INTER STORES

Deliverable

International Innovation Network for the Development of

Cost- and Environmentally Efficient Seasonal Thermal Energy Storages

D2.1 – Demo Report

Demo Report for first review period 01/2024 – 10/2024

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Abbreviations and Acronyms

CTES	Cavern Thermal Energy Storage
EC	European Commission
EU	European Union
HEX	Heat exchanger
LowEx	Low exergy
PU	Public
PGMM	Planungsgruppe M+M AG
SEN	Sensitive
sTES	Seasonal Thermal Energy Storage
T	Task
WGTES	Water-Gravel Thermal Energy Storage
WP	Work Package

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1 Introduction

1.1 Project Overview

Modern energy systems require the integration of diverse and variable renewable energy sources to replace fossil fuels, promote sector coupling, and recover waste heat. Seasonal thermal energy storage systems (sTES) are critical elements of these systems to balance peak loads, enable load shifting, and increase the usability of decentralized heat supply. The INTERSTORES project is a pioneering initiative to develop advanced sTES systems. Funded by the Horizon Europe Innovation Action (IA) programme, the project began in January 2024 and is expected to be completed by December 2027. The project aims to demonstrate the global market potential of selected sTES technologies by demonstrating their advanced features, economic benefits, and environmental benefits.

INTERSTORES focuses on the transformation of industrial infrastructures into renewable sTES systems (Reno-sTES) and the use of an excavated rock cavern for large-scale thermal energy storage (Giga-CTES). Within these two categories, the project supports the construction of two unique facilities: a Reno-sTES facility in Ingolstadt, Germany, and a Giga-CTES facility in the city of Vantaa, Finland. The Reno-sTES plant will be built within an existing basin infrastructure and represents a strategic approach that reduces the initial investment for new developments through the reuse of industrial water basins. This recycling strategy is in line with the principles of the circular economy and ensures a limited environmental footprint and low land use. In contrast, at the Giga-CTES site, natural geological formations are used as storage locations. The excavated rock cavern will hold approximately one million cubic meters of water, enabling significant storage capacity at high temperatures. This large-scale storage is expected to benefit from economies of scale, making the initiative cost-efficient and promising for future market expansion.

The planned full-scale demonstration of sTES technologies will fill critical gaps in terms of reliable assets, robust operational capabilities, and replicable implementation. The two solutions will provide insights into optimal design, integration potential at different levels, operating conditions, costs, and environmental impacts. The project will address this through a holistic environmental assessment using a life cycle assessment framework, as well as local environmental impact assessments. A fundamental element of the project is therefore the development of tailor-made monitoring strategies that focus on measuring local environmental impacts. This development is integrated into the design, installation, and operation phases of the sTES variants at both demonstration sites and is intended to serve as a blueprint for replication sites.

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1.2 Structure of the Report

As part of the INTERSTORES project, the following chapters describe the progress made in planning so far. All planned and implemented construction projects are described. The report is structured in such a way that each chapter covers the specific aspects of the two Demo sites.

At the beginning of the report, an overview of the incampus site in Ingolstadt, Germany, and VECTES in Kuusikonmäki within Vantaa, Finland, is given. This description includes the existing energy and technical infrastructure at both sites, including the type and condition of the energy supply. This forms the basis for understanding the specific requirements and challenges associated with the implementation of seasonal thermal energy storage systems.

Afterward, the tasks in the research project are described in detail. Work Package 2 (WP2) includes the characterization and preparation of the sites, the adaptation, and implementation of the systems, as well as their operation, evaluation, and validation. In this context, the technical and infrastructural investigations of the two locations will be carried out. This preparatory work is crucial to creating the technical prerequisites for the successful implementation of the systems.

Another important component of the report is the description of the adaptation of the existing infrastructure and the implementation of the sTES systems at the two sites. This includes the detailed planning and feasibility analysis of the monitoring systems, the selection and experimental evaluation of insulating materials as well as the installation and commissioning of the monitoring systems. These measures enable the continuous monitoring and optimization of the sTES sytems' efficiency and performance

Finally, the report summarises the main findings of the project and provides an outlook on future developments.

This report is intended for a diverse range of stakeholders and provides information on the current status and progress of the Incampus project.

For the funding body, the report serves as a status update, documenting the project's progress and demonstrating compliance with funding requirements. This ensures transparency and accountability in the project's development.

Research partners will find both a status update and detailed documentation of design decisions within this report. This information supports scientific collaboration and allows for a thorough tracking of the project's evolution.

As the report is classified as public, it also includes general information for third-interested parties. This provides the public with an insight into the project's goals, progress, and outcomes, thus promoting understanding and interest in sustainable energy projects.

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1.3 Reporting period

This report covers the period from the project started in January 2024 to the 3rd of October 2024. Three more reports will follow (D2.2-D2.4), covering the remaining project term until the end of 2027.

In this first reporting period, the two sites reached different stages of work (Table 1).

Table 1: Status of the different stages of work of the two sites.

Subtasks	*Reno-sTES (Ingolstadt)*	*Giga-CTES (Vantaa)*
Characterization	ongoing (90%)	ongoing (50%)
Preparation	ongoing (70%)	ongoing (30%)
Adaptation	ongoing (40%)	ongoing (20%)
Implementation	ongoing (15%)	construction starts in 2025, The end of construction is scheduled for 2027/2028
Operation	start scheduled in June 2025	
Evaluation	start scheduled from August 2025	
Validation	start scheduled from August 2025	
Assessment for Transfer	scheduled for 2027	

Regarding the time schedules, it is to state that while the incampus demonstrator will be in operation soon, full operation cycles of the VECTES demonstrator will be difficult to examine within the research project.

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2 Introduction of the Demo-Sites

2.1 Incampus, Ingolstadt, Germany

2.1.1 Site Description

The incampus is a quarter that was jointly developed by Audi AG and the city of Ingolstadt. Located in southern Germany, in Bavaria, it lies in the southeastern part of Ingolstadt, close to the Danube River. Currently under development, the area is particularly appealing to companies operating in high-tech and innovative sectors. The first buildings have been in operation since 2021. The quarter has an innovative energy concept that uses environmental energy such as groundwater and waste heat from a data center. The core of the energy concept is the LowEx system, a pipe-bound energy network that serves as a source or sink for the distributed heat pumps in the buildings. This concept, in conjunction with basins from the previous use that are no longer required, makes the integration of low-energy, seasonal storage a viable option.

The former usage of the land was a refinery site, which was in operation for 43 years. From 1965 to 2008 (Figure 1), various petroleum products were produced here (Audi, 2024).

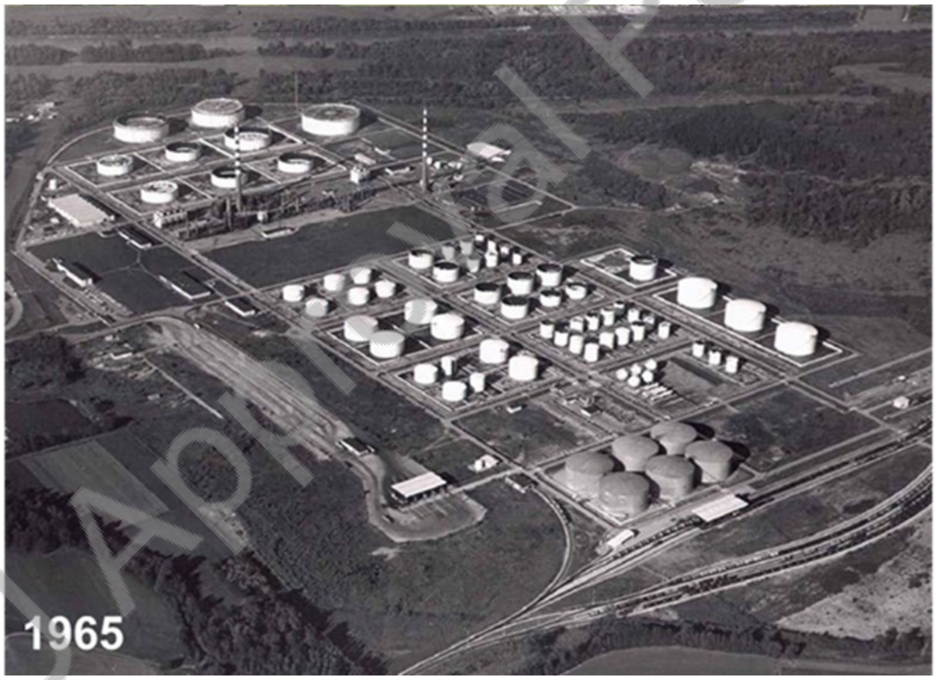

Figure 1: Refinery in Ingolstadt, Germany (Broschüre IN-Campus, 2018).

After the refinery was decommissioned in 2008, the dismantling of the facilities began and was completed by 2013 (Figure 2).

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Figure 2: Demo site (Ingolstadt, Germany) after the dismantling in 2020 (Audi, 2024).

The further transformation into a research and development campus includes an area of around 75 hectares, on which up to 70 non-residential buildings (offices, workshops, industrial laboratories, test benches, computer center, etc.) are to be built.

The development and expansion of the incampus (Figure 3) are divided into four construction phases. These buildings will be used for innovative research and development applications. In the first construction phase, the first buildings will be completed, providing space for 1,400 employees. As a result, the energy requirements of the various buildings will develop dynamically, which poses a challenge for the planning and implementation of the energy system and requires an adaptive planning strategy for an optimal energy supply.

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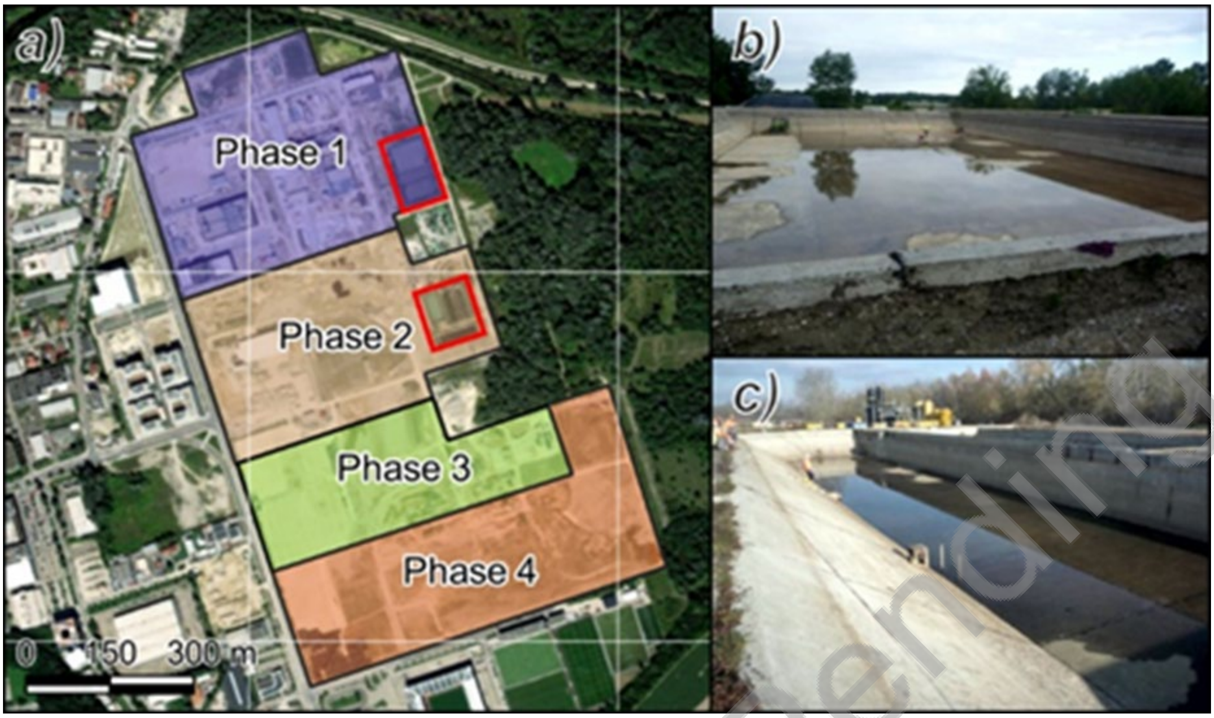

Figure 3: Construction phases at the incampus (a; available basins highlighted in red), and photos of the available basin structures (b: basin A, c: basin D) (LDBV, 2023).

Available Basins

There are basins at the site that were previously used for the storage of extinguishing water and for wastewater treatment (aeration, clarification, re-aeration; Figure 4). These structures are no longer necessary and could potentially be repurposed as seasonal Thermal Energy Storage (sTES) with a total volume of almost 32,300 m³ (excluding internal components, Table 2).

Table 2: Dimensions of the basins at the incampus.

Basin	*Length (m)*	*Width (m)*	*Height (m)*	*Volume (m³)*
A-B-C	59.6	95.1	3.2	18,150
D-E-F	59.6	38.3	3.2	5,839
G	52.0	26.4	2.0	2,299
H	75.0	16.0	5.5	6,960

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Figure 4: Aerial view of the available basin structures at the incampus. Aerial image (LDBV, 2023).

The incampus is a prime example of land conversion processes. Brownfields and existing structures are being redeveloped, and land remediation is being carried out by both public and industrial partners.

The soil remediation project, which involved the extensive cleanup of 900 tons of heavy oil, 200 tons of light gasoline, and per- and polyfluorinated chemicals, utilized the fire extinguishing basins as storage. Consequently, basins A, B, and C (Figure 5 & Figure 6) were sealed with a high-density polyethylene (HDPE) sheet. Specialized techniques such as air sparging and soil washing were employed for the cleanup.

Figure 5: Basins A + B – before the start of the sTES planning process (Planungsgruppe M+M AG, 2013).

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Figure 6: Basin C – before the start of the sTES planning process (Planungsgruppe M+M AG, 2013).

For these reasons, the basins A, B, and C were directly suitable for subsequent energy utilization. In addition, the basins belong to construction phase 1 and would therefore have had to be backfilled or dismantled. Instead, they are being designed as integral components of the INTERSTORES project.

Pump Station

The fire extinguishing storages were also equipped with a pumping station that was used to transport large quantities of water across the site. Figure 7 shows the condition of the pumping station after its deconstruction in 2013.

Figure 7: Pump station after the demolition (Planungsgruppe M+M AG, 2013).

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As part of the INTERSTORES project, the pumping station is being converted into a new hydraulic control room. This control room will serve to hydraulically integrate the existing energy infrastructure at the incampus with basins A, B, and C.

Regional Geological and Hydrogeological Framework

The incampus site is geologically strongly influenced by the River Danube and predominantly consists of sand and gravel, with post-glacial terraces. Quaternary sediments, mainly gravel with sandy and silty layers, are found 6-7 to 12 meters below the surface and have high to very high permeability. Beneath this, the Tertiary freshwater molasse contains fine sands, silts, and clays with lower permeability, serving as limited groundwater aquifers (i.e., low permeabilities), but not as aquitards.

The site is located on a floodplain once traversed by the River Danube. A drainage ditch runs through the northwest, adjacent to the lake Auwaldsee, while the southern and south-eastern areas feature several oxbow lakes and gravel ponds. Thus, the site is surrounded by various surface waters (e.g., ponds, lakes, and trenches). The strata of the subsurface further ensure stable groundwater conditions. Groundwater, influenced by infiltration from the River Danube in the northwest, flows southeast at a rate of nearly 7,000 m^3 per day (Christoph Bott, 2024).

2.1.2 Energy System

The energy supply at the incampus site is designed to be highly self-sufficient and efficient. The goal is to obtain thermal energy from renewable sources and to actively use mechanisms to avoid peak loads and shift loads. Instead of conventional direct connections, the supply of electricity, cooling, and heat is managed through an intelligent system that connects different energy sources and sinks. This system includes combinations of various forms of energy and storage solutions. Figure 8 illustrates the components and energy connections at the incampus.

