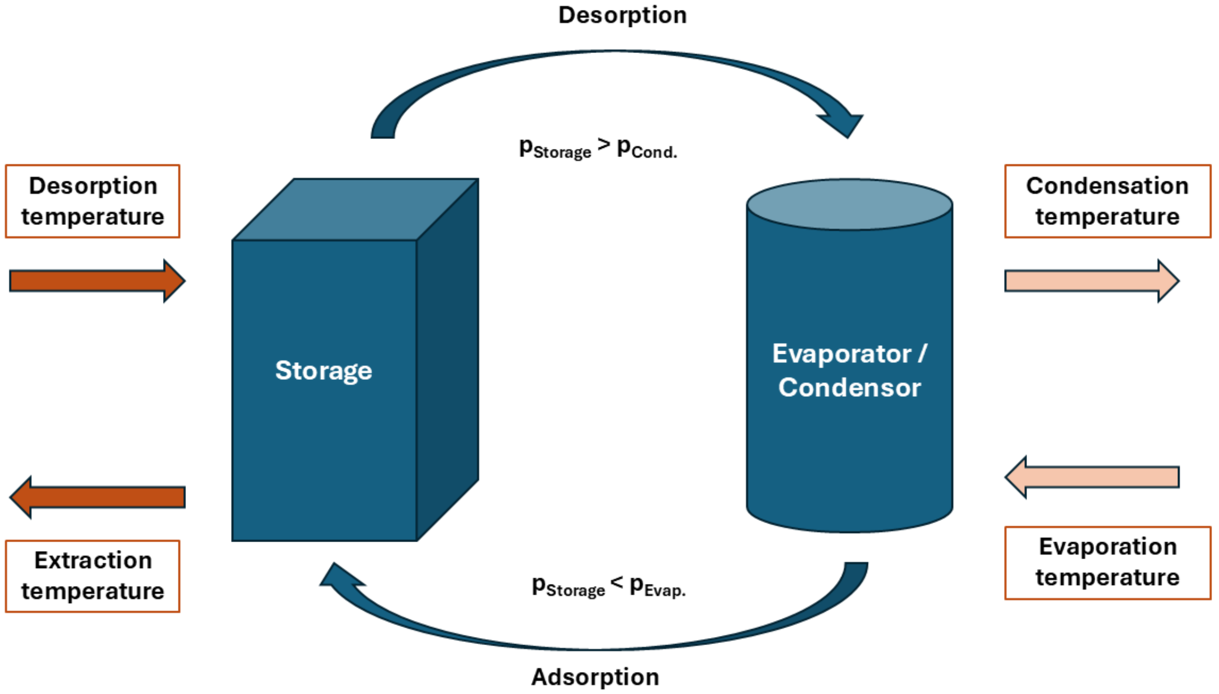


Figure 2 : Closed sorption storage system

2.5 Methods used

The project was divided into four central areas of work – an overview can be found in Figure 3.

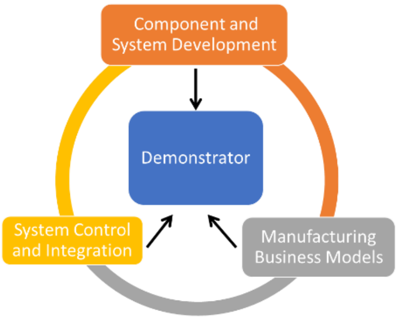


Figure 3 : Overview of the methodological approach in the project

A key objective was to raise the storage system to a higher TRL while simultaneously reducing manufacturing costs. To achieve this, a range of methods was applied:
Building on previous projects with sorption technology, numerous expert discussions were held on the various development topics. In addition to the project partners, experts from IGTE University of Stuttgart and TU Berlin, as well as from the companies SorTech and ZeoSys, contributed their expertise.

- Component and system development
  Extensive investigations into material selection were carried out on the material testing bench at AEE INTEC. Various sorption materials were examined in respect to mechanical and chemical stability, good and rapid water absorption capacity, sufficiently high discharge temperature levels and overall performance.
- Conceptual design, construction and simulation
  This area relied on expert discussions, patent searches, SWOT analyses, 3D CAD designs, FEM simulations and dynamic simulation environments such as TRNSYS and Modelica.
- Manufacturing
  Work focussed on developing processes for large-scale production and identifying economies of scale to reduce production costs.
- Business models / dynamic economic analysis
  Based on the measurement results, a detailed simulation model was developed in MS Excel with its core components e validated using the Simulation Studio (TRNSYS) simulation environment. Energy management calculations and evaluation were performed based on selected KPIs .
- System control & integration
  Development of control strategies and definition of operating modes with the aid of Modelica and TRNSYS.
- Demonstrator
  A complete FlexModul system was set up in the laboratory to verify the functionality of both components and the integrated system. Methods: measurement concept development, sensor selection, data aquisition and transmission, measurement data visualisation, data analysis, optimisation and comparison with simulation results.

2.6 Structure of the work

The following work was carried out during the course of the project and is included in this report:

- Concept development
- Material selection and testing
- Component development and validation
- System design and development
- Control strategy development
- Development of manufacturing processes
- Component manufacturing
- System setup and demonstration
- Testing and performance evaluation
- Economic feasibility assessment

3 Content presentation

3.1 Concept

The main objective of the concept development was to design a modular, scalable and easily expandable storage system that can be seamlessly integrated into existing single-family and multi-family homes or buildings in the tourism sector. As a first step, a comprehensive literature and patent review was conducted to identify comparable concepts.
In expert discussions and workshops, different system concepts were assessed and compared against defined requirements, with the most suitable configuration selected.
Based on developments during the project, several storage concepts for the most promising applications were investigated and evaluated. The individual system components were subsequently calculated, designed and built for operation. Figure 4 presents a simplified diagram of the final system concept, including the following main components:

- High-temperature sorption storage (HTS)
- Sorption storage (S1)
- Sorption storage (S2)
- Evaporator and condenser (E/C)
- Heat pump as low-temperature source for the system (HP)

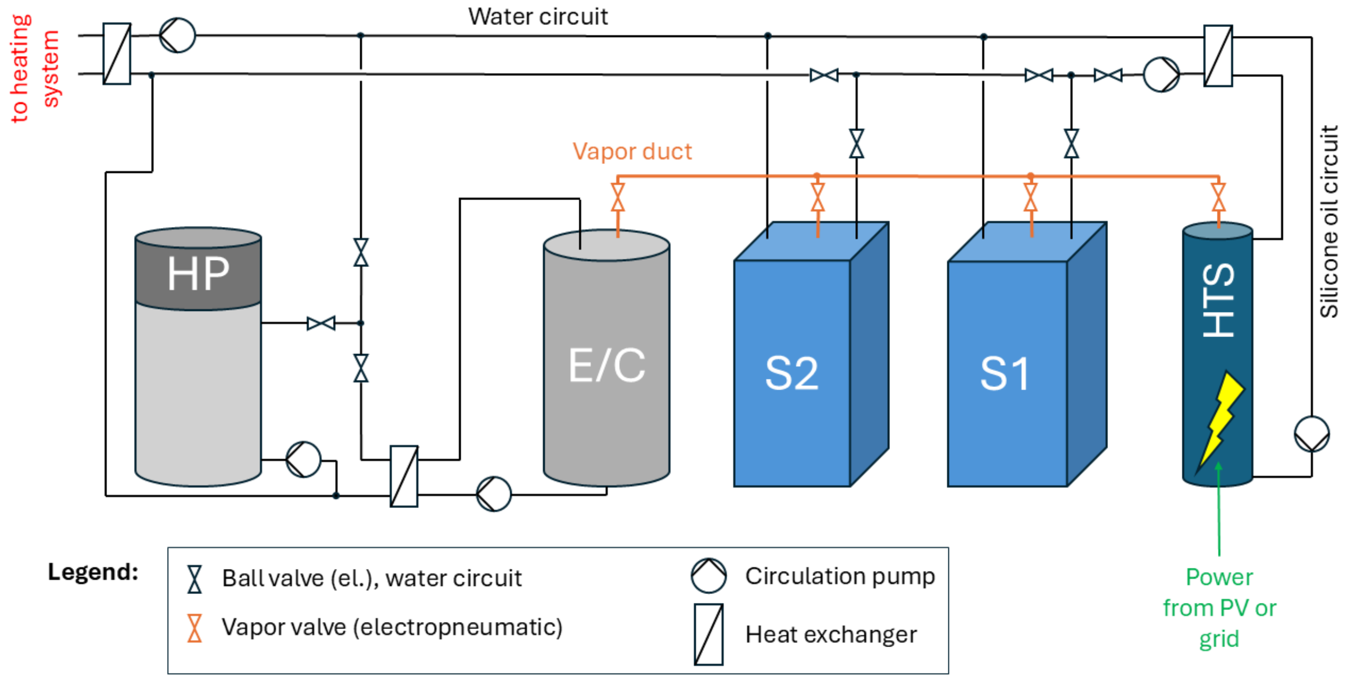


Figure 4 : Diagram of the sorption storage system

On the far right is the HTS (high-temperature storage), where a silicone oil circuit is used due to the high desorption temperatures of approx. 250 °C in the HTS. A power-to-heat (P2H) system was used to utilise surplus PV electricity and to ensure grid-compatible operation by drawing excess energy from the grid.