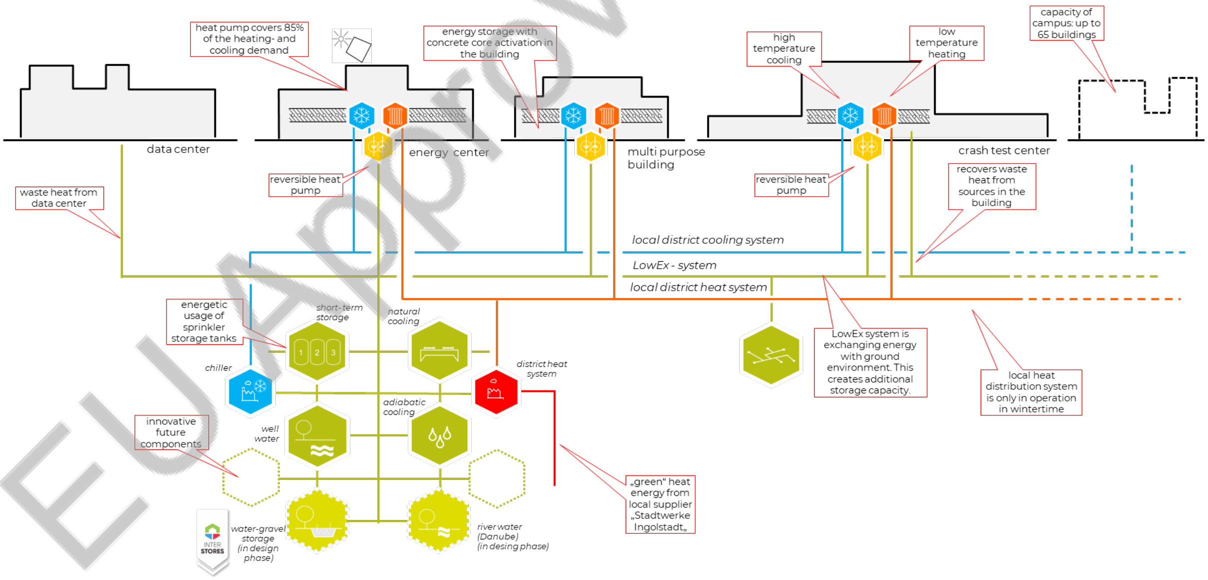

Figure 8: Energy connections of the energy concept at the incampus (Planungsgruppe M+M AG, 2013).

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LowEx Network

A key feature of the incampus energy system is the LowEx network, a combined heating and cooling system classified as a fifth-generation heating network, a low-temperature distribution network where both heating and cooling are supplied. This network facilitates the redistribution of heating and cooling demands across the campus, dynamically balancing loads while integrating waste heat and renewable energy sources. Operating temperatures fluctuate seasonally between 5 °C and 30 °C, with decentralized heat pumps adjusting temperatures to meet specific requirements. This system significantly contributes to energy efficiency and CO_2 neutrality on campus.

The network is designed to serve a 75-hectare campus and will ultimately comprise over 9,100 meters of pipelines, implemented in four construction phases. Once completed, up to 70 non-residential buildings, including offices, laboratories, and test facilities, encompassing approximately 1,000,000 m² of gross floor area, can be supplied. The uninsulated distribution network also functions as both a heat source and sink, as well as a thermal energy storage system.

Energy Sources and Integration

The primary heat source for the network is the waste heat from a corporate data center. In the first expansion phase, 1.8 MW of waste heat is utilized, increasing to 4.0 MW in the final phase. Additionally, 10 groundwater wells established during site remediation serve as both heat sources and sinks, contributing approximately 1 MW of thermal energy. Long-term plans include utilizing the nearby Danube River for heating and cooling. Furthermore, sprinkler basins in the energy center are equipped with heat exchangers, functioning as short-term thermal energy storage systems with a total volume of approximately 3,000 m³ and a storage capacity of 130 MWh (at temperature difference $\Delta T = 35$ K).

Concept Development

The development of the incampus was guided by an integral and holistic approach. A comprehensive sustainability concept was devised, encompassing all aspects from renovation and renaturation to new construction projects. This integrative method facilitated the optimal utilization of existing synergies.

In the era of passive and energy-plus buildings, it is imperative to design entire districts to achieve energy efficiency beyond individual structures. Through collaboration with numerous experts, a concept was developed with the medium-term objective of transforming the incampus into a zero-energy campus. To realize this ambition, the energy potential of the site must be maximally exploited.

Buildings and districts often simultaneously require heating and cooling. The incampus addresses this dual demand through innovative technology, diverging from traditional methods and achieving significant energy savings. The foundational element of this energy concept is the LowEx network, a water-based pipeline system functioning as a heat source and sink for all campus buildings. In the first construction phase, uninsulated plastic pipes with diameters ranging from 60 to 80 centimeters are installed in a ring network beneath the ground. Buildings with high cooling demands, such as data centers, transfer surplus heat into the network, while those with substantial heating requirements draw energy from it. This approach allows consumers to act as energy producers, leveraging seasonal temperature fluctuations within an operating range of 5 °C to 30 °C. This range is suitable for incorporating environmental and waste heat into the system. In addition to recovering up to 2,000 kW of waste heat from the data center, the network can utilize up to 1,500 kW of heating and cooling potential from groundwater. This integration is facilitated by the groundwater collection system established during soil remediation efforts, where

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groundwater is already being pumped and purified. Reversible heat pumps within individual buildings ensure the required system temperatures, enabling the reuse of low-grade energy referred to as anergy and converting it into higher-quality energy or exergy through a form of "upcycling."

Reversible heat pumps efficiently provide heating and cooling for all buildings on the campus. The planning of these heat pumps prioritizes system optimization at the building level. A variety of operational scenarios are considered, including simultaneous heating and cooling requirements within buildings. In such cases, the heat pumps operate in dual mode, shifting energy internally to maximize efficiency. Additional energy, if needed, is supplied by the central LowEx network, thereby reducing network strain and enhancing heat pump performance. For optimal energy efficiency, low system temperatures are required for heating and high temperatures for cooling.

Thermoactivated building components, such as concrete ceilings and floors, contribute significantly to energy efficiency by serving as both heating/cooling elements and energy storage systems. This capability enables energy generation at different times, allowing heat or cold to be stored and used proactively. This approach reduces power peaks and ensures optimal utilization of the renewable energy supply on campus.

Three thermal energy storage systems within the campus energy center further enhance short-term load management and overall energy efficiency. With a combined capacity of approximately 3,000 m^3, these systems store both heat and cold. Over the medium term, a dynamic energy management system referred to as the *Cross Energy Concept* (CEC) system will oversee energy supply operations. This system employs artificial intelligence algorithms for predictive management, optimizing the interaction of energy sources and sinks. In the current stage, the incampus still consumes energy from outside the site. However, the goal of a zero-energy campus is getting closer and closer to no-external consumption with further innovation modules.

2.1.3 Monitoring Concepts

The monitoring concepts regarding the storage project are elaborated in detail within deliverables D4.5 (energy system monitoring) and D5.4 (monitoring concepts for the ambient domain).

Energy system monitoring

Within the INTERSTORES research project, various processes and states of the storage system will be monitored and displayed to ensure efficient and safe energy storage. As a summary, the energy system monitoring of the plant will include:

Fill level:

- Each basin is equipped with a probe that measures the fill level to ensure that the tank is filled correctly.

Temperature

- Temperature probes are installed in well pipes to monitor the temperature distribution in the storage tank and to create detailed temperature profiles.
    - Basin A: 9 measuring points, each with 3 temperature probes
    - Basin B: 3 measuring points with 3 temperature probes each
    - Basin C: 6 measuring points with 3 temperature probes each

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Distributed temperature sensing (DTS):

- DTS systems measure temperature along an optical fiber over time, providing spatial temperature profiles.
- The layout of the DTS cables in the basins is still pending.

By monitoring the temperature, fluctuations can be detected, aiding in the optimization of energy efficiency.

Monitoring and controlling energy systems is essential for ensuring their efficiency and reliability. Modern technologies enable precise control and analysis of various parameters required for optimal operation. By employing advanced measurement and control techniques, energy systems can be continuously monitored and adjusted to ensure maximum performance. The following sections provide a detailed insight into the methods and instruments used to monitor and control these systems.

Energy:

- Measure the amount and temperature difference of the medium flowing through the system to monitor energy flow and ensure efficient operation. Each medium (LowEx, local heating, and local cooling) is measured at the entry and exit points of the storage system. Additionally, each loading level (three per storage) is measured separately.

Temperature:

- Temperature sensors in the pipelines ensure controllability, allowing for the regulation of the system's thermal condition and maximizing the efficiency of heat transfer.

Monitoring concepts for sTES ambient Domains

In summary of the ambient domain, the monitoring concepts include:

At the Reno-sTES site on the incampus, the primary objective of the developed monitoring concept is to ensure the safe and efficient integration of new Reno-sTES/WGTES basins with the existing infrastructure while minimizing the environmental impact on the surrounding Quaternary sediments. The conceptual framework for the Reno-sTES site includes monitoring the interaction between sTES and the geosphere, with a particular focus on temperature changes. The monitoring concept also addresses potential impacts on the hydrosphere, particularly groundwater flow in the area.

At the incampus, the site assessment phase involves detailed geological and hydrological studies to understand the conditions of the existing basin infrastructure and the surrounding domains. These studies provide the baseline data necessary for designing a monitoring system that can detect temperature changes and groundwater flow during operation. The monitoring scheme is designed to capture data from key locations within the sTES and the surrounding environment, including sensors placed at different depths within the basins and in the surrounding ground. The installation includes data transmission systems, calibration, and the initialization of the monitoring system with reference measurements and calibration equipment.

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2.1.4 Conceptual approach Reno-sTES

Reno-sTES is introduced as a storage category that is based on recycling, reusing, and/or renovating existing infrastructure to serve as thermal energy storage in a modern district heating or cooling network. The development of conceptual Reno-sTES scenarios is subject to site-specific boundary conditions, where volume, geometry, and ambient conditions are predefined in the case of re-used infrastructures. Further boundary conditions are given by the energy system and constraints for storage operation.

For the incampus project and due to its complex energy system structure, a multifunctional solution for heat and cold storage, operating both seasonally and as a short-term buffer, is required. In contrast to conventional strategies, this Reno-sTES system will store excess thermal energy at different temperatures from a variety of sources.

As part of the first construction phase, the heat storage focuses on the A-B-C basin compound. Given the public accessibility of the area, it is essential to design a concept for securing and integrating the basins into the surrounding landscape. At the same time, preliminary structural investigations prove that the basins are in a suitable condition to be transformed into a Reno-sTES.

Besides these multiple constraints, many dependent and independent parameters remain for the optimum design of Reno-sTES facilities. These concern the selection of materials and methods that affect the design of each component of the system.

2.1.5 Storage integration and potential

INTERSTORES project aims to seamlessly integrate a new energy storage system into the existing energy infrastructure of incampus. This integration is key as it allows different usage scenarios to be simulated and comprehensive data to be collected. The implementation of the new storage system will enable numerous operational and technical scenarios to be tested, which will help to optimize the efficiency and effectiveness of energy use and distribution.

A special focus is placed on the analysis of load profiles, storage strategies, and the response of the energy infrastructure to different requirements. These tests are crucial for developing a deep understanding of the dynamics of energy management and identifying the best approaches for the efficient use of stored energy.

Figure 9 shows the energy infrastructure at the incampus, which will be integrated with the storage system's hydraulic control room (highlighted in a red circle).

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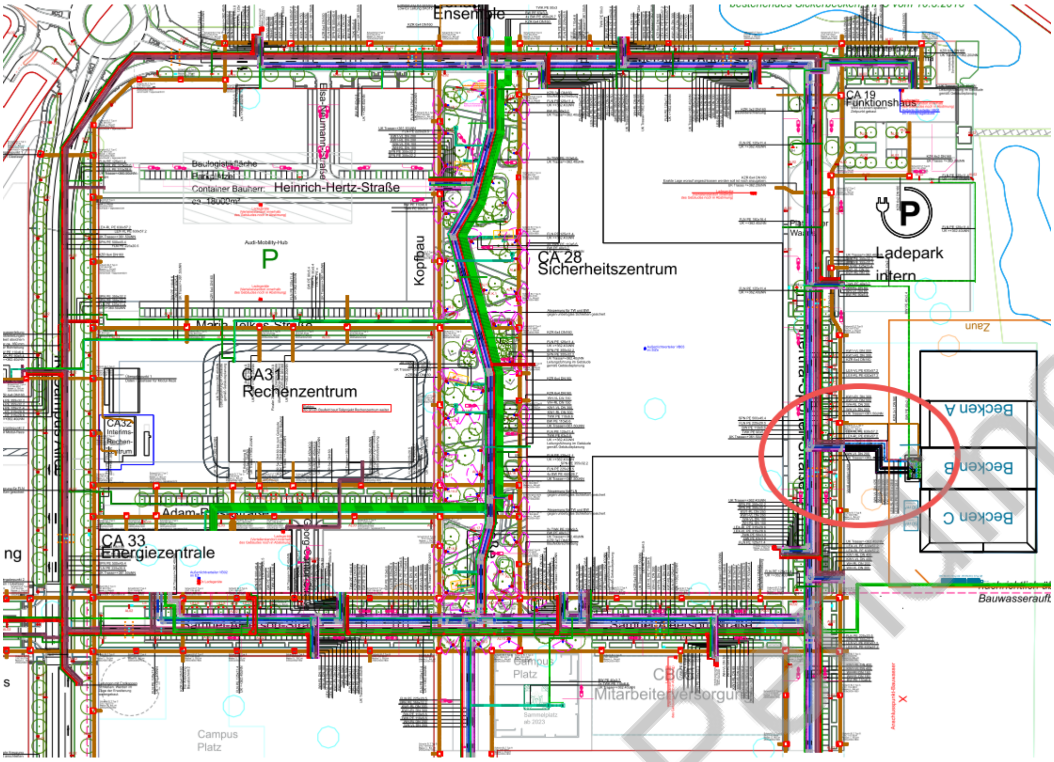

Figure 9: Energy Infrastructure at the incampus (IN-Campus GmbH).

The 3D representation in Figure 10 shows how the infrastructure and the technical center are connected.

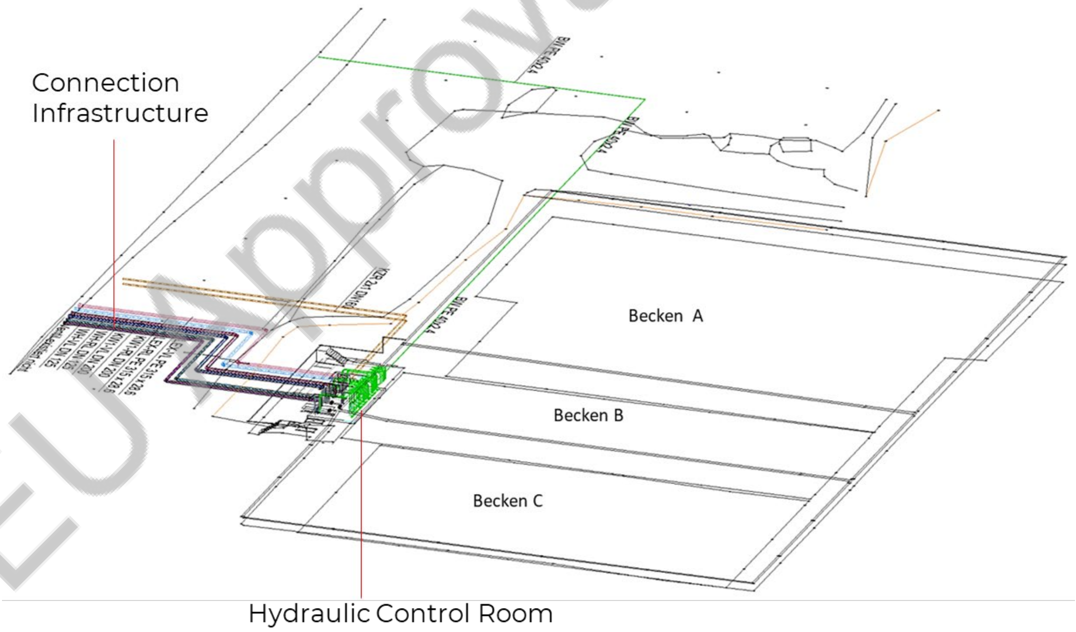

Figure 10: Illustration of infrastructure and technical center (Planungsgruppe M+M AG + IN-Campus, 2024).

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2.1.6 Scope of design Reno-sTES

The existing basin compound "A-B-C" will be transformed into a system with detailed monitoring, and will be connected to the energy system (Figure 11). Aiming to implement a differentiated sTES compound, sub-basins A and B will be upgraded as a fully buried, indirectly charged/discharged water-gravel-based storage (WGTES) basin (filling: re-used, on-site gravel, sealing: re-used plastic foils from site remediation activities) that is sealed on all sides with re-used plastic membranes. By implementation as WGTES, the basin surfaces can be used as green spaces or for parking. Basin C will be transformed and integrated as a study case to optimize technical elements and to test different, innovative insulation materials.

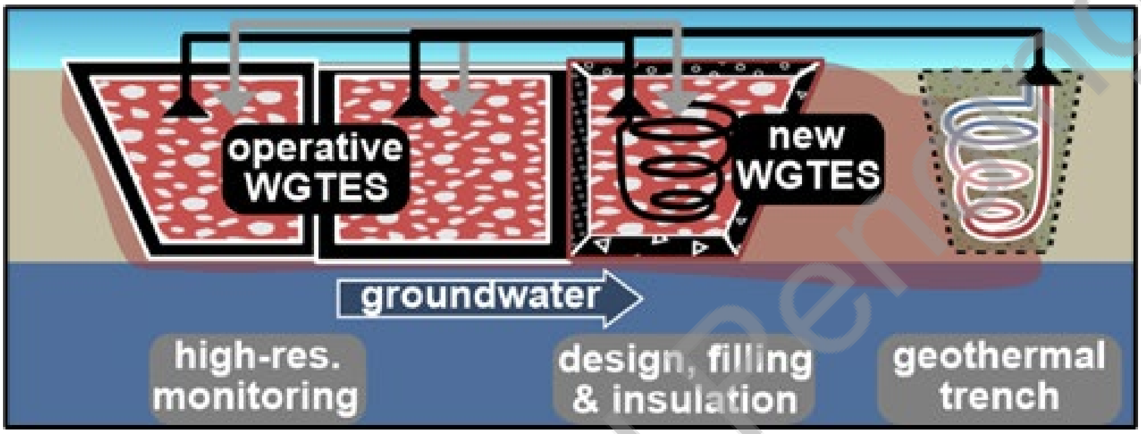

Figure 11: Planned realization of the ABC basin compound as Reno-sTES system with complementary research activities.

<u>*Scope of the planning process*</u>

The planning phase involves a series of technical and construction tasks to prepare the site for effective energy storage and distribution. The following steps show the sequence of construction activities.

Demolition pump station:

- The existing pump station will be deconstructed to allow for the construction of a hydraulic control room.

Construction hydraulic control room:

- The new control room will feature advanced hydraulic systems to manage energy flow and optimize the charging and discharging processes for basins A, B, and C.
- This control room will serve as the central hub for energy transfer between the storage basins and the campus energy system.

Connection to the infrastructure:

- Connection of the energy Infrastructure (LowEx, district heating & district cooling) to the hydraulic control room.

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Earthwork:

- Preparation of the site for the construction phase, including excavation and levelling.

Piping hydraulic control room:

- This step includes the installation of pipes, valves, and control systems in the hydraulic control room to efficiently control the distribution of thermal energy.

Inspection of the sealing sheet:

- Inspection of damage to the existing High-Density Polyethylene (HDPE) sealing sheet to determine possible repairs.

Patching the sealing sheet and leak Testing:

- Any damages identified during inspections will be patched.
- A comprehensive leak test will follow to certify the structural integrity of the storage basins.

Filling the basins:

- Preparation of basins A, B, and C with tailored insulation and thermal storage materials.

The involvement of around 10 companies underlines the interdisciplinary nature of this planning and construction phase, where expertise from different fields is combined to develop a robust and innovative energy storage solution.

Timetable

Figure 12 provides a rough overview of the timetable for the INTERSTORES project and the construction schedule.

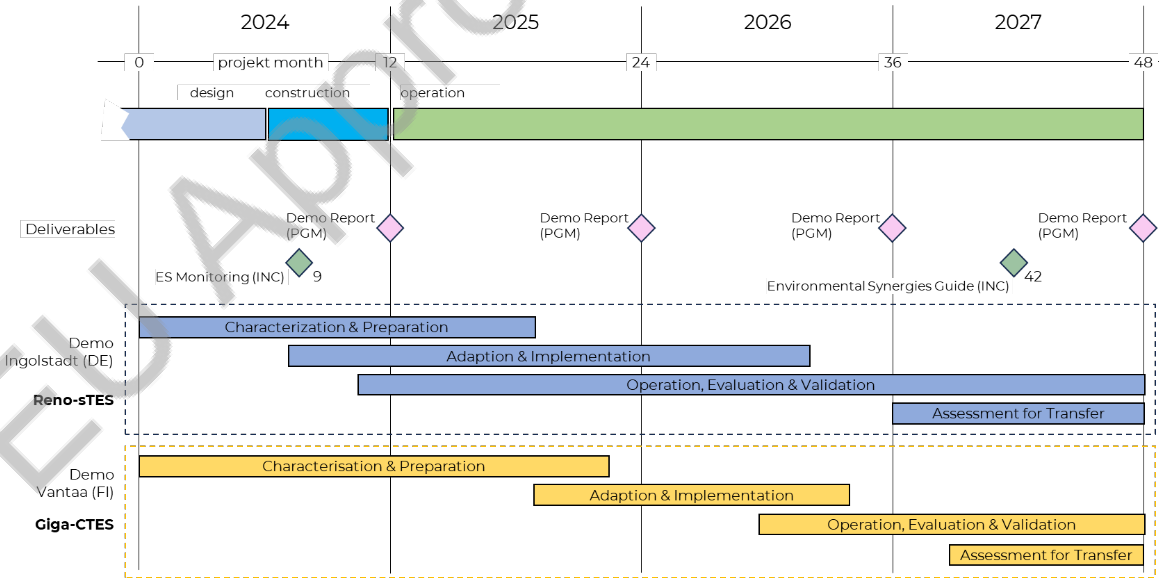

Figure 12: Project time schedule (Planungsgruppe M+M AG, 2024b).

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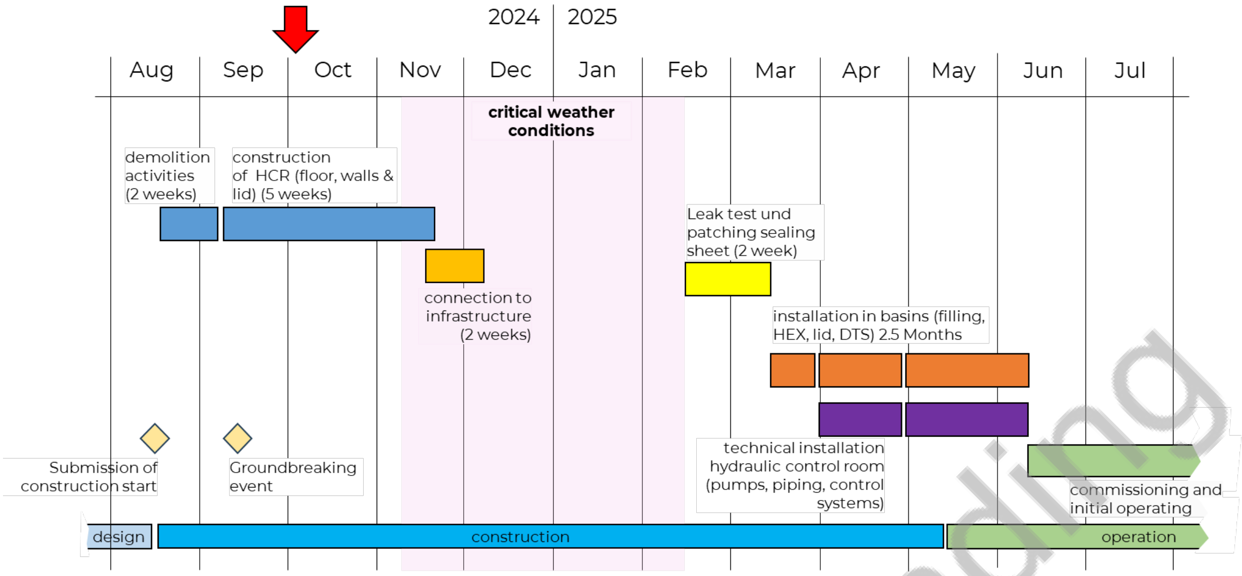

Figure 13: Construction time schedule (Planungsgruppe M+M AG, 2024b).

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2.2 Varanto, Vantaa/Helsinki, Finland

2.2.1 Site Description

The *Varanto* project focuses on constructing a large-scale, seasonal thermal energy storage connected to the city-wide district heating system in the city of Vantaa, Finland. The storage is planned to be implemented as a cavern heat storage, constructed approximately 140 m underground in bedrock. The total excavated volume, including the process space, is 1,100,000 m^3. The actual storage volume consists of three interlinked chambers that are about 300 m long, 40 m high, and 20 m wide each. The storage is visualized in Figure 14.

Although the storage itself is a new development, i.e. no existing structures or infrastructure are utilized as such in its construction, the planned storage unit is to be integrated into an existing district heating system. Thus, its purpose and design are derived from the characteristics of the system.

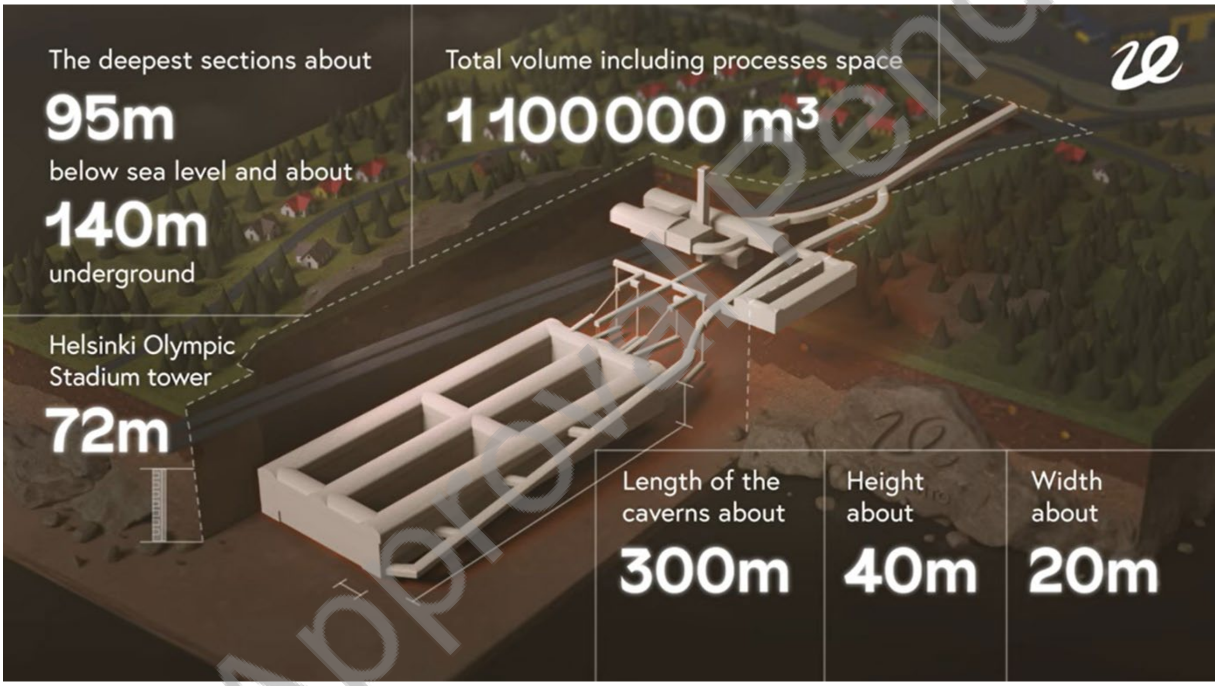

Figure 14:. Visualisation of the Varanto thermal energy storage with key dimensions (Vantaan Energia, 2024).

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2.2.2 Energy System

The existing energy system that the planned storage unit is to be integrated into is the Vantaa district heating system. In 2023, the district heating deliveries were 1,720 GWh. The supply mix behind the deliveries consists of 51 % municipal and other waste, 16 % biomass, 15 % coal, 11 % heat recovery, 5 % natural gas, and less than 3 % other fossil fuels. The share of heat recovery and electrified heat supply options (i.e. heat pumps and electric boilers) is expected to grow in the near future (Figure 15).

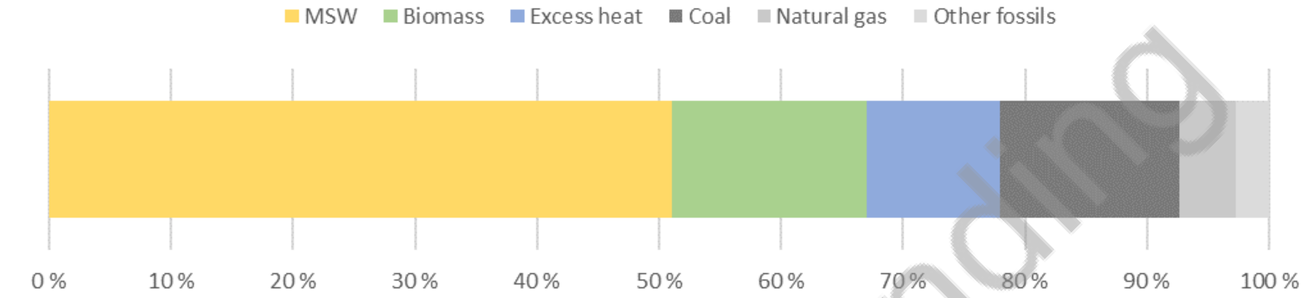

Figure 15: Heat sources utilised by the Vantaa district heating system (Energia, statistic by Finnish Energy, 2023).

The total length of the district heating network is approximately 600 km, and the annual heat losses were 6.3 % in 2023 (Figure 16).

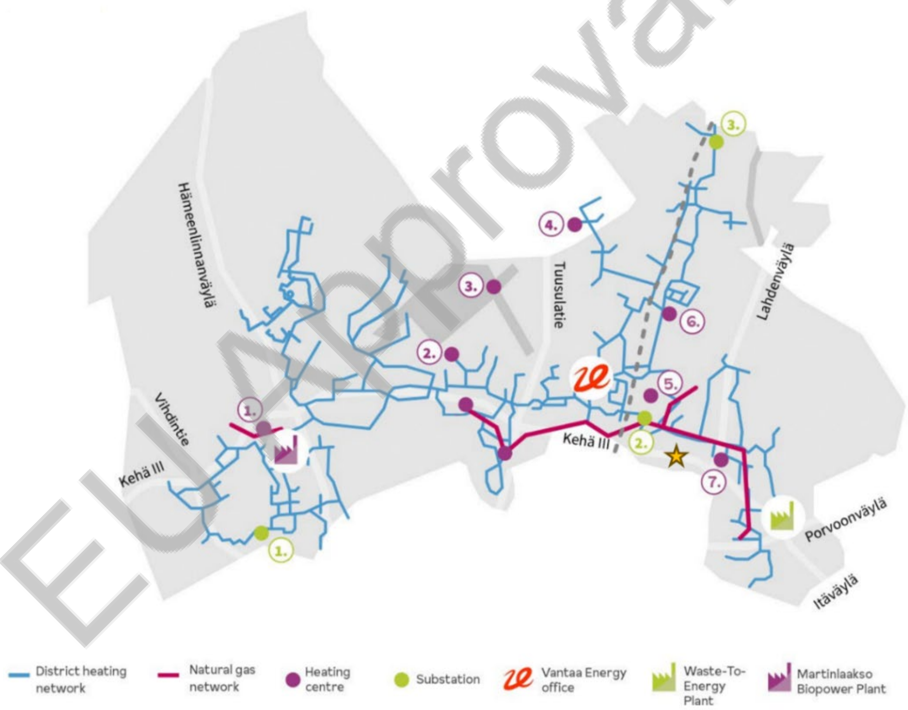

Figure 16: Illustration of the Vantaa district heating network and the points of supply. The approximate location of the Varanto storage is marked by a star (Vantaan Energia, 2024).

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The city of Vantaa is also neighboring the capital Helsinki and the city of Espoo, the second largest city in Finland. These two cities have the two largest DH systems in Finland. Interconnections between them and Vantaa exist, and their capacity increase is underway. The heated trade between the systems will undoubtedly grow, partly due to the Varanto project and the resulting storage capabilities.

2.2.3 Monitoring Concepts

The monitoring concepts regarding the storage project are elaborated in detail within deliverables D4.5 and D5.4 for the energy system monitoring and monitoring concepts for the ambient domain, respectively.

In summary, the technical monitoring of the plant will include:

- Temperatures and pressures within the CTES and the charging/discharging systems
- Water quality for checking impurities, pH levels, and other chemical properties
- Structural monitoring via displacement sensors (cavern walls and built structures)
- Flow rates and energy flows (together with temperature measurements)
- Various monitoring of equipment (pumps, valves, etc.) related to the CTES operation

Of the ambient domain, the most important monitoring concepts include:

- Automatic groundwater level monitoring systems
- Seismic measurements

2.2.4 Conceptual approach Giga CTES

The primary purpose of the planned thermal energy storage is to fulfill the potential of the main heat supply unit within the system, the waste incineration plant located in Långmossebergen of Eastern Vantaa (Figure 17). The current potential surplus heat during the summertime can be stored to replace the peak boiler heat supply based on natural gas. This results in a direct reduction of greenhouse gas emissions by 65,000 tCO_2. In addition, the significant storage capacity is seen as a key element in any district heating systems due to the growing share of variable renewable energy-based electricity generation such as wind and solar power, and due to the currently growing utilization of excess heat. Power-to-heat concepts (electric boilers, heat pumps), i.e. electrification of district heating supply, are seen as a strong overall trend in developing district heating.