For this purpose, an electrically operated heating element is centrally installed in the middle of the HT storage tank. This generates the necessary high charging temperatures only in the middle of the storage tank, allowing the storage system to be charged efficiently. During the charging phase (desorption), the sorbent (water vapour) is fed to the condenser without mechanical drive, but solely by pressure difference, where it condenses. The condensation heat is used for hot water production or space heating. To charge the sorption storage tanks S1 and S2 with energy, energy can be supplied directly via the water circuit up to a desorption temperature of approximately 100 °C. To achieve further charging, the respective main storage tank (S1 or S2) is connected to the HTS via the open vapour valves and the vapour duct. A prerequisite for charging S1 or S2 via the HTS is that there is a lower pressure in the HTS, i.e. the vapour flows from S1 or S2 to the HTS. This process is also known as charge boost and has already been developed in previous projects and proven to work. In addition to the storage charging process, the released adsorption heat is transferred to the connected sorption storage S1 or S2 via the silicone oil circuit separated by a heat exchanger and the water circuit.

To discharge the sorption storage tank (S1 or S2) in terms of energy, the water in the E/C is heated until it evaporates. Due to the low pressure in the system, the water evaporates between 5 °C and 15 °C, depending on the state of charge. The resulting increase in pressure causes the vapour to flow through the pipe to the fully charged main storage tank. The thermochemical process (adsorption on the adsorbent) releases heat, which is transferred via the water circuit to the heating and hot water system at temperatures of approx. 50 °C to 55 °C, depending on the requirements (see control strategies) of the demonstrator.
The energetic discharge of the high-temperature storage tank via the E/C works on the same principle. In this case, however, the heat released is transferred via a heat exchanger from the silicone oil circuit to the water circuit and subsequently to the heating and hot water system.

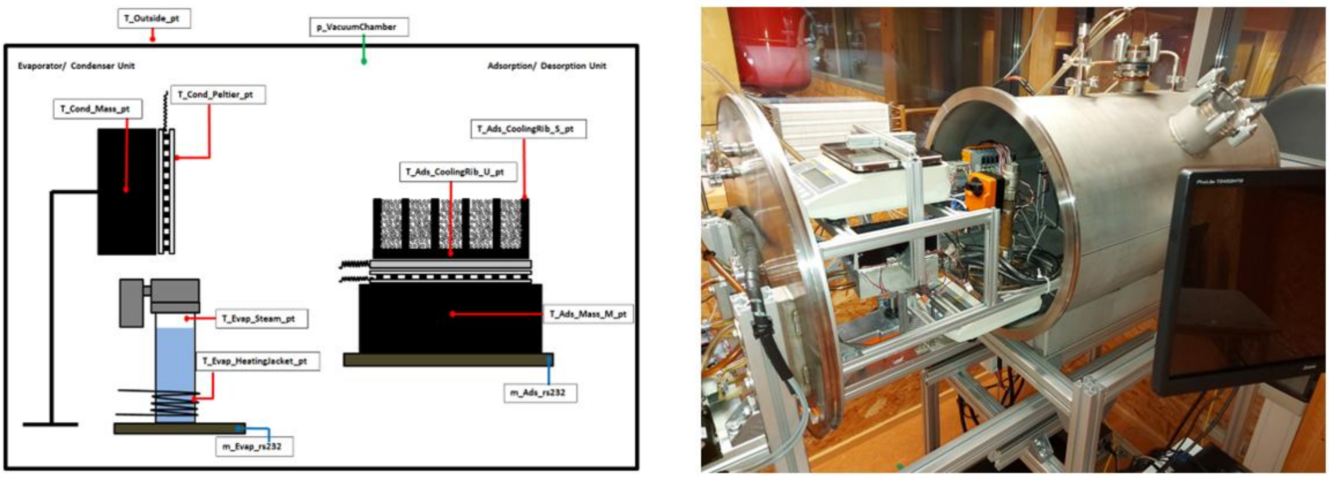
A standard low-power heat pump was installed to evaporate the water in the E/C. The heat pump can also be used to feed directly into the heating and hot water system and as emergency heating. The entire control strategy is described in the chapter 3.5 in this report.

To further increase system efficiency, additional functions were also implemented such as the utilisation of condensation heat for domestic hot water production and space heating.
For the final testing the complete system was assembled by combining three sorption storage units (HTS, S1 and S2), an evaporator/condenser (E/C) and a micro heat pump as a low-temperature source (HP). This configuration represents an innovative system concept designed to maximise the benefits of of sorption technology. The system’s efficiency is evaluated using the KPIs defined in Chapter 3.6, techno-economic aspects are discussed in Chapter 3.7.

3.2 Selection of materials

When selecting a suitable sorption material for a thermal storage system, several key criteria must be considered to ensure the efficient and long-lasting functionality of the storage system. A key selection criterion is the material's ability to deliver sufficiently high discharge temperatures for the intended

application. Furthermore, the material must be both mechanically and chemically stable to maintain functionality after repeated charging and discharging cycles under changing temperature and humidity conditions.
In addition to thermal and stability-related properties, the economic aspect are highly relevant. The sorption material should be as cost-effective, have a low carbon footprint and be available in sufficient quantities to safeguard the feasibility and scalability of the storage system. Materials with favourable dynamic properties regarding temperature behaviour should be preferred, meaning they should respond rapidly to temperature changes and enable efficient heat transfer.
To thoroughly evaluate these criteria, material tests can be carried out under controlled conditions in the laboratory. Such tests provide insights into the thermophysical properties of the materials and are essential to informed selection of the sorption material and for verifying suitability in thermal storage applications. Figure 5 shows a diagram and a photo of the material test bench at AEE INTEC.



a) b)

Figure 5 : Material test stand at AEE INTEC; a) diagram, b) photo © AEE INTEC - R. Kerschenbauer

After extensive research and thorough evaluation of technical suitability, manufacturing options and economic viability, zeolite 13X was selected as the sorption material. From the project's perpective, it represents the most advantagous techno-economic solution.

3.3 Component development and testing

Evaporator/condenser E/C

The evaporator/condenser consists of a steel container with a diameter of 650 mm, which also serves to store the necessary volume of water (water supply for the process). The E/C is part of the vacuum system. A circulation pump (PU_VK) is located in a pipe section below the container, through which the water is circulated via a heat exchanger (HX_VK). The pump is also located in the vacuum. The water pumped out at the bottom is "rained down" into the upper part of the container interior via a large-area distribution system. The inside of the tank is filled with plastic filling elements to increase the surface area. The principle is the same as that of a falling film evaporator. Depending on the temperature level and difference, either the sprayed water evaporates or the vapour entering via the vapour channel condenses. The amount of demineralised water must be at least equal to the sum of the maximum water loads of all connected main storage tanks (in this case two). Figure 6 shows a sectional view of the empty E/C tank and the filling elements used, which completely fill the interior of the tank. This reduces the available volume for the water supply by only 9 %.

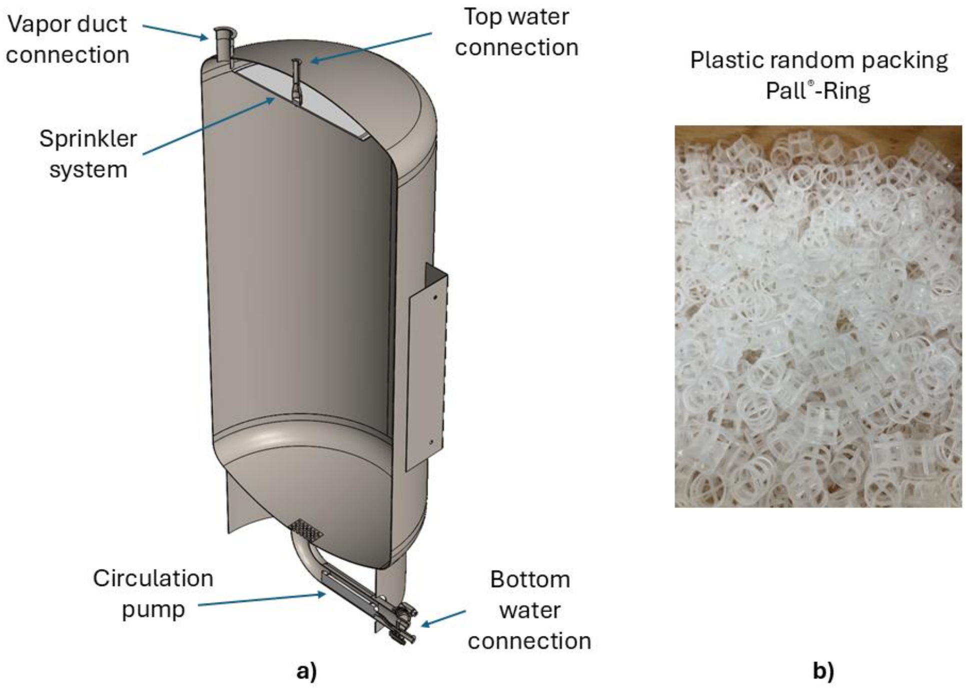


Figure 6 : Evaporator/condenser; a) section cut © Pink GmbH, b) random packing © AEE INTEC – A. Krainer

Depending on the switch positions of the valves in the water circuit and the operating states of the circulation pumps, the heat flows can be directed so that the E/C functions either as an evaporator or as a condenser. The circulation pump at the bottom of the E/C must be in operation in all cases.