As described in Chapter 2.2.1 the storage unit is implemented as an excavated rock cavern, consisting of three large, interconnected chambers. The storage is loaded and unloaded directly from the district heating network. However, the maximum capacity is reached by utilizing electric boilers as the normal district heating supply temperature level (around 100 °C, closer to 80-90 °C during the summertime) is lower than the design temperature of the storage (140 °C). The district heating supply temperature and its impact on how the storage is loaded (operation of the electric boilers) creates an optimization problem, where the expected electricity prices play a part.

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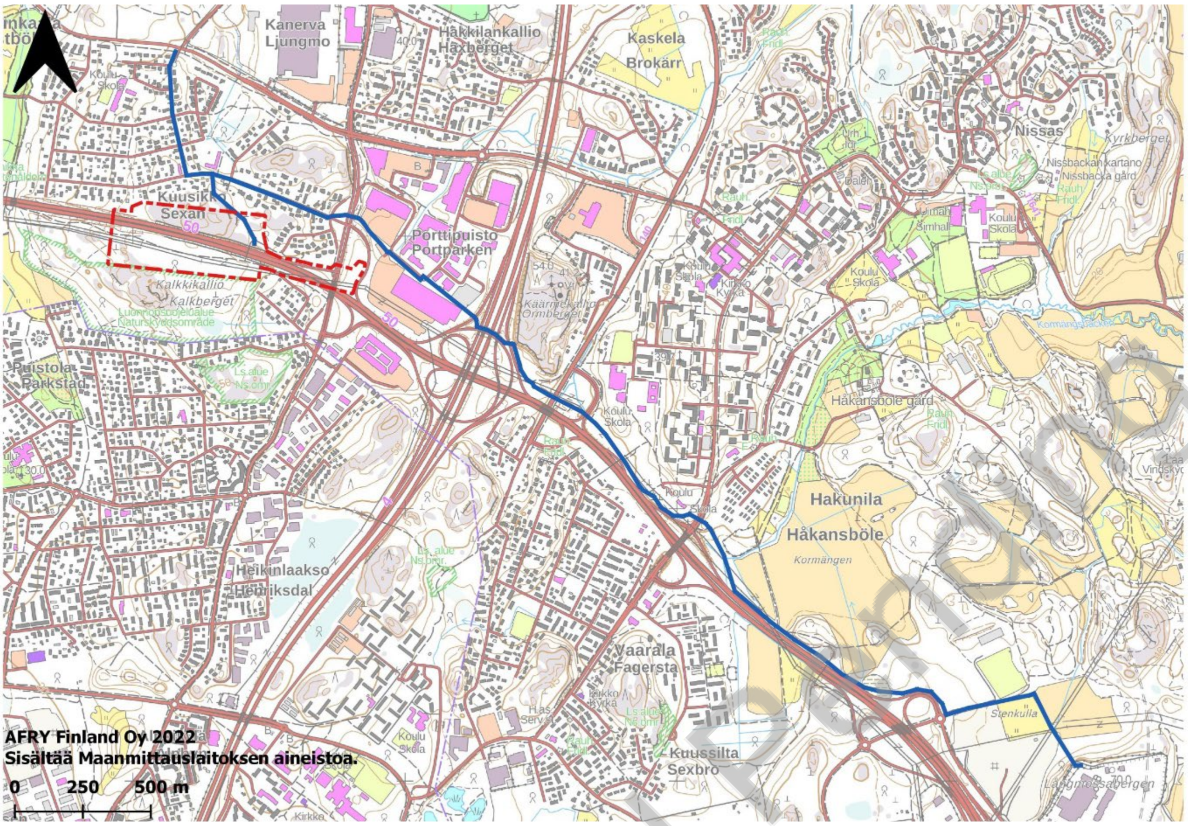

Figure 17: Location of the Varanto thermal energy storage (red, dashed line) and the main district heating pipeline between the storage and the waste incineration plant (Vantaan Energia, 2024).

The exact location of the storage unit has been planned carefully. The criteria include location as close as possible to the existing district heating network and the primary heat supply unit (waste incineration plant), suitable rock quality and location in the context of the city's built environment, and finally, the impact of the construction and the finished facility to the environment and the people. e.g. the location of the service tunnel (and excavation/construction) entrance was moved as far as possible from residential areas. This also enables efficient logistics arrangements as the heavy traffic during the construction can be directed almost directly onto Ring Road III around the metropolitan area.

2.2.5 Storage integration and potential

As explained, the storage unit is to be integrated into the district heating system of Vantaa and will be tapping into the unutilized potential (summer surplus heat) of the existing waste incineration plant. Furthermore, the storage can be also used to provide short-term flexibility to the district heating and power systems. The electric boilers that are used in order the boost the temperature up to 140 °C can be operated partially based on market conditions. The short-term flexibility enabled by the storage can, in fact, be an essential feature in increasing the number of storage cycles well beyond one (pure, theoretical seasonal storage). This considerably improves the economic feasibility of the storage investment.

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The integration potential and the optimal operation of the Vantaa district heating system within the Finnish and Nordic energy systems is a topic of research during the INTERSTORES project and advanced in WP4.

2.2.6 Planned site development

The basic engineering tasks are ongoing and the above-ground works are to be finished early next year. The excavation work, which will take approximately 2.5 years, is scheduled to begin in early 2025. The construction is expected to continue until 2028 after which the commissioning period will start. At this point, the storage will be in operation. Other preceding activities have been test drillings (bedrock) and setting up monitoring for the wells and groundwater (water quality and level).

Currently, the focus of the engineering work is on selecting materials for the construction and refining the design and plans based on findings.

The rough schedule is presented in Figure 18.

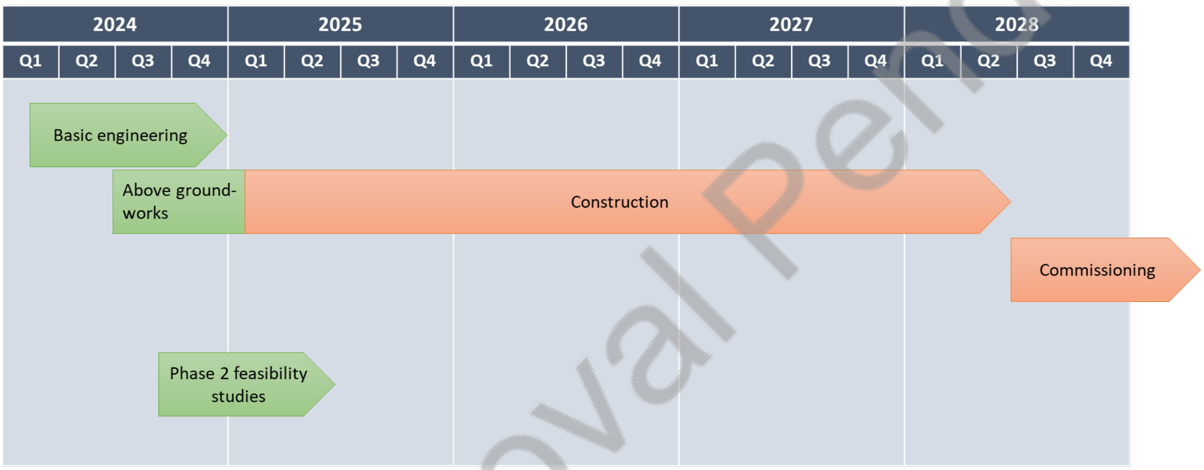

Figure 18: An estimated timeline for the Varanto project (VTT Technical Research Centre of Finland , 2024).

In addition to advancing the Varanto project, the board of Vantaan Energia has approved the start of phase 2 feasibility studies. These studies aim to lay the basis for another similar heat storage unit elsewhere in Vantaa. The lessons learned from phase 1 (Varanto) are thus very useful in planning the next storage.

The site development and concrete activities are well-described within a website (Vantaan Energia, 2024) provided by Vantaan Energia following the construction work.

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3 Incampus (Reno-sTES) – Implementation, Results, and Evaluation

3.1 Key design aspects

In addition to all the aspects and dependencies identified so far, three key aspects emerged during the planning process that are most important for the overall system.

3.1.1 Realization within cost budget

Since the granted budget from the EU and the budget of the IN-Campus GmbH are fixed, increases in costs must be offset by design optimizations that have as little impact on usability as possible.

3.1.2 Durability

The longevity of the system is essential because the development of the incampus site will take decades. The important aspect here is, that the effort involved in making future changes to the underground components and installations (Insulation, filling, and heat exchangers) during operation is expected so high, that this can be practically ruled out. This is achieved by the choice of materials. The selection of durable materials is crucial for the system. All sensible components need to be accessible for maintenance, repair, replacement, or future changes if it is possible. This also corresponds to the aspect of flexibility.

3.1.3 Flexibility

The flexibility of the Reno-sTES system is another decisive factor, as it allows the system to react to future requirements. Because the energy requirements can change significantly with the future development of the site, a high degree of flexibility is required in terms of the options for storing energy. For example, future buildings can play a major role in the storage of heat or cooling energy. The use cases can vary between short-term use seasonal use or both. The integration of so far not considered sources is to be considered.

This is achieved by the implementation of the versatile hydraulic connections of the heat exchangers as described in Table 8 and Table 9:

- Versatile operating modes: the various hydraulic connections (single and multiple connections) allow the system to be flexibly controlled depending on energy requirements.
- The ability to charge or discharge different heat exchanger layers (top, middle, and bottom layer) allows the system to respond flexibly to different temperature requirements.
- Well-insulated and not insulated basins provide high flexibility for storing or releasing energy

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3.2 Geometry

The geometry of the incampus energy storage system is a fundamental aspect that influences its overall performance and efficiency. Figure 19 illustrates the geometry of Basins A, B, and C. As described in Chapter 2.2.6, Basin C will be transformed and integrated as a study case to optimize technical elements and to test different, innovative insulation materials.

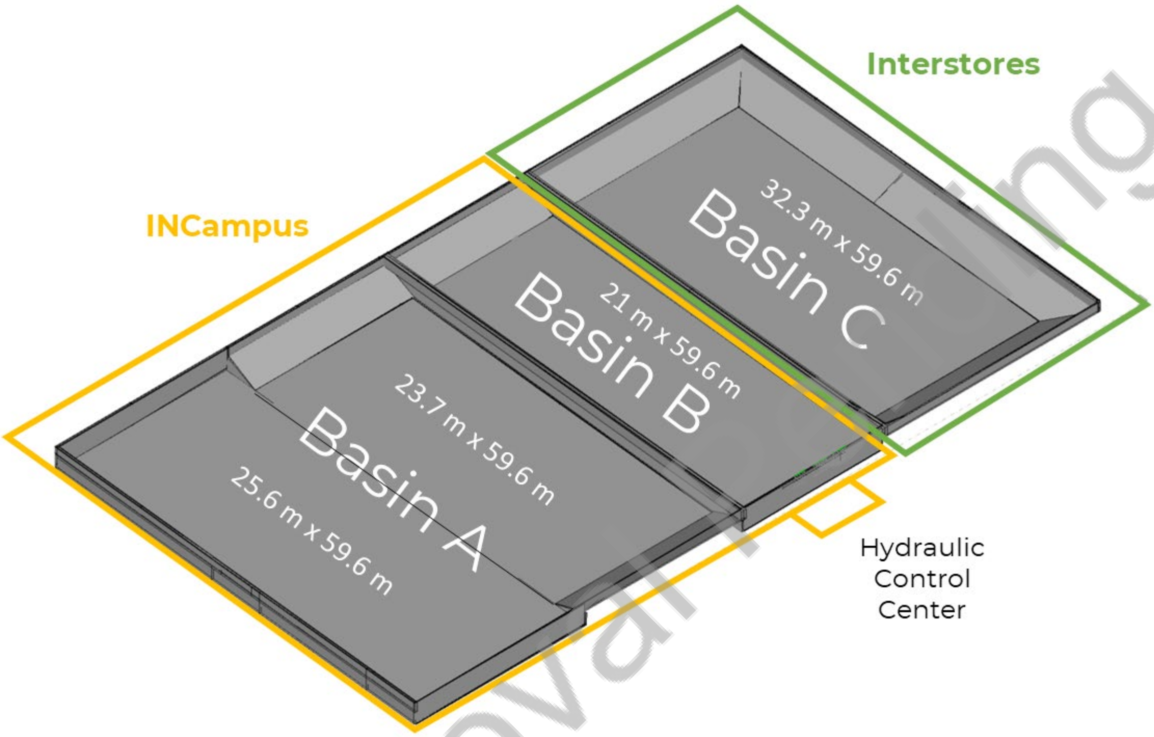

Figure 19: Overview of the Storage System (Planungsgruppe M+M AG, 2024b).

The total storage volume without insulation is 18,150 m³ (Table 3).

Table 3: Filling Volumes without insulation

Basin	*[m³]*
A	9,230
B	3,700
C	5,220

Because the geometries are given, there are generally three degrees of freedom left to optimize the overall performance. Those are the design of the insulation, the filling, and the design of the heat exchanger. To achieve the objectives in the best possible way the design of these components is discussed as follows.

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3.3 Insulation

In this section, materials generally considered for the design and construction of the energy storage system are described. The selection of appropriate materials is important to ensure the system's efficiency, durability, and overall performance. Various factors such as thermal conductivity, resistance to environmental influences, and compatibility with other system components are taken into account. The following materials have been evaluated based on these criteria to determine their suitability for use in the energy storage system.

3.3.1 Materials

The selection of the right insulation material for sTES is critical, as it must tolerate temperature fluctuations, resist moisture infiltration and accumulation, and maintain long-term thermal performance and mechanical stability. A variety of materials are commonly employed for sTES insulation, each tailored to meet these demanding requirements

Wood chips

Wood chips are a natural and renewable insulation material. They are produced from the by-products of wood processing and are known for their good thermal insulation properties. Wood chips have a low thermal conductivity, which makes them effective in reducing heat loss. Additionally, they are biodegradable and have a low environmental impact. Figure 20 shows a sample of wood chips.

Figure 20: A sample of wood chips.

Advantages:

- Sustainable and renewable: Made from wood waste, sourced locally (Europe), reducing environmental impact.
- Good thermal insulation: Low thermal conductivity (see 3.3.2 for more details) minimizes heat loss.
- Biodegradable: No long-term environmental issues.

Disadvantages:

- Moisture-sensitive: Must be kept dry to maintain insulation properties.
- Bulky: Requires more space compared to synthetic materials.

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Coconut fibers

Coconut fibers, or coir, are a natural insulation material obtained from the husks of coconuts (Figure 21). They are biodegradable, environmentally friendly, and offer reasonable thermal resistance, with thermal conductivity values ranging from 0.04 to 0.06 W/(m·K). Despite their advantages, coconut fibers are highly susceptible to moisture, which can lead to material decay and diminished performance in sTES applications. They also lack the structural strength of other insulation materials, limiting their use in scenarios where structural stability is critical. Additionally, the quality and performance of coconut fibers can vary significantly depending on the processing methods used.

Figure 21: A sample of coconut fiber before thermophysical measurements.

Advantages:

- Biodegradable: Environmentally friendly and sustainable.
- Thermal resistance: Provides reasonable insulation within a moderate range of thermal conductivity.
- Low cost: Often an economical insulation option.
- Environmental compatibility: Favorable ecological profile due to natural origin.

Disadvantages:

- Moisture vulnerability: Prone to decay and reduced thermal performance when exposed to high humidity.
- Structural weakness: Lacks the strength needed for applications requiring mechanical stability.
- Variable quality: Performance can fluctuate based on processing and sourcing methods.

Styrofoam XPS

Extruded Polystyrene (XPS), commonly known as Styrofoam, is a type of rigid foam insulation material made from polystyrene, a synthetic polymer derived from petroleum. The manufacturing process involves melting polystyrene beads and extruding them through a die to form a continuous, closed-cell structure. This results in foam boards with a smooth, dense surface and uniform structure, available in various thicknesses, densities, and dimensions to suit different insulation requirements.

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Advantages:

- High Thermal Resistance: XPS insulation provides excellent thermal performance with a high R-value per inch, typically around 5.0. This makes it effective in reducing heat transfer through building components, improving energy efficiency, and maintaining consistent indoor temperatures.
- Moisture Resistance: The closed-cell structure of XPS makes it highly resistant to moisture absorption. This helps protect against mold, mildew, and rot, promoting a healthier indoor environment.
- Durability and Longevity: XPS is known for its strength and durability. It can withstand heavy loads without deforming or compressing, making it suitable for load-bearing applications. It retains its insulation properties over time, providing long-term energy efficiency benefits.
- Lightweight: Despite its strength, XPS is relatively lightweight, making it easier to handle, transport, and install, which can reduce labor and installation costs.