The final component is the result of extensive variant comparisons and optimisations from previous projects. In addition to flawless functionality, the main focus was on low material usage and cost-effective production.
It was important to use as few screw or flange connections as possible in order to ensure maximum vacuum tightness.

Main storage units S1, S2

Each main storage unit essentially consists of an upright, rectangular lamella heat exchanger encased in a sheet metal housing. This design replaces the cylindrical variants used in previous projects and offers immense advantages in terms of space requirements at the installation site of the storage units. The heat exchanger serves as an essential structural element of the storage unit and, in combination with the sorption material, can absorb the vacuum forces. This design reduces the required material thickness from 4 mm to 1.5 mm, resulting in enormous weight and cost savings. All spaces in the heat exchanger are filled with the adsorbent Zeolith ZAG-13X from the manufacturer Silkem, Slovenia. This adsorbent is available in granular form with a grain size of 1.6 mm to 2.5 mm. 473 kg of zeolite was used per storage tank. The narrow spacing between the fins ensures good heat transfer between the heat exchanger and the zeolite. The optimised adsorbent-heat exchanger design also results in a 5 % improvement in the filling rate of the storage tank.

Figure 7 shows a longitudinal section through a storage module and the integrated heat exchanger, as well as a simulation of the mechanical stress on the outer shell.

The design has already been optimised for future automated production and robot-guided welding of almost all housing parts. When dimensioning the modules, care was taken to minimise the use of materials, reduce the number of production steps and minimise the number of weld seams.

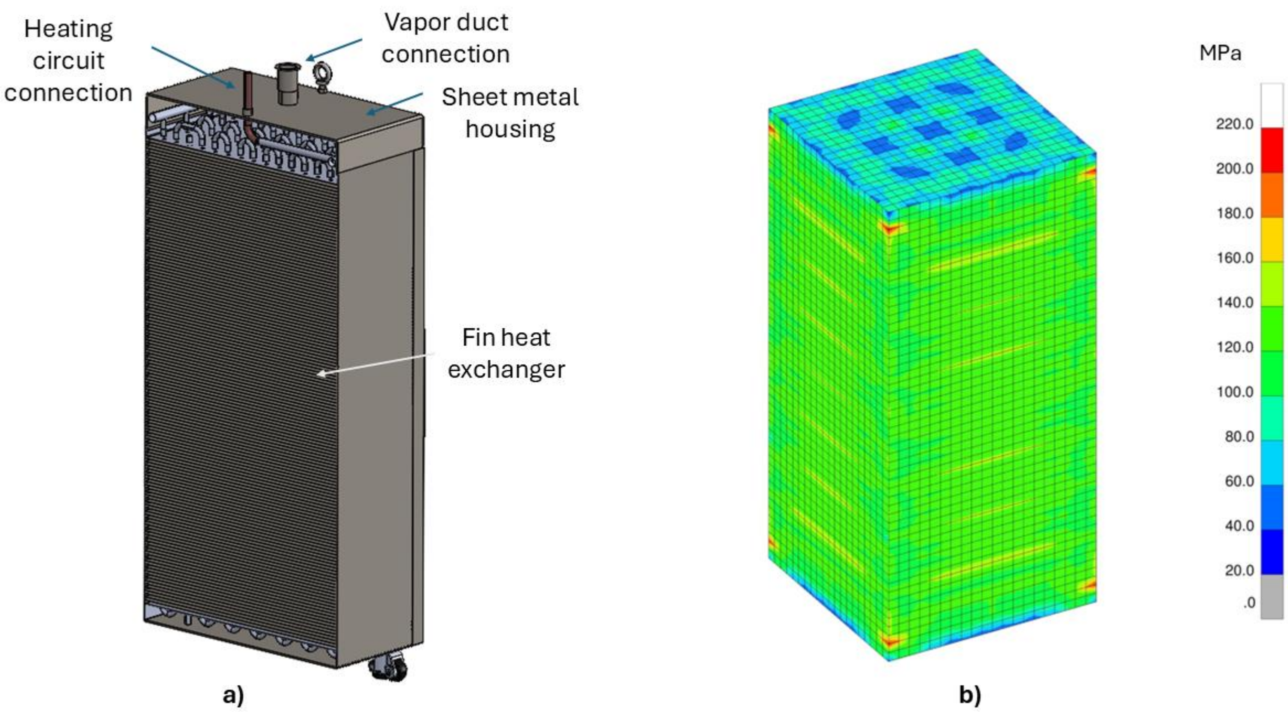


Figure 7 : Main sorption storage module; a) section cut of module and heat exchanger © Pink GmbH, b) strength simulation © SinusPro GmbH

Figure 8 shows the storage modules during the manufacturing process. The heat exchanger, enclosed in the sheet metal casing except for the final cover, was filled with the sorption material under constant vibration. The container was clamped in a dimensionally stable auxiliary structure. The container was then vacuum-sealed and checked for leaks. Before the auxiliary structure was erected and removed, the interior of the container had to be evacuated to ensure structural stability.

Three Pt100 temperature sensors are installed at different heights in each of the storage modules, with an additional sensor on the outer surface of the storage tank.

a) b) c) d)

Figure 8 : a) and b) Filling of the heat exchanger and compacting, c) welding, d) final check © AEE INTEC – W. Wagner

<u>High-temperature storage tank HTS</u>

The last important main component is the high-temperature storage tank (HTS), also known as a charge boost storage tank or drying module. This is responsible for regenerating the storage system, i.e. for charging it in terms of energy. To this end, water vapour is "transferred" from a main storage tank S1 or S2, which is filled to a certain percentage with water, into the dry HTS. When the two storage tanks are at the same temperature, the pressure difference between them due to the different filling states is sufficient to enable vapour transport. The adsorption heat generated in the HTS is to be transferred to the relevant storage tank via the water circuit in order to raise its temperature, which in turn drives the charge boost process again. At the very least, cooling of the main storage tank and the associated drop in pressure due to the desorption process must be prevented.

The high-temperature storage tank consists of a cylindrical shell with a diameter of 400 mm and is equipped with dome shaped bottom and top ends. A cylindrical pipe is installed concentrically to this over almost the entire length. This serves as a housing for an electric heating element with a power rating of 4.5 kW and as a reservoir for the silicone oil-based heat transfer medium. Connection lines to a high-temperature heat exchanger are attached to the top and bottom of this cylinder. This makes it possible to operate the oil circuit at a temperature of up to 280 °C, which has advantages for desorption. The higher the desorption temperature, the more water can be expelled from the adsorbent, i.e. the further the water load can be reduced. However, no circulation of the heat transfer medium is necessary during the desorption process, i.e. the pump does not have to be designed for high temperatures, which reduces costs.
Figure 9 shows the complete high-temperature storage tank (including insulation) as well as its internal structure and the centrally located heat exchanger.

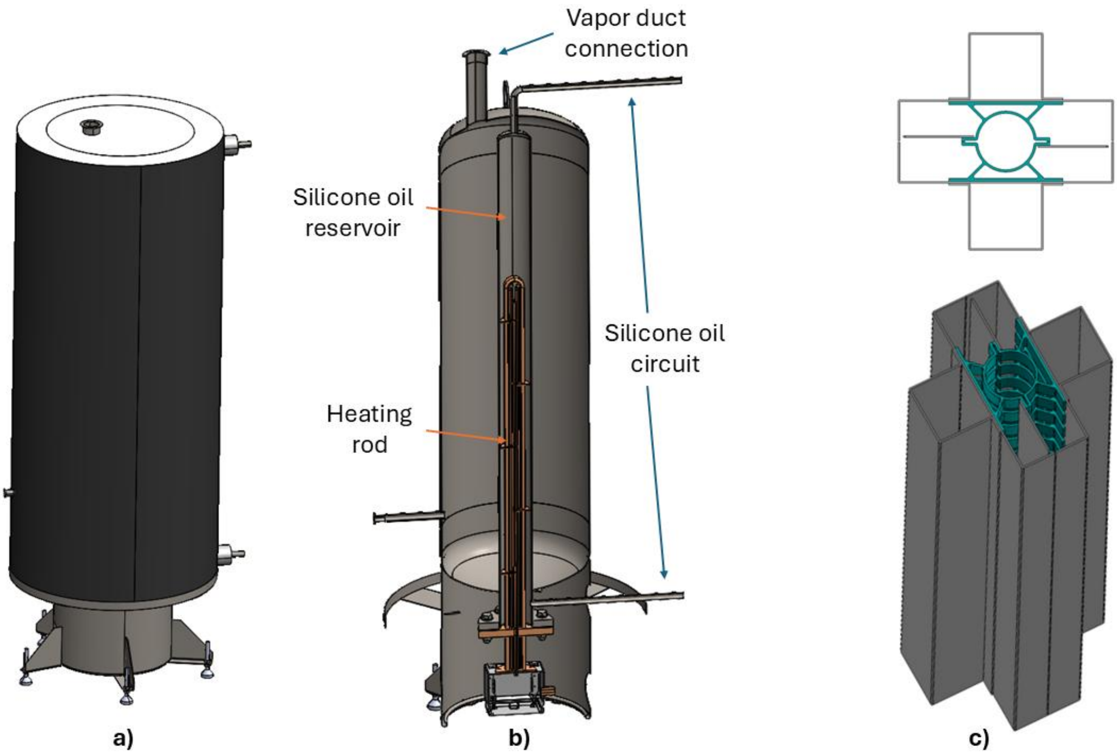


Figure 9 : HTS; a) complete module incl. insulation © Pink GmbH, b) section cut without central heat exchanger © Pink GmbH, c) central heat exchanger

To ensure good heat transfer from the central silicone oil tank to the sorption material, a heat exchanger made of aluminium components was integrated. The functionality of various heat exchanger variants was evaluated in advance using 3D temperature simulations and the design was optimised on this basis. The individual parts are made of perforated sheet metal to enable efficient vapour transport. Figure 10 shows the temperature distribution over time at a silicone oil temperature of 280 °C.