Disadvantages:

- Higher Cost: XPS is generally more expensive compared to other insulation materials like Expanded Polystyrene (EPS). This higher cost can be a consideration in budget-sensitive projects.
- Environmental Impact: The production of XPS involves the use of blowing agents that can have environmental impacts. Additionally, XPS is more challenging to recycle compared to EPS.
- Potential for Condensation: Due to its low permeability, XPS can lead to condensation issues if not properly managed, which can affect the overall building envelope performance.
- Compatibility Issues: XPS can be incompatible with certain materials, such as some thermoplastics, which can limit its use in specific applications.
- Non-biodegradable: Can release microplastics to the environment, especially during construction and disposal.

Styrofoam EPS

Expanded Polystyrene (EPS), is a synthetic insulation material made from polystyrene beads. EPS is lightweight, has excellent thermal insulation properties, and is resistant to moisture. It is widely used in construction due to its durability and ease of installation. EPS is not biodegradable and can have environmental impacts if not properly managed.

Advantages:

- Lightweight: Easy to handle and install.
- Excellent insulation: Very low thermal conductivity.
- Moisture-resistant: Does not rot and is resistant to mold.

Disadvantages:

- Non-biodegradable: Can release microplastics to the environment, especially during construction and disposal.
- Flammable: Can melt and release toxic fumes at high temperatures.

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Aerogel

Aerogel is a highly porous and lightweight material known for its exceptional thermal insulation properties. It is composed of a gel in which the liquid component has been replaced with gas, resulting in a material with very low thermal conductivity. Aerogel is often used in high-performance insulation applications, including space exploration and advanced building materials. Its high cost can be a limiting factor for widespread use. In this context, Figure 22 shows the sample of aerogel delivered to AIT and prepared for characterization. The sample is Ultrawool 650, which is an aerogel insulation material.

Advantages:

- Exceptional insulation: Extremely low thermal conductivity.
- Lightweight: Very low weight with high performance.
- Versatile: Can be used in various applications, including space exploration.

Disadvantages:

- High cost: Very expensive compared to other insulation materials.
- Fragile: Can easily break or be damaged.

Figure 22: A sample of Aerogel Ultrawool 650 prepared for measurements.

Vacuumed tiles

Vacuum Insulated Panels (VIPs) consist of a core material enclosed in a vacuum-sealed envelope. The vacuum significantly reduces heat transfer, making VIPs one of the most efficient insulation materials available. They are used in applications where space is limited, and high thermal performance is required. VIPs are more expensive than traditional insulation materials but offer superior insulation performance. Figure 23 shows the sample delivered to AIT and characterized in the Thermophysics lab.

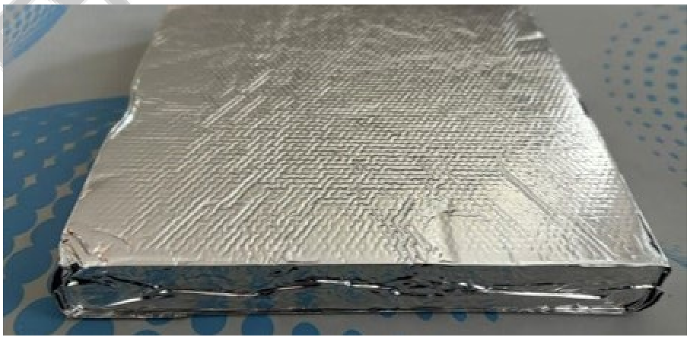

Figure 23: A sample of vacuum insulation panel.

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Advantages:

- Superior insulation performance: Very low thermal conductivity due to the vacuum.
- Space-saving: Provides high insulation performance with minimal thickness.
- Durable: Long lifespan with proper handling.

Disadvantages:

- High cost: More expensive than conventional insulation materials.
- Sensitive: Can lose insulation performance if the vacuum is compromised.

3.3.2 Measurements

Accurate thermal conductivity measurements are essential for evaluating the performance of insulation materials used in sTES systems. This section presents the thermal conductivity results for five distinct insulation materials: woodchips, sawdust, coconut fibers, Ultrawool 650, and vacuumed tiles. These materials were selected to represent a diverse range of insulation options, spanning natural, recycled, and advanced synthetic materials, each with unique thermal and mechanical properties.

The measurements provide critical insights into the suitability of these materials for sTES applications, particularly under conditions of temperature fluctuations and long-term exposure. The results highlight the comparative thermal performance of each material, shedding light on their potential roles in achieving effective thermal resistance while promoting sustainability and cost-efficiency in energy storage systems.

Herein, thermal conductivity measurements were conducted using a heat flow meter (HFM) that are a widely recognized and standardized method for evaluating the thermal performance of insulation materials. This technique operates by placing a sample material between two parallel plates: a hot plate and a cold plate. The plates impose a steady temperature gradient across the material, inducing heat flow from the hot to the cold side. Figure 23 shows the heat flow meter device used for thermal conductivity measurements at the AIT-Thermophysics lab and its working principle.

(a) Heat flow meter device used for thermal conductivity measurements at the AIT-Thermophysics lab.

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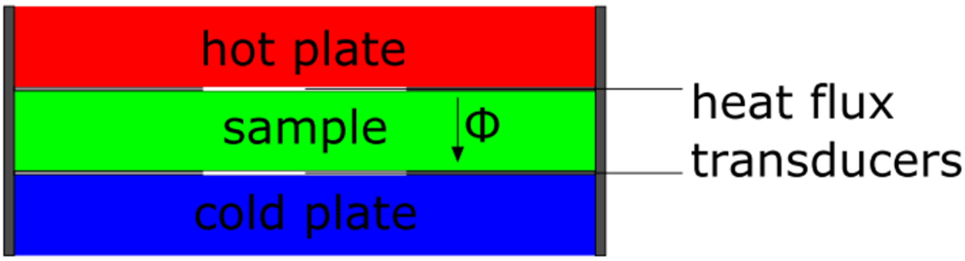

(b) Operation principle of HFM device.

Figure 24: Heat flow meter device for thermal conductivity measurements.

Sensors embedded within the plates measure the heat flux and the temperature difference across the sample. Using Fourier's law of heat conduction, the thermal conductivity is calculated as:

$$\lambda = \frac{q}{\Delta T} \cdot \frac{d}{A} \qquad \text{3-1}$$

Where:

- λ: Thermal conductivity (W/m K),
- q: Heat flux (W),
- ΔT: Temperature difference (K),
- d: Sample thickness (m),
- A: Cross-sectional area (m^2).

This method is precise, efficient, and suitable for testing a variety of materials, including natural fibers, composites, and advanced synthetic insulations. The repeatability and standardized nature of HFM testing make it ideal for comparing the thermal performance of diverse insulation materials, as in this study.

To ensure accurate and reliable thermal conductivity measurements, a rigorous testing protocol was followed for each material using the HFM. The procedure included the following steps:

1. Calibration: HFM was calibrated using a reference material, glass wool, with a known thermal conductivity of 0.0324 W/m K at 20 °C.
2. Validation: Calibration was validated by testing the reference material, ensuring deviations were below 3 %.
3. Measurement: Thermal conductivity measurements were performed on prepared samples.
4. Recalibration: Additional calibration was conducted as needed during the measurement process to maintain accuracy.

While the measurement process included the following steps:

- Sample preparation: Multiple samples were prepared for each material. Sawdust samples were packed in thin aluminum foil to maintain uniformity.
- Measurement positions: Samples were measured in various orientations to ensure consistency.

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- Pressure adjustment: Pressure was varied to achieve similar thicknesses across all measured samples, ensuring comparability.
- Lateral insulation: Lateral insulation was applied during measurements to minimize heat losses and improve accuracy.
- Temperature program: Measurements were conducted at three temperatures: 20 °C, 45 °C, and 70 °C, with a constant temperature difference of 20K between the hot and cold plates.

The testing was structured into three phases to comprehensively characterize the thermal conductivity of the materials under different conditions:

- Phase 1: Initial characterization
  - Compactness level: Minimal (as delivered, uncompressed).
  - Moisture level: Unknown, as received from the supplier.
- Phase 2: Influence of compactness
  - Compactness level: Varied between 10 %, 20 %, and 50 %.
  - Moisture level: Maintained constant to isolate the effect of compactness.
- Phase 3: Influence of moisture
  - Compactness level: Held constant.
  - Moisture level: Tested under extreme conditions (completely dry and saturated) and one intermediate state.

This structured approach ensured that the influence of both compactness and moisture on thermal conductivity could be independently assessed, providing valuable insights into the behavior of the materials under realistic and extreme conditions. However, the following measurement results are based on phase 1, whereas the other two phases are ongoing.

Wood chips

In total, eight measurements were carried out for two samples of wood chips to determine their thermal conductivity in its "as delivered" state. The physical properties of both samples were as follows:

- Weight: 233.3 g
- Density: 224.2 kg/m³ and 238.3 kg/m³
- Dimensions: 17 x 17 x 3.6 cm³ and 17 x 17 x 3.4 cm³

The tests were conducted without any additional preparation or modification to the sample, ensuring that the results reflected its initial, delivered condition. This approach provided a baseline characterization of the thermal performance for further analysis. Later, the samples were dried to observe the change in thermal conductivity. Therefore, three further measurements were carried out for both samples after drying.

Figure 25 shows the results of thermal conductivity measurements on the delivered and dried woodchips. The first two measurements on Sample 1 in its case “as delivered” showed high values for thermal conductivity and an increase in thermal conductivity as temperature increases from 20 °C up to 45 °C and, then, a drastic decrease as temperature rises to 70°C further. Therefore, it was decided to repeat the measurements and explore the thermal conductivity when the woodchips dried. Figure 25 shows, that wood chips material

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has an average thermal conductivity of 0.08 at 20 °C and decreases to 0.065 W/(m K) at a temperature of 70 °C.

The variation in thermal conductivity values (see Figure 25) can be attributed to several factors. Key influences include the characteristics of the samples such as the composition and type of wood, the dimensions of the wood particles (e.g., inhomogeneous particle sizes), and the orientation of the wood fibres, which affect the formation and distribution of air cavities within the material. Additionally, these cavities may trap moisture, increasing the effective thermal conductivity due to the impact of natural convection. The degree of compaction also plays a significant role, as higher compaction levels can reduce air cavities, altering the material's thermal performance.

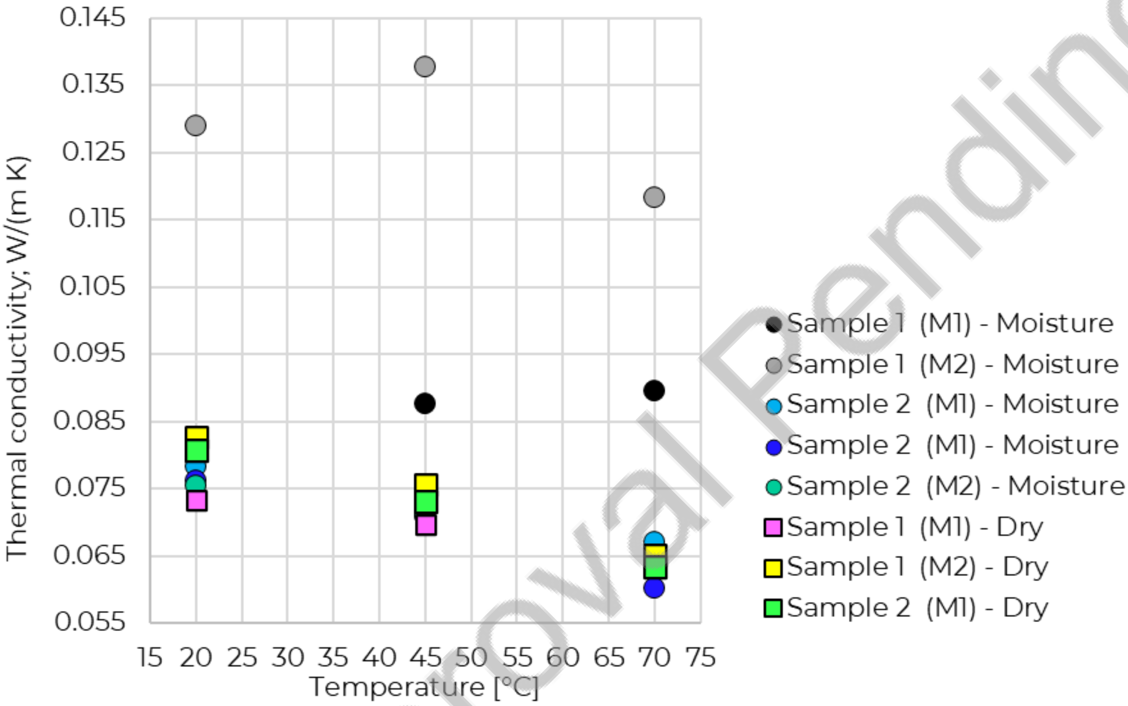

Figure 25: Measured thermal conductivity for wood chips under different conditions.

Coconut fibers

In total, five measurements were carried out for two samples of coconut fibers to determine their thermal conductivity in its "as delivered" state. The tests were conducted without any additional preparation or modification to the sample, ensuring that the results reflected its initial, delivered condition. This approach provided a baseline characterization of the thermal performance for further analysis.

Figure 26 shows the results of five thermal conductivity measurements on the delivered coconut fibres. The conclusion is, that coconut fibres material has an average thermal conductivity between 0.047 W/(m K) and 0.061 W/(m K) with a slight deviation of ± 0.0005 W/(m K) in the investigated temperature range.

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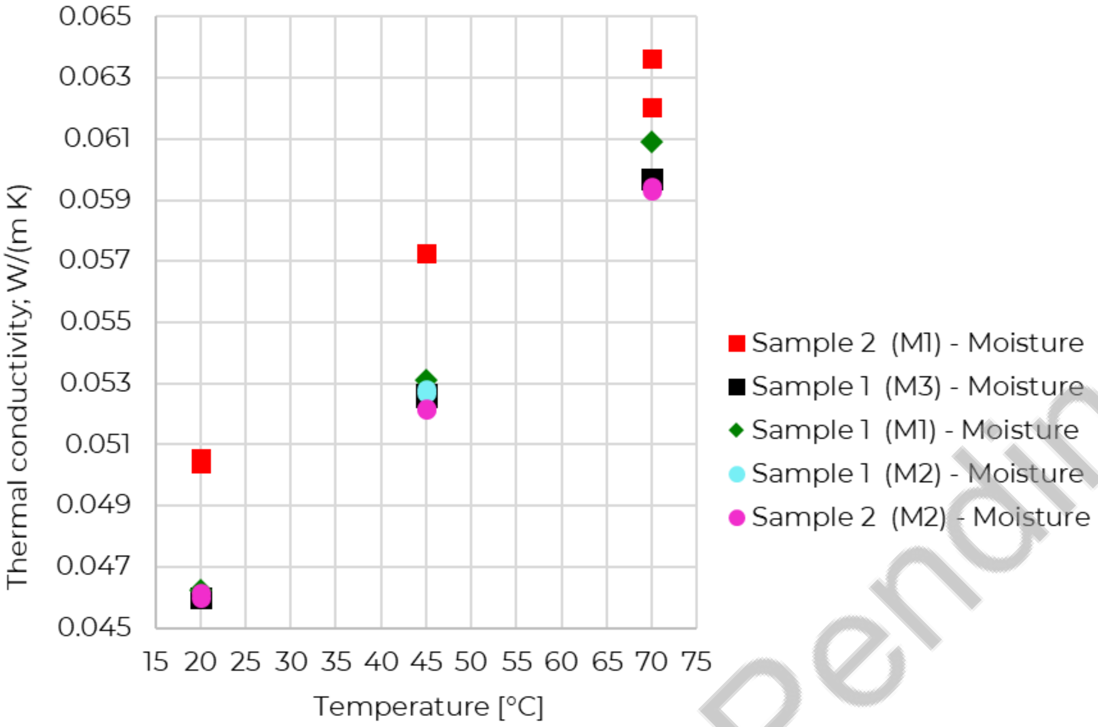

Figure 26: Measured thermal conductivity for coconut fibers under different conditions.

Aerogel – Ultrawool 650

Three measurements were carried out for two samples of Ultrawool 650 to determine its thermal conductivity in its "as delivered" state. The tests were conducted without any additional preparation or modification to the sample, ensuring that the results reflected its initial, delivered condition. This approach provided a baseline characterization of the thermal performance for further analysis.

Figure 27 shows the results of three thermal conductivity measurements on the delivered Ultrawool 650. The result is that sample 1 (M1) and sample 2 (M3) show similar thermal conductivity values at the temperature of 20 °C and 45 °C, whereas there is a slight deviation at a temperature of 70 °C. Notably, the first measurement of sample 2 (M1) shows higher values compared to the other two measurements. Yet, it can be held that Ultrawool 650 has an average thermal conductivity between 0.0163 W/(m K) and 0.0169 W/(m K) in the investigated temperature range.

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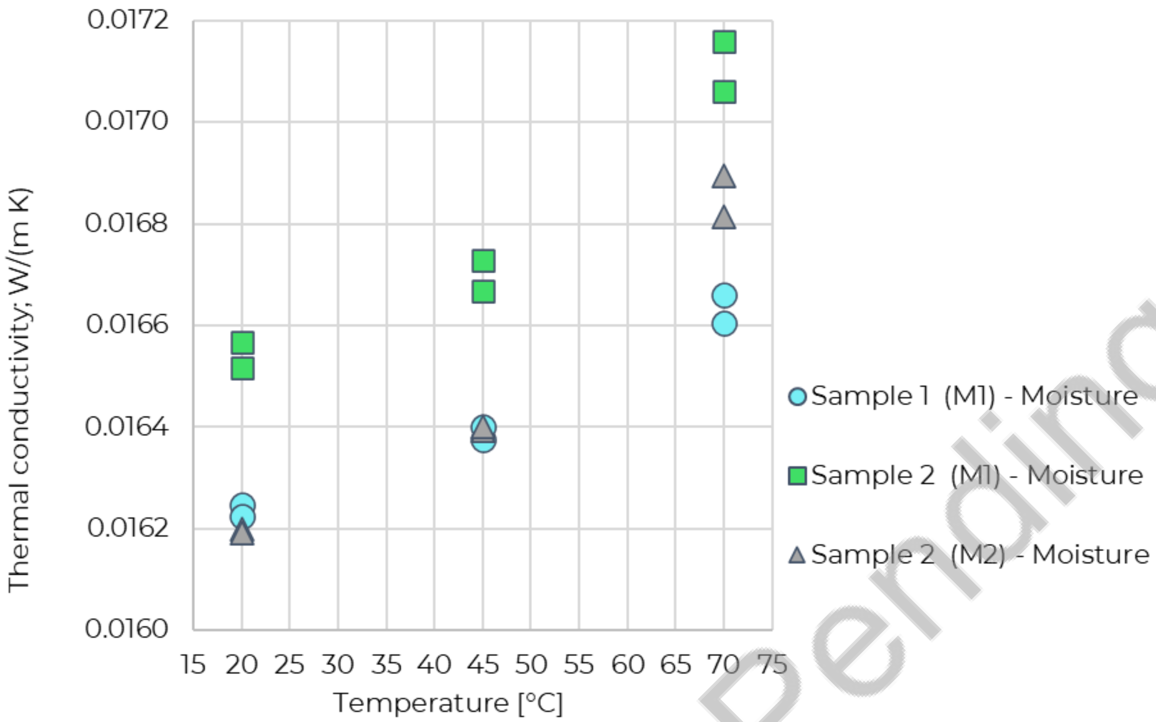

Figure 27: Measured thermal conductivity for Ultrawool 650 under different conditions.

Vacuumed tiles

Two measurements were performed on the delivered VIP sample to determine its thermal conductivity in its "as delivered" state. The sample's physical properties were as follows:

- Weight: 134.2 g
- Density: 220.4 kg/m³
- Dimensions: 16 × 16 × 2.38 cm³

The tests were conducted without any additional preparation or modification to the sample, ensuring that the results reflected its initial, delivered condition. This approach provided a baseline characterization of the VIP's thermal performance for further analysis.

Figure 28 shows the results of two thermal conductivity measurements on the delivered VIP sample. The material has a thermal conductivity ranging between 0.005 W/(m K) and 0.0069 W/(m K) in the investigated temperature range.

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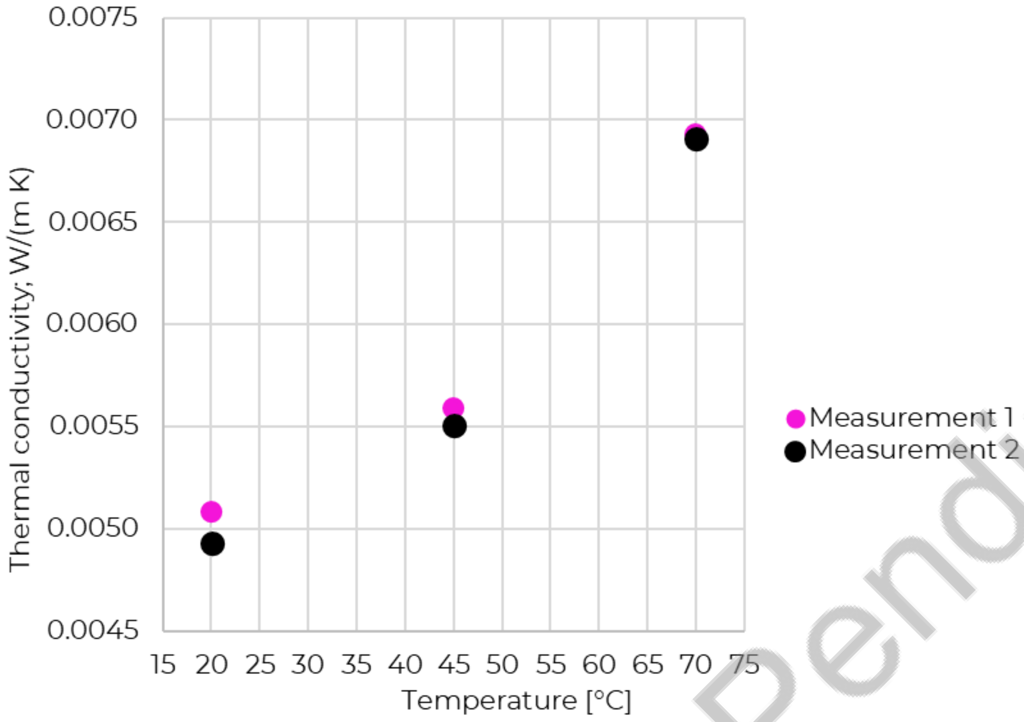

Figure 28: Measured thermal conductivity for VIP under the test conditions.

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3.3.3 Considered insulation options for incampus Reno-sTES

To achieve the lowest possible settlement and compression of the insulation layers, an insulation material with a high compressive strength must be selected for the floor and walls. Therefore, sustainable options (coconut fibers, wood chips, sawdust) are only considered for the top layer (lid) of the basins.

All basins are equipped with a High-Density Polyethylene (HDPE) sheet for sealing. The basic structure is in Figure 29. A protective mat, protective tile, and geotextile are used for further sealing and protection. The insulation layer is always located between the waterproofing membrane and the protective mat and can be varied.

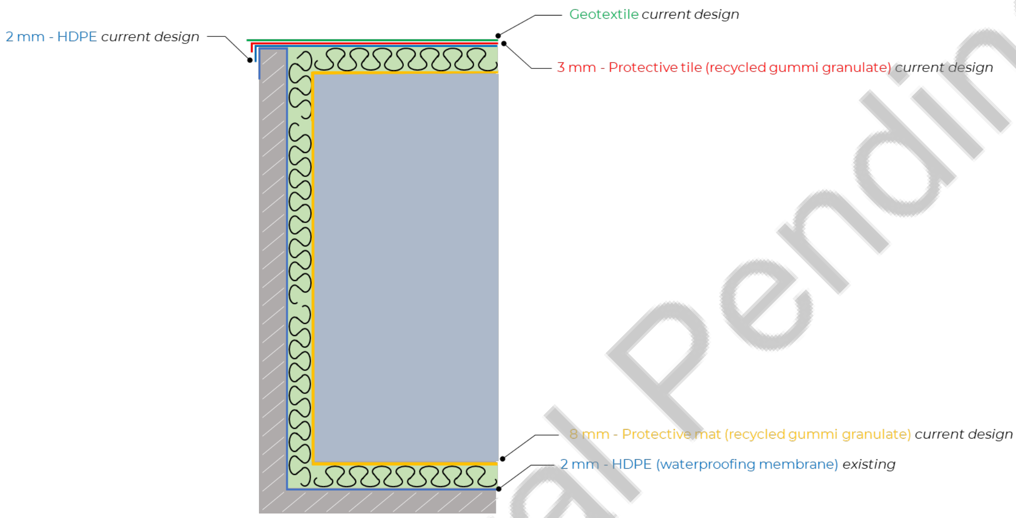

Figure 29: Sealing Design of Basins A, B, and C (Planungsgruppe M+M AG, 2024b).

Initially, the following design in Figure 30 for the insulation was considered for the basins (basic design):

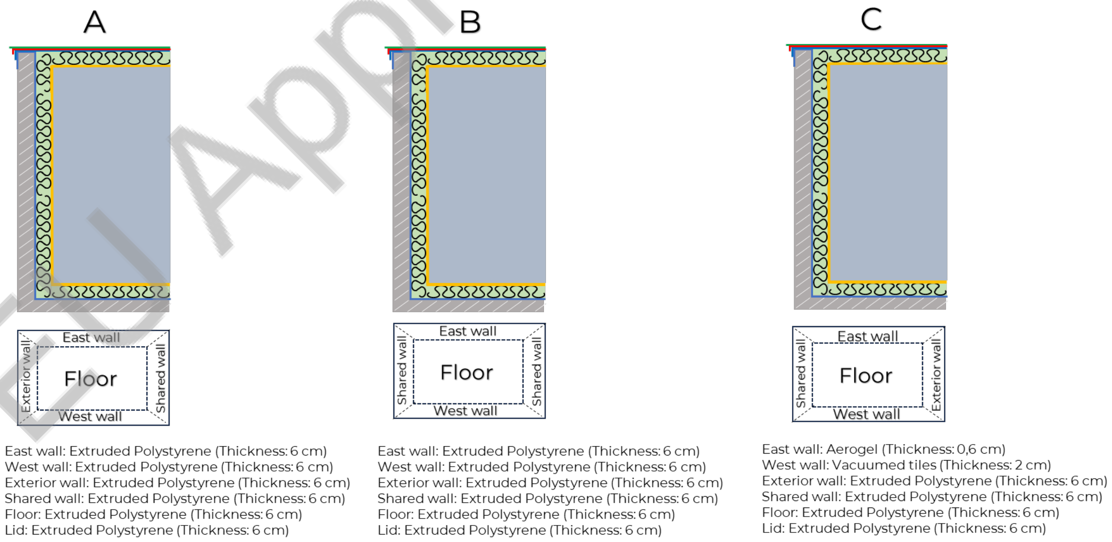

Figure 30: basic design insulation for basins A, B, and C (Planungsgruppe M+M AG, 2024b).

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Design Progress Insulation

Before the initial tender, the plan was to insulate all sides with XPS material (Option I1). The result of the tender process was that the costs far exceeded the budget. Therefore, options for cost reduction were developed.

One idea was to use natural insulation materials, which require significantly more volume to achieve the same insulation quality, thereby increasing sustainability and reducing filling costs due to the higher space requirement for insulation (Option I2). However, this option significantly reduces durability, as the intended arrangement of the sealing membranes cannot prevent water saturation and decay.

Further cost-saving potential was identified by not insulating the partition walls (Option I3). This option significantly reduces flexibility and efficiency, as the two adjacent basins can only be operated sensibly at similar temperatures.

Another option that offers significantly higher savings potential is to forgo insulation for the entire basin A (Option I4). This reduces flexibility only in that basin A can only be used effectively as a long-term storage at low temperatures, but at the same time increases flexibility because a basin with a strong thermal connection to the ground is available, which can be used to dissipate heat or utilize environmental energy. Additionally, the lack of insulation increases storage capacity.

The use of different insulation materials for the planned measurements in the installed state offers additional savings potential, which was investigated in combination with Option I4 as Option I5. However, discussions with project partners revealed that the importance of this aspect is generally given little significance.

These options and assessments were depicted in a value-benefit analysis.

3.3.4 Summary Insulation

Value benefit analysis

This chapter explains the evaluation and decision-making process for the various insulation options. The evaluation is based on a value-benefit analysis developed by PGMM.

To make a decision, this analysis was also conducted for the filling options and the design variant of the heat exchangers. These are explained in more detail in the following chapters 3.4.3 and 3.5.3. Table 4 shows the evaluation of the analysis and the criteria considered for the insulation assessment. The distribution of the weighting is derived by PGMM based on the defined key design aspects.

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Table 4: Value benefit analysis insulation (Planungsgruppe M+M AG, 2024b).

Aspects	*Description*	*Weighting factor*	*I1 (Basic Design)*	*Rating (0-10)*	*I2 (Natural Insulation Materials)*	*Rating (0-10)*	*I3 (No Insulation between A+B)*	*Rating (0-10)*	*I4 (No Insulation for Basin A)*	*Rating (0-10)*	*I5 (I4 and one type of insulation)*	*Rating (0-10)*
Durability	Long-term durability of insulation	30	XPS	10	Lid wood chips and sawdust, rest acc. I1	3	XPS	10	XPS	10	XPS	10
LCA	Carbon Emission balance from sourcing to disposal of materials is low.	20	new, not reused, products	5	Lid wood chips and sawdust, rest acc. I1	8	acc. I1	5	acc. I1	5	acc. I4	5
Capacity	Maximized energy capacity through low space consumption of insulation.	15	capacity 617 MWh@30K	9	capacity 550 MWh@30K	7	capacity 660 MWh@30K	10	capacity 680 MWh@30K	10	acc. I4	10
Flexibility sources	different basins can be operated on different temperature levels with low mutual influence.	30	all basins insulated	10	acc. I1	10	Higher heat transfer between basins A+B.	3	Different temperatures are still possible, Basin A only for low temperatures. But also useable as a heat sink.	10	acc. I4	10
Variety of Insulation materials	Usage of different insulation materials for in-situ measurement.	5	usage of aerogel and vacuum tiles for basin C	10	acc. I1	10	acc. I1	10	acc. I1	10	only on the type of insulation	0
		Usability value		8,70		7,05		6,75		9,00		8,50
		capex		100%		129%		97%		61%		51%

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Figure 31 depicts the evaluation of the different insulation options in terms of usability and investment costs. It is noticeable that option I2 performs the worst in both criteria. In this variant, wood chips are used for the insulation of the lid, which reduces the storage capacity and simultaneously increases the investment costs. Another important aspect is that the durability of wood chips is significantly impaired by moisture absorption.

In comparison to the other variants, option I5 shows the best relationship between investment costs and usability. Here, insulation is completely omitted in Basin A, while only one insulation material (XPS) is used in Basins B and C. This variant is the most cost-effective in terms of investment costs. Usability is only minimally affected.

Additionally, the analysis shows that the use of XPS in Basins B and C offers a good balance between cost and performance. XPS is moisture-resistant and durable, making it a suitable choice for insulation.

Finally, based on the table-defined usability value, it can be stated that within option I5, the costs can be substantially reduced without accepting significant restrictions.

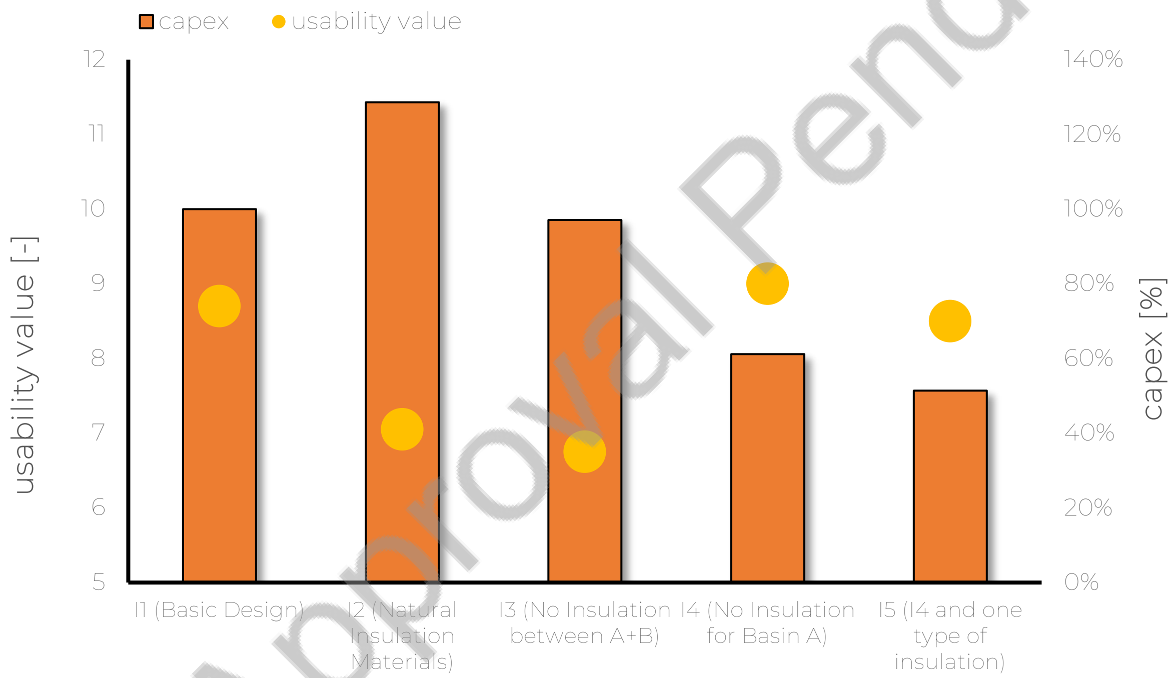

Figure 31: Comparison of capex and usability value of the insulation options (Planungsgruppe M+M AG, 2024b).