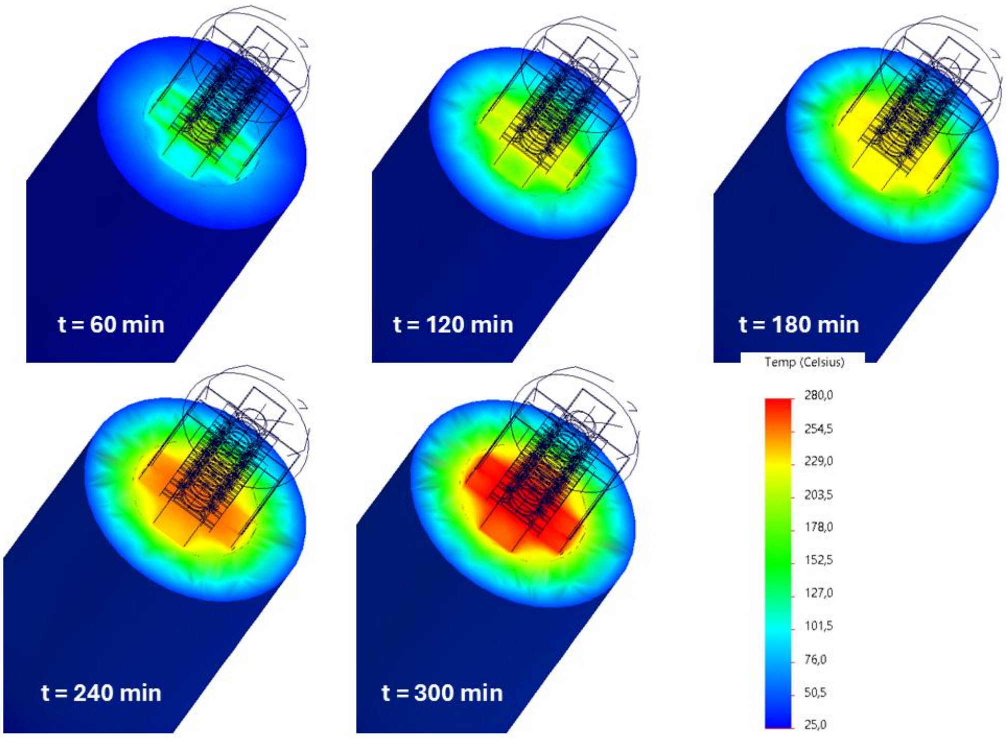


Figure 10 : Simulation of the temperature profile over time (Krainer, 2025)

To further optimise vapour transport in the storage tank, a ring-shaped vapour channel with a width of 15 mm was provided between the zeolite bed and the inner wall of the tank. The bed is supported by a stainless steel mesh basket surrounding the heat exchanger. During adsorption, this basket allows the vapour flowing from top to bottom in the annular gap to penetrate radially into the bed, ensuring efficient adsorption.

During the design of the storage components, emphasis was placed on cost-effective manufacturing and components available on an industrial scale.

Figure 11 shows photos of the production of the internal storage components. As with S1 and S2, the space between the internal silicone oil tank and the HTS grid basket is filled with Zeolite 13X. The filling capacity of the HTS is 69 kg. To ensure vacuum tightness, the container parts were welded, and the number of flange or screw connections was minimised. A final leak test (helium leak test) was carried out on all storage tanks.

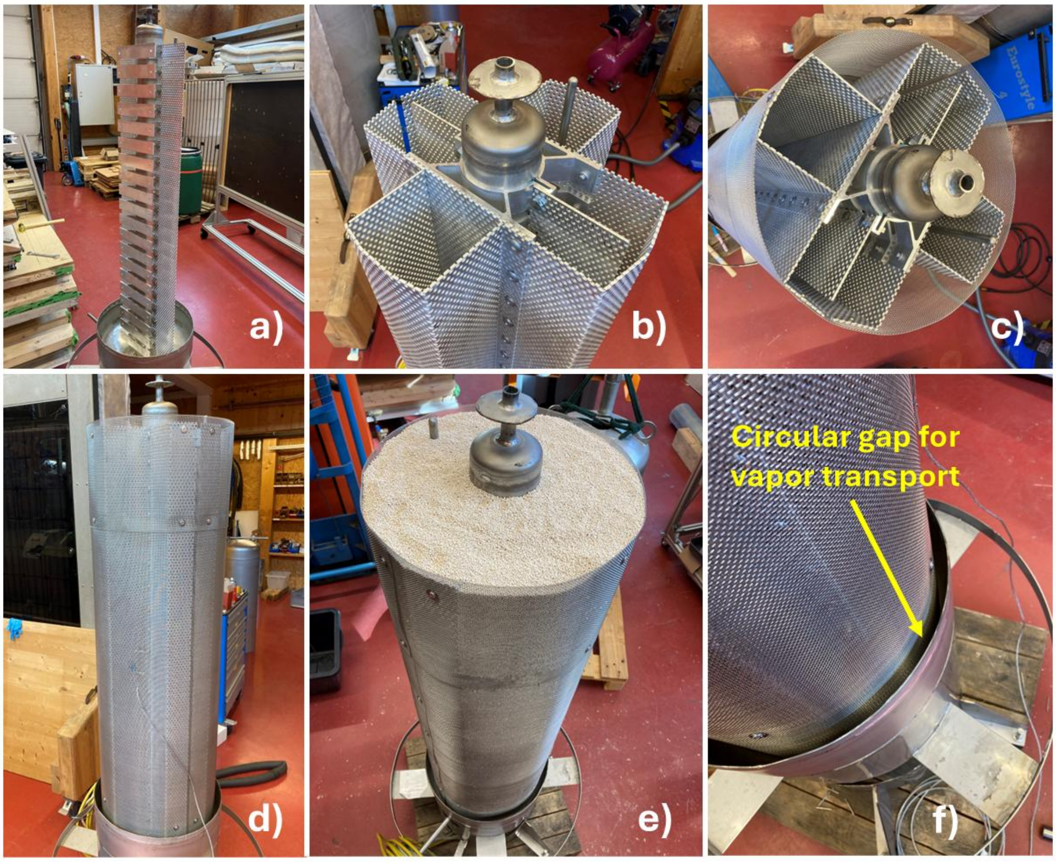


Figure 11 : Photos of heat exchanger production for the HTS. a) central tube with 20 vertically mounted aluminium clamps, b) riveted perforated plate heat exchanger mounted on clamps, c) heat exchanger with attached stainless steel grid basket, d) outside of the basket, e) basket filled with zeolite 13X, f) circular gap for vapour transport © AEE INTEC – A. Krainer

<u>Heat pump as a low-temperature source</u>

A micro heat pump (max. electrical power: 700 W) was specified to provide the necessary evaporation energy for the evaporator/condenser. The BWWP-4E-270 heat pump from Austria Email has an internal storage volume of 270 l and serves as a low-temperature heat source for the storage system. In real-world applications, it can also be used to achieve fail-safe operation.

3.4 System development

Parallel to the material selection and the design and testing of components, the hydraulic and control concept for the entire storage system was developed. To test and optimise both functionality and control behaviour, a complete demonstration plant, dimensioned to supply an average single-family home, was set up and commissioned in the AEE INTEC laboratory. Figure 12 presents the overall schematic of the laboratory plant and the interconnection of its individual components.

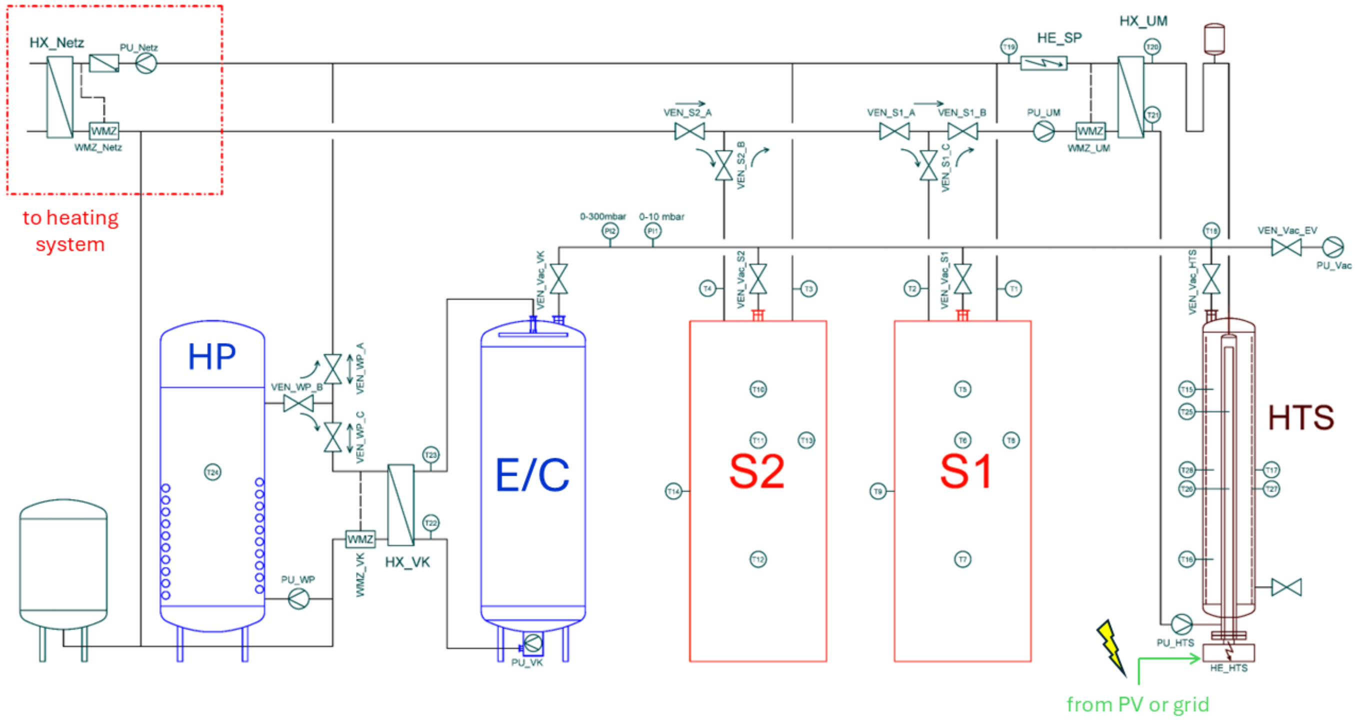


Figure 12 : Diagram of the complete storage system

The two main storage tanks and the high-temperature storage tank were provided with adequate thermal insulation. All four containers of the vacuum system (i.e. E/C, S2, S1 and HTS) are connected at the top to the vapour duct, which has a slight slope towards the E/C. This is to allow any condensate that may occur in the line to drain towards the E/C.
The hydraulic system of the water circuit connects all components via the respective heat exchangers to the transfer station of the heating network. The heat energy transferred here can be used for space heating or hot water production. This water circuit can be used to pre-condition the storage tanks, e.g. to increase vapour transport in the system. Furthermore, the sensitive residual heat from the storage tanks that is not stored during the desorption process can be dissipated and used, for example, for hot water preparation.
The third circuit of the storage system is the high-temperature circuit, which is filled with silicone oil as the heat transfer medium. It is therefore suitable for operation at high temperatures of up to 280 °C. For this purpose, a heating element is installed directly in the storage tank of the silicone oil circuit to charge the storage system. This circuit serves to dissipate the sensitive heat after the desorption process (charging process) with high efficiency. The sensitive heat released is then transferred from the silicone oil circuit to the water circuit via a heat exchanger. It is also necessary to dissipate the heat generated during the adsorption process, which also works with this circuit.
The figure below shows the test rig set up in the AEE INTEC laboratory.

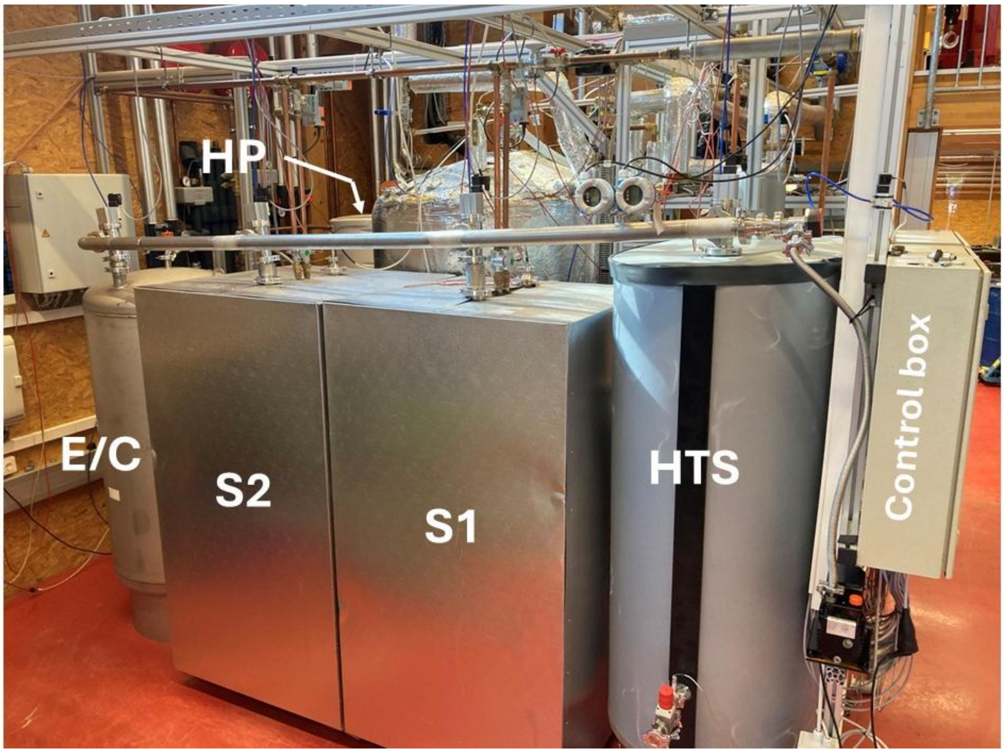


Figure 13 : Test stand in the laboratory of AEE INTEC © AEE INTEC – A. Krainer

3.5 Control strategy

Various operating modes were defined during the design and development of the FlexModul storage system. These can be selected depending on the switch positions of the valves in the hydraulic circuit and the vapour duct, or the operating states of the circulation pumps and heating elements. The operating modes include adsorption and desorption as well as the use of sensitive heat for the heating or hot water system (DHW) and more. Depending on operating parameters, limit values, performance and temperature requirements of the heating system and other boundary conditions, efficient operation of the storage system can be ensured by a logical sequence of the individual operating modes. A total of 15 operating modes have been defined, which are briefly explained below.

Mode 1.1: HTS charging

In this mode, the HTS is charged in terms of energy. The water bound in the adsorbent is expelled by supplying heat energy. The vapour produced by this desorption process is transported to the E/C due to the pressure difference and condenses there. The condensation heat produced can be used for further operating modes.

Mode 1.2: HTS charging and preheating of S1

The condensation heat generated during the desorption process of the HTS, as already described in mode 1.1, can be used to precondition the main storage S1. The increased temperature level results in a greater pressure difference for subsequent transfer processes between S1 and HTS (charge boost). This mode should mainly be used when the HP storage is already charged.

Mode 1.3: **HTS charging and preheating of S2**
Same mode as 1.2, but for storage tank S2.

Mode 1.4: **HTS charging and heat transfer to the heating system**
The condensation heat from the desorption process can also be made available directly to the heating circuit. Either for space heating or for hot water preparation.

Mode 1.5: **HTS charging and heating of the water supply in the E/C**
The condensation heat can also be stored only in the water supply of the E/C. There it is available for subsequent processes.

Mode 2.1: **Use of the HP storage tank for heating purposes**
The thermal energy stored in the internal storage of the HP can be fed into the heating system.

Mode 2.2: **Sensitive heat from the HTS for heating purposes**
The sensible heat introduced into the adsorbent during the desorption process can be fed into the heating system.

Mode 2.3: **Sensitive heat from S1 for heating purposes**
The sensible heat energy stored in the main storage tank S1 can be fed into the heating system.

Mode 2.4: **Sensitive heat from S2 for heating purposes**
Same mode as 2.3, but for storage tank S2.

Mode 2.5: **Transfer process (charge boost) from S1 to HTS / Energy charging of S1**
Here, the higher pressure in S1, caused by higher water load and/or higher temperature than in HTS, initiates vapour transport from S1 to HTS. At the start of the transfer process, HTS is ideally completely desorbed and cooled down.

Mode 2.6: **Transfer process (charge boost) from S2 to HTS / Energy charging of S2**
Same mode as 2.5, but for storage tank S2.

Mode 3.1: **Discharge of the HTS – heat for heating purposes**
In this mode, the HTS is energetically discharged, i.e. the storage tank is supplied with vapour from the E/C via the vapour duct and an adsorption process takes place. The evaporation heat is provided by the HP. The adsorption heat generated in the HTS can be used for heating or hot water preparation.

Mode 3.2: **Discharge of main storage S2 – heat for heating purposes**
Same mode as 3.1, but here the main storage tank S2 is discharged (adsorption).

Mode 3.3: **Discharge of main storage S1 – heat for heating purposes**
Same mode as 3.1, but here the main storage tank S1 is discharged (adsorption).

Mode 4.0: **HP supplies heat for the heating system**
Emergency operation of the heating system. Here, the heat pump and the built-in heating element are used for direct heating.