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3.4 Filling

3.4.1 Material

In the course of the renovation project on the site, river gravel was extracted that can be used in the incampus demonstrator. This amounts to approximately 5,500m³. The original plan was to fill all the basins with gravel. Given the high cost of the overall package, as with the insulation, cheaper alternatives for the filling material had to be found. The requirements for the filling material are:

1. structural integrity
2. high porosity
3. installation of plastic pipes must be possible.

The costs of filling materials can vary greatly and depend on various factors. One of the factors is the region in which the materials are procured. In regions with high availability and production, prices are generally lower. Conversely, in regions with limited availability, costs can be considerably higher.

Another decisive factor is the current market situation. Prices for filling materials are subject to fluctuations that are influenced by supply and demand. In times of high demand or supply shortages, prices can rise significantly. It is therefore advisable to monitor market developments regularly and consider alternative procurement sources if necessary.

During investigations also uncommon materials such as hollow plastic spheres or infiltration structures ("Rigolen") were considered as filling material but not investigated further due to high costs.

The filling materials identified that meet mostly these requirements are described below.

Gravel

Gravel is a naturally occurring material formed by the weathering and erosion of rock. It has a rounded shape and is often used in construction projects due to its good drainage properties (GRA-ROCK, 2019).

- Grain Size: 2 mm to 64 mm
- Density: 1,600 to 1,800 kg/m³
- Drainage Capability: Excellent drainage properties
- Strength: Very stable and resistant to high loads
- Specific Heat Capacity: Approximately 800 J/kg·K (The Engineering ToolBox, 2003; Minerals Education Coalition, 2024)
- Costs: 62.98 €/m³ (Planungsgruppe M+M AG, 2024c)
- Porosity 30 vol%

Sand

Sand consists of fine, granular particles formed by the weathering of rock. It is often used as a filling material because it is easy to compact and has good drainage properties (Dirt Connections, 2019).

- Grain Size: 0.075 mm to 4.75 mm.
- Density: 1,450 to 1,600 kg/m³.
- Compactability: Easily compactable and provides a stable base.

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- Water Absorption: Moderate water absorption capability
- Specific Heat Capacity: Approximately 830 J/kg·K (The Engineering ToolBox, 2003; Minerals Education Coalition, 2024)
- Costs: 42.71 €/m³ (Planungsgruppe M+M AG, 2024c)
- Porosity 40 vol%

Crushed Rock

Crushed rock is produced by crushing larger rock fragments into smaller pieces. It has an angular shape and is frequently used in construction projects due to its high stability and load-bearing capacity (Koche, 2024).

- Grain Size: 0.5 mm to 50 mm
- Density: 1,600 to 2,000 kg/m³
- Strength: High strength and stability
- Wear Resistance: Very resistant to wear
- Specific Heat Capacity: Between 800 J/kg·K and 2000 J/kg·K, depending on the exact composition (The Engineering ToolBox, 2003; Minerals Education Coalition, 2024)
- Costs: 52.46 €/m³ (Planungsgruppe M+M AG, 2024c)
- Porosity 45 vol%

3.4.2 Filling options

The sharp-edged crushed rock is not suitable for the direct installation of the heat exchanger pipes, so reasonable combinations of gravel, sand, and crushed rock had to be developed, in which the heat exchanger pipes and insulation are protected, and the existing gravel can be used (Table 5).

Table 5: Filling variations with different materials (Planungsgruppe M+M AG, 2024b).

Basin	*Option F1*	*Option F2*	*Option F3*
A	100 % Water-saturated Gravel	1,0 m water-saturated sand and the rest is water-saturated gravel	Combination of Sand, Gravel, and Crushed rock
B	100 % Water-saturated Gravel	1,0 m water-saturated sand and the rest is water-saturated gravel	Combination of Sand, Gravel, and Crushed rock
C	100 % Water-saturated Gravel	1,0 m water-saturated sand and the rest is water-saturated gravel	Combination of Sand, Gravel, and Crushed rock

These filling options are shown in detail via a sectional view (Figure 32 - Figure 35).

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Option F1 (basin A, B, and C)

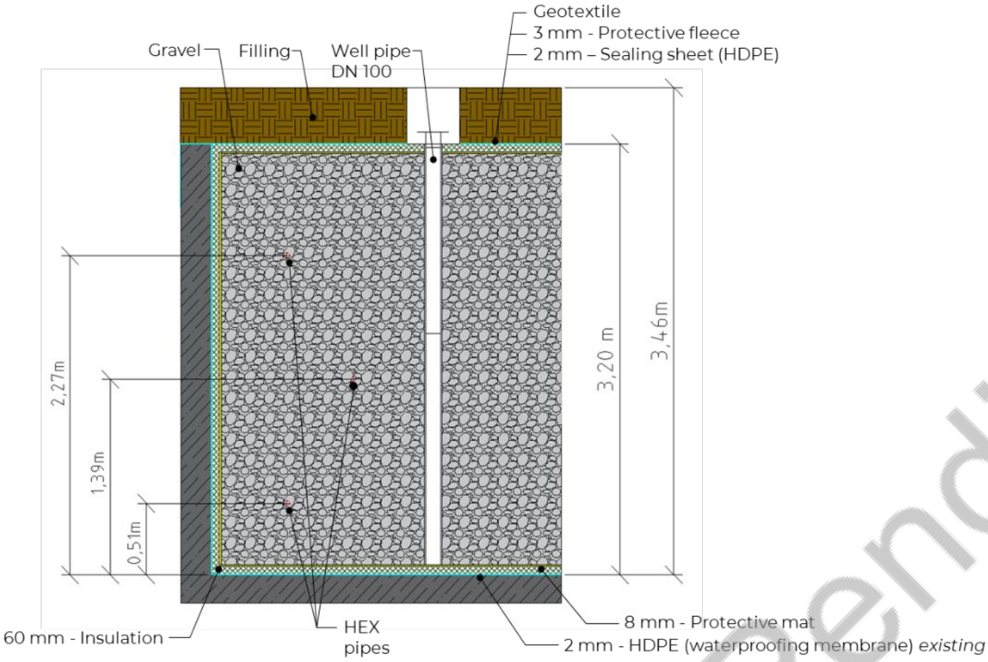

Figure 32: Filling option F1 for basins A, B, and C (Planungsgruppe M+M AG, 2024b).

Option F2 (basin A, B, and C)

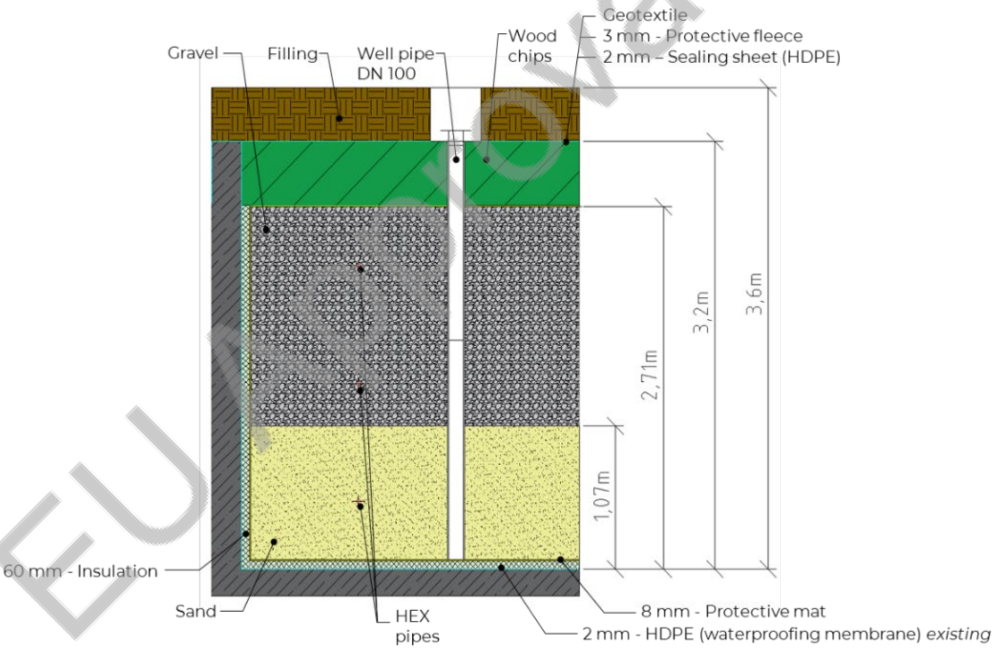

Figure 33: Filling option F2 for basins A, B, and C. (Planungsgruppe M+M AG, 2024b).

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Option F3 (basin A, B, and C)

Basin A (no insulation):

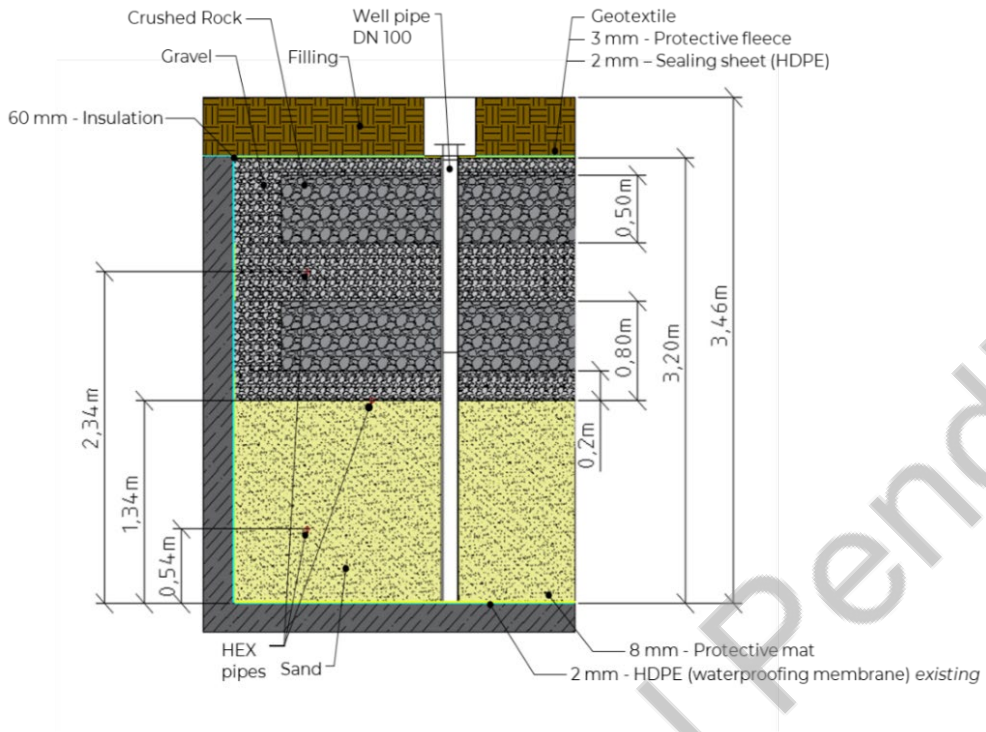

Figure 34: Filling option F3 for basin A (Planungsgruppe M+M AG, 2024b).

Basin B and C (with insulation):

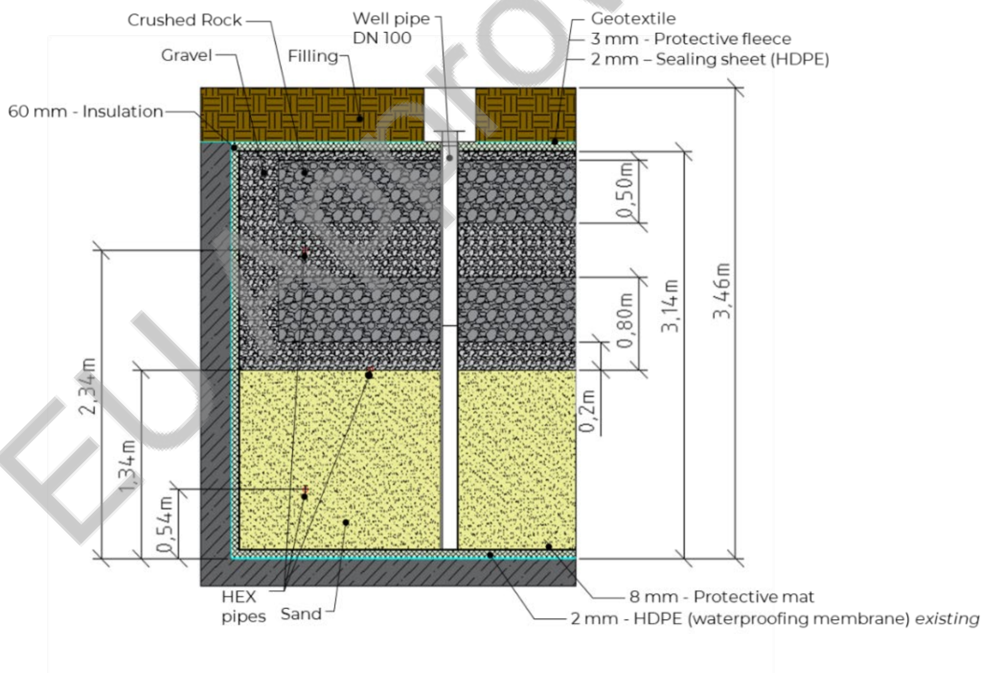

Figure 35: Filling option F3 for basins B and C (Planungsgruppe M+M AG, 2024b).

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3.4.3 Summary Filling

Value benefit analysis

The value-benefit analysis was conducted to assess the different filling options in terms of their energy capacity, durability, and investment costs. The evaluation is based on the previously selected insulation variant "I5" In chapter 3.3.3. The previously mentioned filling options were examined as listed in Table 6.

Table 6: Value benefit analysis fillings. (Planungsgruppe M+M AG, 2024b).

aspect	*description*	*weighting factor*	*F1 (100% gravel – Basic Design)*	*Rating (0-10)*	*F2 Gravel & Sand*	*Rating (0-10)*	*F3 Gravel, Sand & Crushed rock*	*Rating (0-10)*
Capacity	Maximized energy capacity through high water share of fillings.	50	capacity 636 MWh@30K	8	capacity 653 MWh@30K	9	capacity 680 MWh@30K	10
Durability, static integrity	long term durability of materials for filling	50	Gravel	10	Gravel & Sand	10	Gravel, Sand, Crushed rock	10
		Usability value		9,00		9,50		10,00
		Capex		100%		90%		80%

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The weighting of the criteria and the evaluation were carried out by PGMM. Various aspects were considered to make an informed decision. The allocation of points is based on the data collected and the specific properties of the materials used.

In the evaluation of investment costs, option F1 is used as the baseline design. This option serves as a reference since it was identified as the first and most expensive variant. By analyzing this baseline option, the costs and benefits of the other filling options could be better assessed.

The weighting of the criteria relates to the energy capacity and durability of the materials. These properties were each weighted with a factor of 50. The energy capacity was considered to ensure that the fillings allow for maximum energy storage. The durability of the materials was also considered to ensure the long-term stability of the fillings.

Based on this evaluation, further optimizations of the filling options were carried out. The goal was to find the best possible combination of high energy capacity and low investment costs. Various material combinations were tested and evaluated to identify the most efficient and cost-effective solutions.

Figure 36 shows the overall evaluation of the filling options. The analysis shows that option F3 (without insulation of tank A) has the best ratio of utility value to investment costs. Therefore, this option was selected.

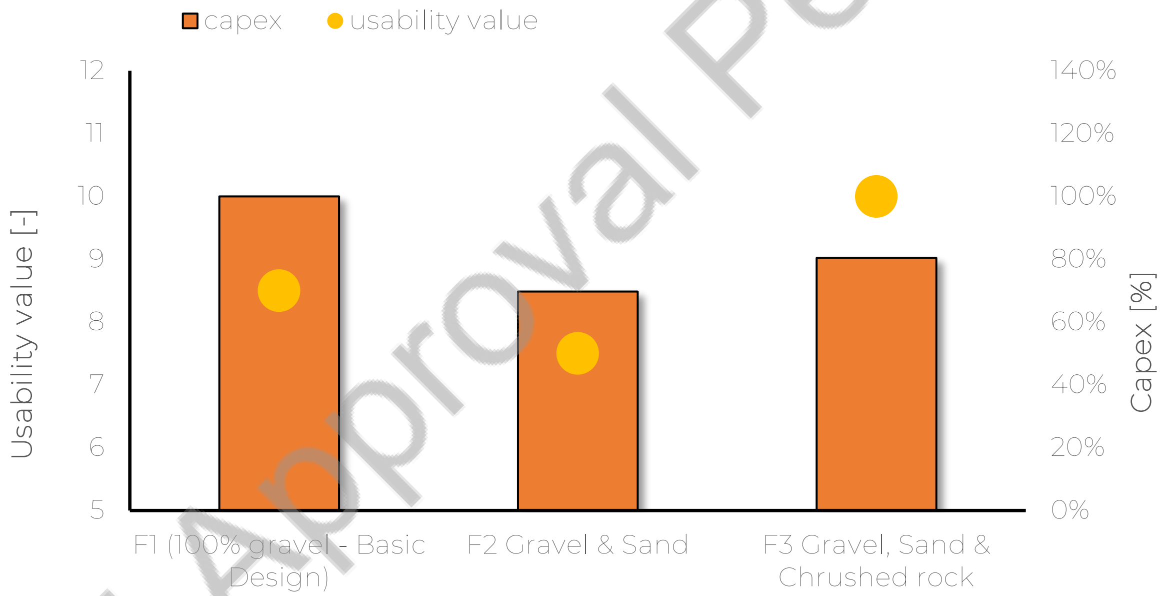

Figure 36: Comparison of capex and usability value of the filling options. (Planungsgruppe M+M AG, 2024b).