3.6 Measurements

Numerous measurements were carried out to characterise the individual components and to check the performance of the overall system. Some of these are illustrated and explained below.

3.6.1 Function test of vapour transport in the HT storage tank – adsorption process

In this test, the functionality of the HT storage tank was checked by means of an adsorption test. The aim of this test was to investigate the properties of vapour transport within the storage tank on the one hand and the performance of the storage tank and the propagation speed of the sorption front in the storage material on the other.

Figure 14 shows the first 90 minutes of the test. As can be seen in the upper diagram in Figure 14 , there is a very rapid rise in the storage temperatures in the zeolite bed. The temperature sensor on the mesh basket reacts the fastest. This is where the vapour first hits the bed and is adsorbed. The curves of the upper and middle temperatures in the zeolite bed are almost identical. This indicates very effective vapour transport in the ring-shaped vapour channel. The temperature gradients achieved are shown in the lower diagram of the graph. The maximum temperature gradients once again demonstrate the rapid rise in temperature at the grid basket immediately after the vapour valves were opened (Grad_T_HTS_Korb).

A maximum temperature of 171 °C is reached in the bed.

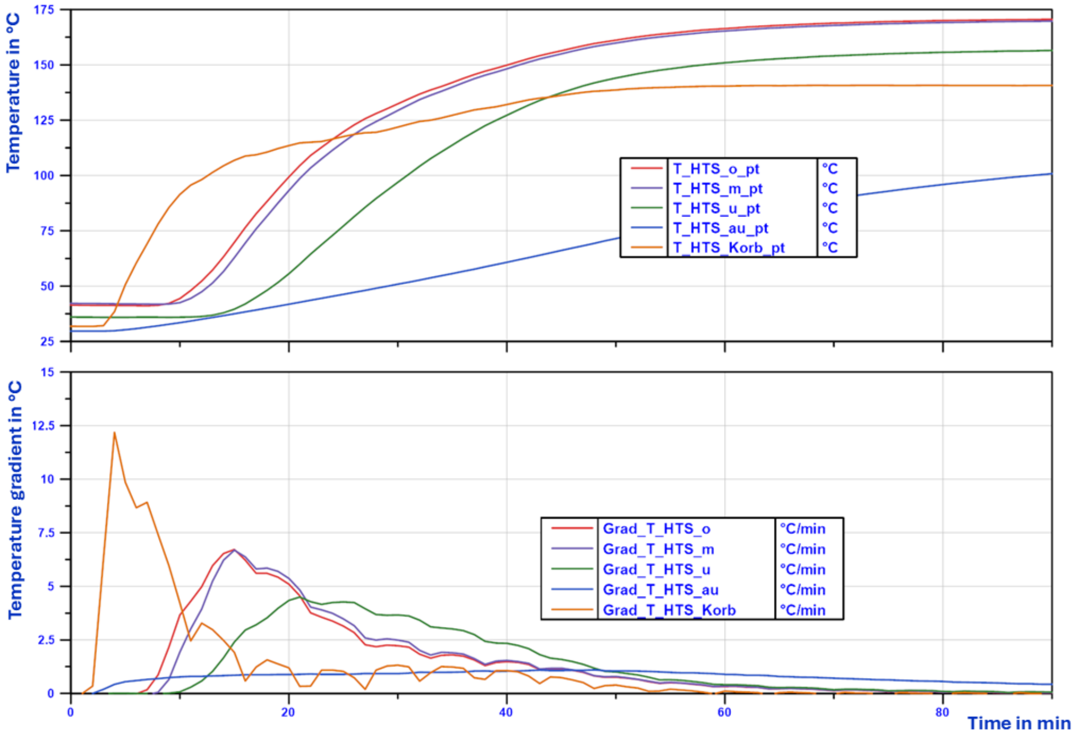


Figure 14 : Adsorption HTS

3.6.2 Discharge of the storage system by adsorption of S1

This experiment was used to determine the possible storage capacity of a main storage tank. For this purpose, adsorption experiments were carried out on the main storage tank S1. A storage tank charged as far as possible serves as the starting point. The evaporation heat required for the process was provided by the heat pump. A withdrawal temperature of 35 °C was selected, as this temperature is sufficient for heating purposes in practice. Figure 15 shows the performance curves in the storage tank and the corresponding heat quantities or the electrical energy consumed by the heat pump. The three power outputs are shown in the lower diagram. *"P_heat"* is the power drawn from the storage tank that is available for heating purposes, *"P_EC"* is the evaporator power, and *"P_HP"* is the electrical power of the heat pump. The same designation scheme applies to the associated work. The test was carried out in two parts over a period of 1650 minutes. The time span from 1650 to 1950 minutes was linearly interpolated to show the amount of heat available up to a withdrawal power of 500 W.
Table 1 shows the heat quantities determined for adsorption in S1 and the evaporator, as well as the electrical energy required to operate the heat pump for a withdrawal temperature of 35 °C. The coefficients of performance were then calculated from these values using equations 1 to 3.

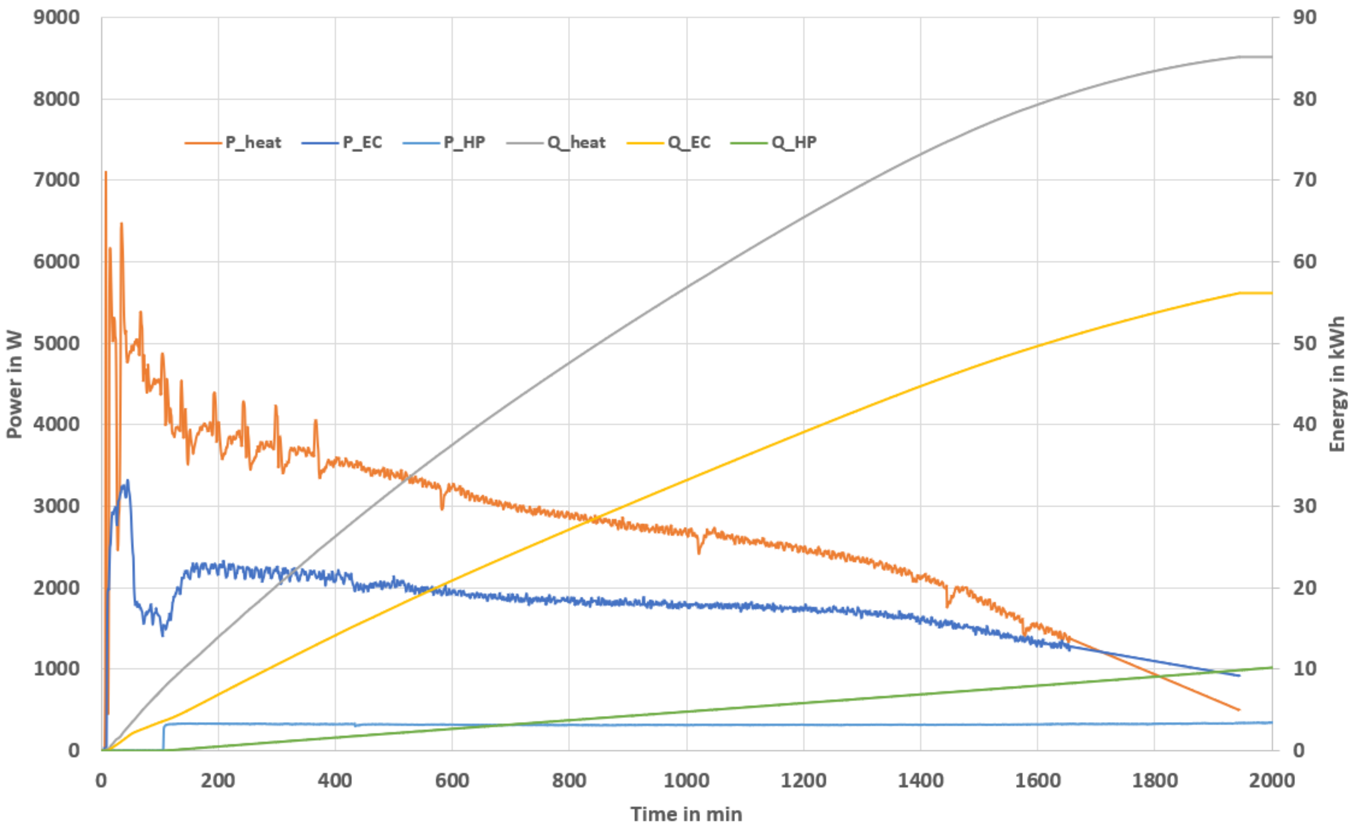


Figure 15 : Discharging of one main storage @ 35 °C

Equation 1 : Heat ratio Heating / heat pump

$$HR_{Heating-HP} = \frac{Q_{Heating}}{Q_{HP}}$$

Equation 2: Heat ratio Heating / EC

$$HR_{Heating-EC} = \frac{Q_{Heating}}{Q_{EC}}$$

Equation2: Heat ratio EC / heat pump

$$HR_{EC-HP} = \frac{Q_{EC}}{Q_{HP}}$$

Table 1 : Adsorption heat quantities and heat ratios

$Q_{Heating}$ in kWh	85.15
Q_{EC} in kWh	56.17
Q_{HP} in kWh	9.89
$HR_{Heating-HP}$	8.61
$HR_{Heating-EC}$	1.52
HR_{EC-HP}	5.68

The storage capacity of 85.15 kWh determined above represents the energy that can be used under optimal operating conditions. This requires continuous charging and discharging processes. For the following economic analysis, a dynamic storage capacity of 71 kWh per storage tank was used. This is the energy that can be used for short-term (dynamic) charging and discharging processes, as they occur in the following simulation model.

3.7 Economic efficiency analyses based on an energy management model

A concrete assessment of the performance of the FlexModul system under specific application conditions over a full calendar year is complex. This requires a dynamic analysis (at least on an hourly basis) of all load profiles (heat and electricity demand of the underlying building), all generation profiles (PV system) and the electricity exchange prices. This chapter presents the method developed for this purpose, sets out the framework conditions, applies it to a representative single-family home and interprets the results from a business perspective.

3.7.1 Method

Based on the measurement results, a detailed simulation model was developed in MS Excel, the core components were validated using the Simulation Studio (TRNSYS) simulation environment. The simulation model calculates the heat and energy flows of the sorption and buffer storage tanks and the building on an hourly basis. It dynamically determines the demand for space heating, hot water and electricity based on hourly load profiles (SIA 2021) and compares this with the PV yields on an hourly basis to determine the necessary grid electricity consumption. The heat is initially supplied from the buffer storage tank. If this is not sufficient, the sorption storage tank discharges via heat pump-assisted adsorption. Surplus electricity charges the sorption storage tank via an electric heating element, with the condensation heat released being stored in the buffer storage tank. If the energy content falls below a minimum value, the storage tank can also be charged via the electric grid. The model provides the basis for an energetic and economic evaluation of the overall system. Figure 16 shows schematically the energy flows and conversions that were mapped in the simulation model.

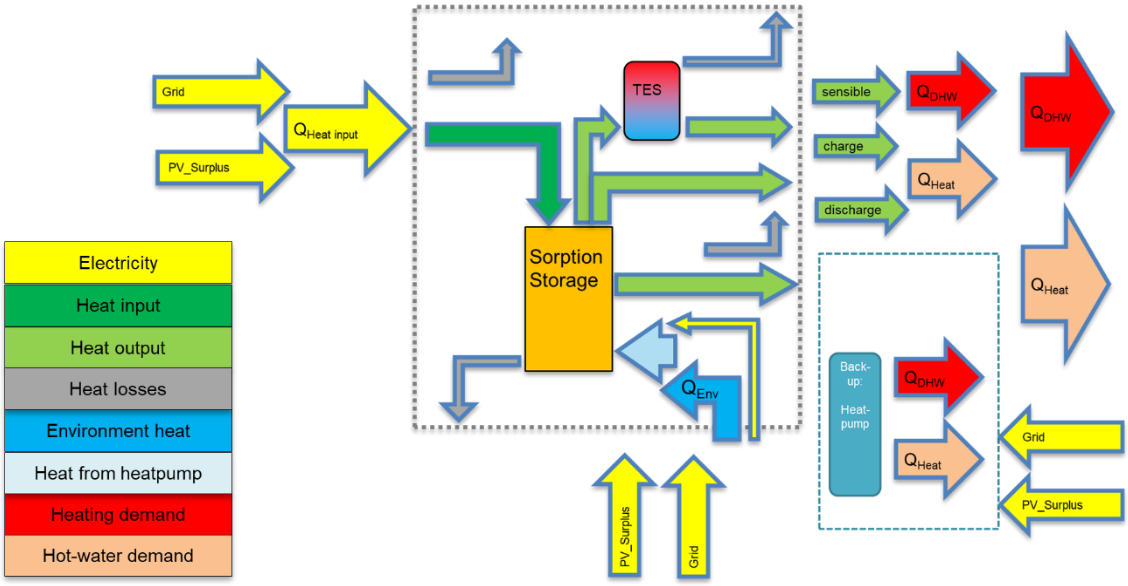


Figure 16 : Schematic electricity and heat flows and their conversion in the FlexModul model

The control of the FlexModul system was gradually developed from a simple on/off logic dependent on the electricity exchange price (EPEX SPOT day-ahead energy-only price, excluding network charges, taxes and levies) to a multi-stage strategy based on the storage level (SoC State of Charge). The starting point was a hysteresis control (charging below 50 €/MWh, stopping above 75 €/MWh), which made good use of low electricity exchange prices but was unable to take advantage of daily minimums in higher-price periods. An annual and monthly analysis of hourly prices in the 2023 calendar year showed that price maximums occur mainly in the early morning and late evening, while minimums occur in the early morning and midday hours. This was used to derive a charging logic based on five thresholds: (1) Emergency reserve < 8 % (charging regardless of price), (2) Safety reserve < 10 % (charging only at < 150 €/MWh), (3) Standby reserve < 20 % (charging only if < 50 €/MWh), (4) Use low-price phases to charge to 65 % capacity if < 25 €/MWh, (5) Summer capacity target ≥ 65 % to maximise the use of PV surpluses. This effectively bridges short and longer high-price phases, maximises the own use of PV electricity and increases grid serviceability through consumption at negative prices. The model is flexibly scalable to single-family homes of different sizes, but can also be used for multi-family homes and other building uses. Furthermore, the model uses a conventional heat pump system (air-water) as a reference.

3.7.2 Boundary conditions

The year 2023 was chosen for the annual simulation because the working prices on the European electricity exchange (EPEX SPOT) offer a realistic but less distorted price level after the severe volatility in 2022. The hourly weather data comes from the GeoSphere Austria station in Gleisdorf (GeoSphere Austria, n.d.) (ID 16501; 377 m above sea level): T_{min} = -9.6 °C, T_{max} = 33.0 °C, $\bar{T}$ = 10.8 °C; Global

radiation 1 234 kWh m^{-2} a^{-1} or 141 W/m² average power. Temperature and radiation data are the basis for heating load of the building and PV yield calculations.
The electricity requirements for appliances, lighting and building services are described by hourly standard load profiles from the SIA 2024 room data sheets; these take into account daily, weekly and seasonal fluctuations. All building are equipped with a variably dimensioned PV system (orientation / inclination freely definable).
For the single-family house (SFH), a gross floor area of 150 m² (4 persons) was assumed with a household electricity requirement of 3 375 kWh m^{-2} a^{-1} (excluding space heating/hot water). The heating requirement can vary between 45 kWh m^{-2} a^{-1} (renovated building) and 90 kWh m^{-2} a^{-1} (unrenovated building), with 60 kWh m^{-2} a^{-1} assumed in the base case. The storage capacity of the FlexModul system is 144 kWh (2 modules). The PV area in the base case is 7 kWp with a 45° south-facing orientation.
The period under consideration in the economic analysis was set at 20 years, which also corresponds to the assumed service life of both systems.

3.7.3 Energy results

In the base case, the FlexModul system saved 380 kWh of grid electricity compared to the reference system (air-water heat pump) and utilised PV surpluses of 3 200 kWh, significantly increasing the solar coverage ratio. Critical months are February (low PV yields) and November / December (high heat demand). Here, it was successfully demonstrated that the control strategy was able to successfully buffer long periods of high prices. The table below provides an overview of the most important key figures:

Table 2 : Energy comparison

	Reference system (air-source heat pump)	FlexModul system
Grid electricity import	4 020 kWh	3 637 kWh (-10 %)
Utilised PV surplus*	799 kWh	4 042 kWh (+406 %**)
PV self-consumption share	> 30 %	> 70 %

* PV energy that is self-consumed or stored

Despite € 3 165 higher investment and maintenance costs, the FlexModul system saves a total of € 575 over the entire 20-year period thanks to lower operating costs (-€ 3 739 or -€ 187/year), resulting in a total of € 57 335 instead of € 57 910. This proves that the FlexModul system is competitive under the current conditions, both in terms of energy and economics.

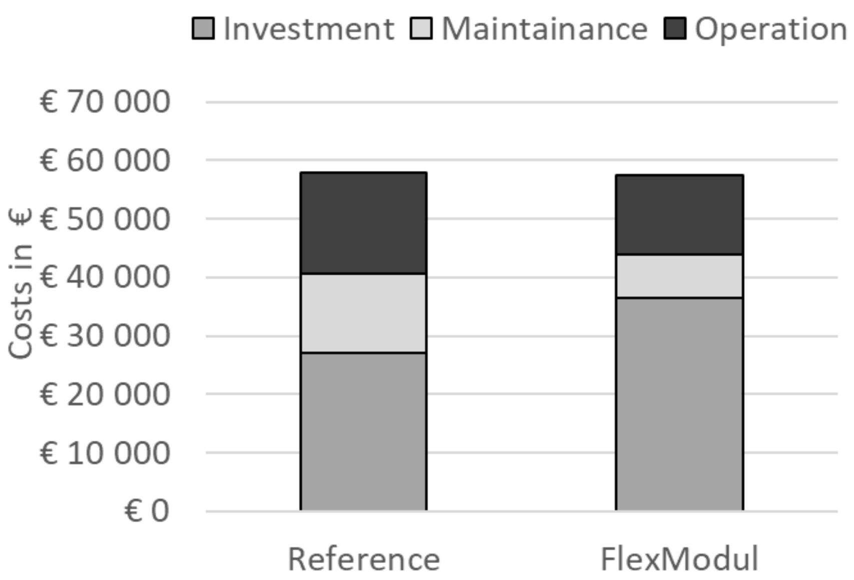


Figure 17 : Cost comparison between reference and FlexModul system for single-family house

Table 3 : Overview of costs over a 20-year period

Cost	Reference system	FlexModul	Difference
Investment and commissioning costs*	€ 27 090	€ 36 500	+€ 9 410
Maintenance costs (20 years)	€ 13 540	€ 7 300	–€ 6 240
Operating costs (20 years)	€ 17 280	€ 13 541	–€ 3 739
Total costs (20 years)	€ 57 910	€ 57 335	–€ 575

* The higher investment costs are completely offset by lower maintenance and operating costs; break-even point after ≈ 17 years.

3.7.4 Sensitivity and variant analysis (single-family home)

Following the system simulations, a comprehensive variant and sensitivity analysis was carried out for the single-family home, in which 1 967 combinations of heating requirements (45–90 kWh m^{-2} a^{-1}), PV output (5–12 kWp), grid electricity tariffs (0.10–0.20 €/kWh), PV orientation / inclination and control parameters are compared. The analysis showed that in 1 160 cases, the FlexModul system's higher investment and maintenance costs compared to the reference air source heat pump were completely offset by lower operating costs over the defined 20-year period. The advantage is particularly pronounced when the heating requirement does not exceed 60 kWh m^{-2} a^{-1} because winter PV surpluses can then be stored efficiently while reducing peak loads on the grid. Rising grid fees increase the economic benefits for renovated buildings, while for unrenovated properties (90 kWh m^{-2} a^{-1}), the benefits only become apparent when grid fees exceed around 0.15 €/kWh. Larger PV systems increase the cost advantage linearly: at 7 kWp, the annual savings are around 180 €, and at 12 kWp, over 400 € can be achieved. In terms of energy, the FlexModul system in 1 361 variants reduces grid power consumption by an average of 5 %, which can be up to 54 % under optimal conditions, while the PV self-consumption rate is always significantly higher than that of the reference system (average 399 % vs. 100 %). For planning purposes, we therefore recommend a well-insulated building with a minimum

7 kWp PV system facing approximately south (45–70° inclination). In this environment, the FlexModul system is competitive and at the same time provides noticeable relief for the power grid.

Table 4 : Overview of the parameters of sensitivity analysis and their effects

Parameters	Impact on FlexModul cost advantage
PV capacity 5 → 12 kWp	Linear increase; savings of around € 400 per year at 12 kWp
Grid costs 0.10 → 0.20 €/kWh	Strong positive effect when the specific heating demand ≤ 60 kWh m^{-2} a^{-1}
Specific heating demand 45 → 90 kWh m^{-2} a^{-1}	Advantage declines; cost parity reached only from ≈ 9 kWp at 90 kWh m^{-2} a^{-1}
PV azimuth −30° ... +15°	Only minor deviations (< ±€ 40 per year); optimum at −15° (south-east)
PV tilt 45° ... 70°	Optimum at 55 – 60°; steeper angles (>70°) lower the annual yield

*In 1 160 of 1 967 variants (59 %), the FlexModul system exceeds the cost parity threshold.

3.7.5 Conclusion

A simulation-based comparison of an innovative PV-coupled FlexModul system with thermochemical sorption storage and a conventional air heat pump shows that both PV surpluses from solar power and periods with low electricity prices can be used effectively, allowing this system to reduce the load on the electricity grid and, in many cases, lower overall costs.

Recommendations

The FlexModul system is particularly suitable for new buildings and well-renovated existing buildings (heating requirement ≤ 60 kWh m^{-2} a^{-1}). In this configuration, the combination of low load and high PV self-consumption significantly reduces the payback period. The minimum output of a PV system should be 7 kWp for a 150 m^2 single-family home with 60 kWh m^{-2} a^{-1} heating demand so that the specific annual yield covers the heating demand (space heating and hot water). A larger system increases the economic efficiency accordingly. Roof surfaces that are oriented between south -30° and south +15° and have a pitch of 55–60° offer the best ratio of annual yield and winter coverage. Significant deviations to the east or west or particularly flat pitches reduce the cost advantage noticeably. The use of hourly EPEX SPOT prices on the electricity exchange influences the savings potential. When electricity exchange prices are below 25 €/MWh, storage should be prioritised, whereas when prices are above 150 €/MWh, storage should be avoided. Both cases contribute to a reduction in grid load.

4 Results and conclusions

In the course of the project, it became clear that there is extreme added value in viewing the "FlexModul" not only as an efficient and compact heat storage unit, but also as a complete heat supply system. This approach gains essential significance due to the following considerations and achievable benefits:

- Sector coupling, storage, grid service
  Regardless of the household's heat demand, the system can absorb excess electricity from the grid and PV at any time and store it in thermochemical form. The system can also respond to very short-term grid fluctuations and thus be operated in a grid-friendly manner.
- Efficiency, storage density
  In charging mode, the heat generated during the condensation of water is used for space heating or hot water production, which makes the system very efficient. The thermochemically stored energy can be stored for any length of time without loss after the charging process.
- Compactness, modularity
  The prismatic shape of the storage units and their modularity allow different storage sizes to be achieved with the same storage modules. The storage capacity can be varied from 85 kWh with one storage module to 850 kWh with 10 modules.
- Production costs
  Great importance was also attached to optimising the components in terms of production costs and near-series production of the system. Designs were therefore chosen that require as little material as possible and enable series production. The storage material Zeolite 13X was also selected with a view to achieving a good compromise between performance and cost.
- Economic efficiency
  Under realistic conditions, the FlexModul system shows considerable potential for economically combining renewable heat, solar power self-sufficiency and grid flexibility in residential buildings. In buildings with a good standard of renovation, a sufficiently large and correctly oriented PV area and dynamic electricity tariffs, it can undercut the costs of conventional heat pump heating over its lifetime while also improving CO_2-emissions and grid stability.

5 Outlook and recommendations

As described above, a very robust and practical demo plant in "real scale" format was set up and operated in the laboratory. A number of suggestions for improvement were identified:

- It is advisable to adapt the heat exchanger in the high-temperature storage tank in order to further increase the heat exchange between the sorption material and the fluid circuit. In principle, this could also be built into the design of the main storage tank, thus further simplifying the system.
- The heat required for evaporation in the storage tank's discharge mode is currently provided by a standard hot water heat pump. The COP of 5.7 achieved here is well below the COP possible with a heat pump designed for this application. Furthermore, the unused area of the discharge curve below 35 °C could be used to provide the evaporation energy.
- By using forecast models such as weather forecasts and estimates of electricity price trends and heat demand forecasts, the system could be significantly improved in terms of efficiency.

6 Bibliography

GeoSphere Austria (n. d.). *Dataset API Frontend.* https://dataset.api.hub.geosphere.at/app/frontend/station/historical/klima-v2-1h

Hauer, A. (2002). *Beurteilung fester Adsorbentien in offenen Sorptionssystemen für energetische Anwendungen* [Dissertation, TU Berlin]. https://d-nb.info/964995476/34

Krainer, A. (2025). *Experimentelle Untersuchungen und Optimierungen an dem Sorptionsspeichersystem "FlexModul"* [unveröffentlichte Masterarbeit]. Hochschule Burgenland Pinkafeld.

Meitner, D. (2016). *Analytische Beschreibung eines Kompositmaterials bestehend aus dem Trägermaterial Klinoptilolith, dem Aktivstoff Calciumchlorid und Silan* [Dissertation, Montanuniversität Leoben]. https://pureadmin.unileoben.ac.at/ws/portalfiles/portal/1836473/AC13411151n01vt.pdf

Pfeiffer, S. (2015). *Theoretische und experimentelle Untersuchungen zur thermochemischen und sorptiven Energiespeicherung* [Diplomarbeit, TU Wien]. https://repositum.tuwien.at/bitstream/20.500.12708/9113/2/Pfeiffer%20Stephan%20-%202015%20-%20Theoretische%20und%20experimentelle%20Untersuchungen%20zur...pdf

Statistik Austria. (n. d.). *Energieeinsatz der Haushalte. STATISTIK AUSTRIA.* https://www.statistik.at/statistiken/energie-und-umwelt/energie/energieeinsatz-der-haushalte

SIA (2021): SIA 2024: Raumprogramm – Raumdatenblätter. Zürich: Schweizerischer Ingenieur- und Architektenverein.

Storch, J. G. C. (2010). *Materialwissenschaftliche Untersuchungen an zeolithischen Adsorbenzien für den Einsatz in offenen Sorptionssystemen zur Wärmespeicherung* [Dissertation, TU München]. https://mediatum.ub.tum.de/doc/820976/820976.pdf

Wagner, W., Jähnig, D., Isaksson, C., Hausner, R., Jungreithmayr, G. & Pink, W. (2006). *Modularer Energiespeicher nach dem Sorptionsprinzip mit hoher Energiedichte (MODESTORE)*. (Berichte aus der Energie- und Umweltforschung, 81/2006). Bundesministerium für Verkehr, Innovation und Technologie. https://www.nachhaltigwirtschaften.at/resources/hdz_pdf/endbericht_modularer_energiespeicher.pdf

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