The analysis shows that the use of alternative filling materials in variant F3 has reduced costs and increased storage capacity.

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3.5 Heat exchanger

In indirect charging and discharging, heat exchangers are integrated into the sTES system to transfer thermal energy from the source to the storage medium, accommodating a variety of media such as gravel or sand. This approach is particularly beneficial when direct integration between the thermal energy source and the storage medium is impractical due to differences in material properties. Heat exchangers, either embedded within or placed externally to the sTES, provide flexibility in system design. For the Reno-sTES within the INTERSTORES project, the first approach to embedding heat exchangers in sTES will be the mechanism for charging and discharging.

3.5.1 Design options

The Tichelmann configuration — also known as the reverse return flow design — is a widely recognized hydraulic approach that ensures uniform fluid flow across multiple parallel branches. This concept is particularly effective for maintaining consistent heat transfer and optimizing system performance. Figure 37 and Figure 38 show the proposed design options H1 and H2 – Tichelmann double-sided for HEX pipe within sTES.

The Tichelmann layout balances the flow by ensuring that the supply and return pipes for each branch are of equal total length. This arrangement results in identical pressure drops across all branches, promoting uniform fluid distribution. Such balance reduces the likelihood of flow imbalances, which could otherwise cause uneven thermal energy charging or discharging.

Advantages

- Uniform heat distribution: Ensures consistent performance across the storage system.
- Improved system stability: Minimizes risks like localized overheating or disruptions in thermal stratification.
- Reduced energy costs: Balanced flow decreases the energy needed for pumping.

Disadvantages

- Complexity in design: Requires precise pipe layout and accurate balancing, increasing installation difficulty.
- Higher initial investment: The need for additional piping and components raises upfront costs.
- Limited adaptability: Adjusting the system to handle variable flow rates effectively can be challenging.

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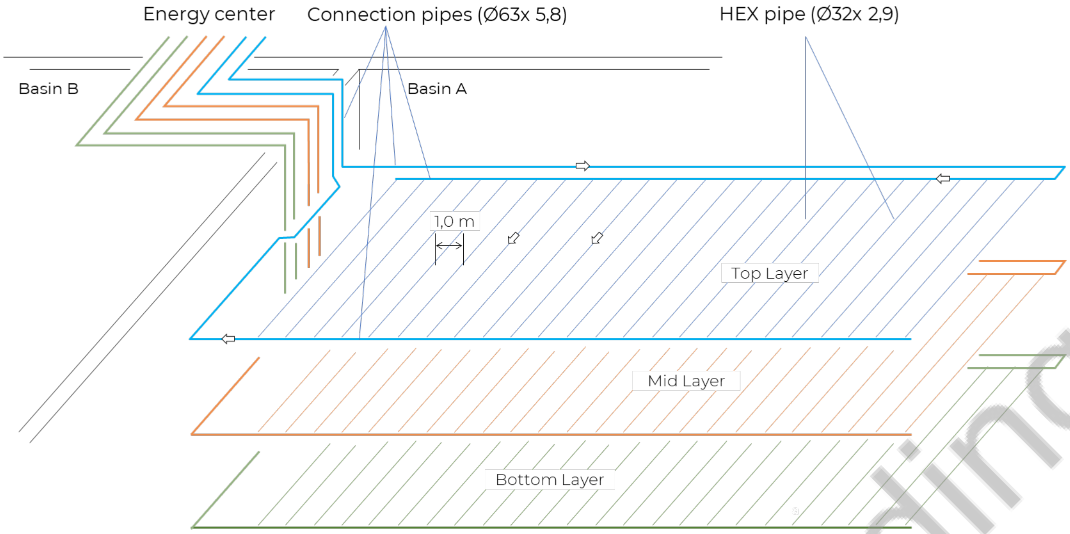

Figure 37: HEX pipe – Option H1 ("Tichelmann double-sided") (Planungsgruppe M+M AG, 2024b).

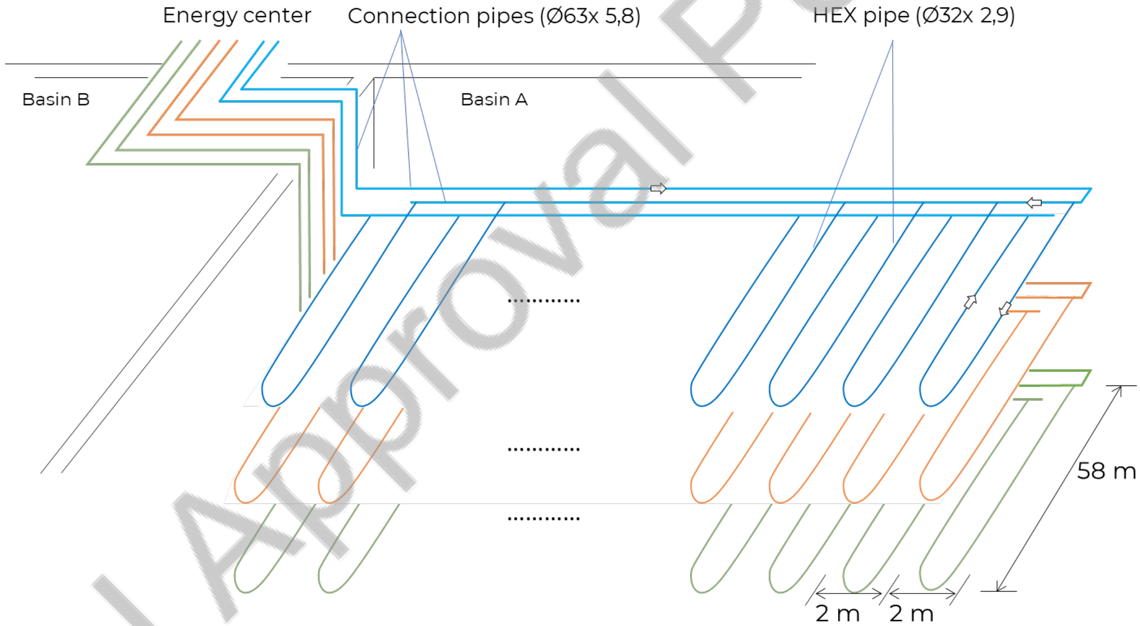

Figure 38: HEX pipe – Option H2 ("Tichelmann single-sided") (Planungsgruppe M+M AG, 2024b)

Another significant drawback of the design option H1 is its susceptibility to interruptions in the event of damage. A single compromised pipe can necessitate the complete cessation of charging or discharging operations, disrupting system functionality. To overcome this limitation, an alternative design has been introduced, offering improved robustness and the ability to maintain partial operation even when damage occurs. Accordingly, Figure 39 shows a new design option – H3 to overcome this issue.

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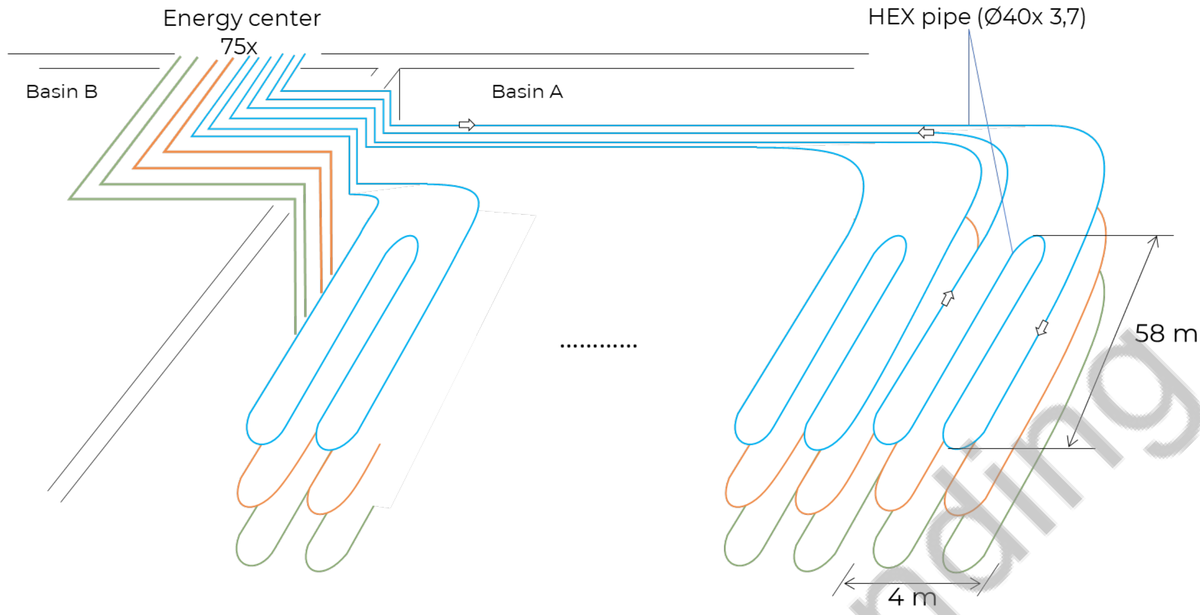

Figure 39: HEX pipe – Option H3 ("Loops"). (Planungsgruppe M+M AG, 2024b).

To find the optimal design for HEX in sTES, it is decided to develop numerical models in COMSOL Multiphysics to simulate the designs and understand their performance. These models were calibrated against detailed CFD models developed in ANSYS–Fluent. The numerical simulations focused on Basin C at incampus as it is the core of the INTERSTORES project.

3.5.2 Simulation result

The models simulated Basin C with a total volume of 5,280 m^3 and a total height of 3.2 m. It is assumed that the basin is equipped with a top insulation thickness of 50 cm and a U-value of 0.16 W/(m^2 K), whereas the bottom insulation is set to 6 cm of EPS. This eventually reduced the total effective height to 2.64 m. Figure 40 depicts the sectional view of the HEXs embedded within sTES – Basin C. Therein, the dimensions and relevant distances are also shown. These aspects were considered in the simulation models. Furthermore, the simulations investigated the charging phase in a stationary mode focusing on understanding the impact of significant design aspects on the thermo-hydraulic performance of HEX. Therefore, it is assumed that the charging temperature is set to 60°C, while the volumetric flow rate ranges between 0.25 l/s and 20 l/s.

The first set of simulations focused on pipes with an outer diameter of 24 mm, a distance of 1 m, and a total number of 26 pipes for each level. The distributor has an outer diameter of 125 mm. During the simulations, it was found that it is crucial to maintain the following constraints:

$$A_{\text{distributor}} = n \cdot A_{\text{pipe}} \tag{3-2}$$

The violation of the upper constraint might lead to imbalanced flows within the pipes resulting in a concentration of thermal energy on a single side of Basin C, whereas the rest remains unchanged. Therefore, this constraint remains valid for the following cases as well.

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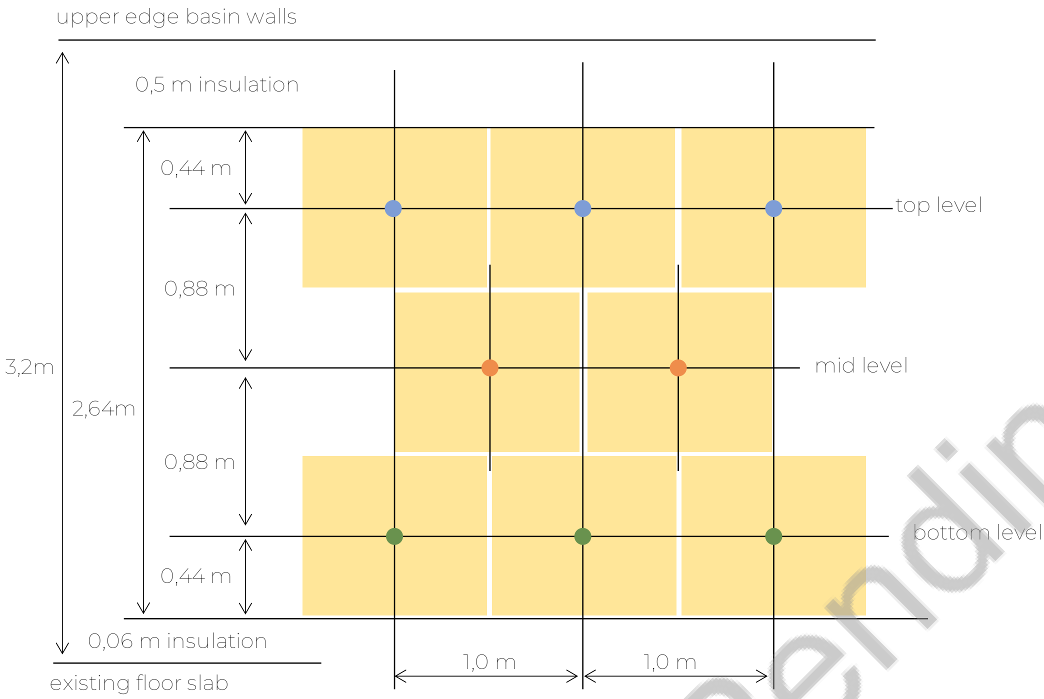

Figure 40: Sectional view of embedded HEXs following design H1 in Basin C.

Figure 41 shows the results of the numerical simulation for the three levels of heat exchange (top, mid, and bottom). Therein, the inlet temperature is set to 60°C, whereas the outlet temperature is a function of the flow rate passing through pipes. As the flow rate increases from 0.25 l/s up to 20 l/s for each level, the outlet temperature increases significantly for all levels. The top level shows the lowest outlet temperature due to the imposition of top thermal losses with a significantly large heat exchange area compared to the bottom one. As the flow rate increases beyond 4 l/s, the difference between inlet and outlet temperatures becomes marginal and eventually vanishes.

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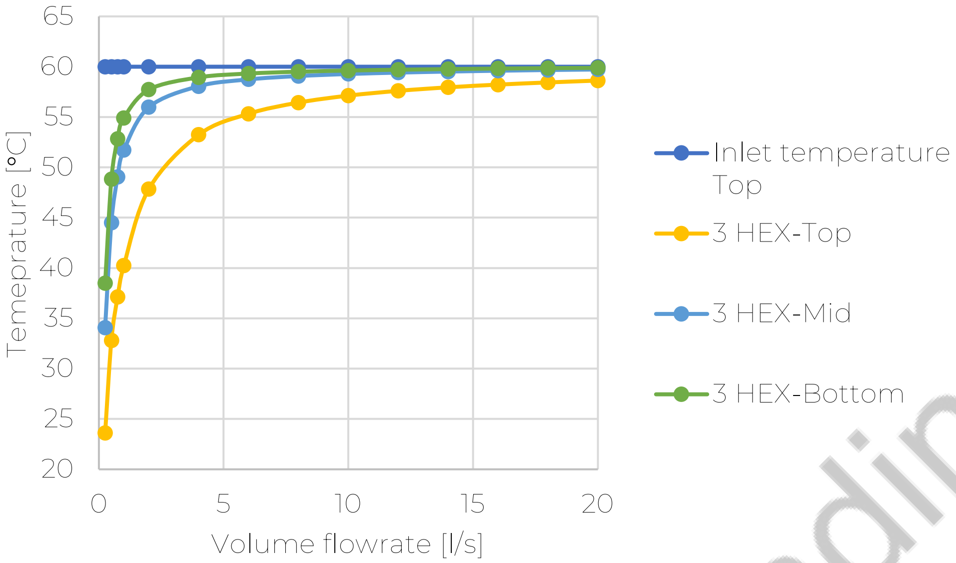

Figure 41: Inlet and outlet temperatures for the Tichelmann design H1.

The pipes show an increase in the pressure drop (i.e. inlet pressure minus outlet pressure) when the flow rate for a single level of heat exchange is increased. The pressure drop remains similar for each level due to the application of similar boundary conditions (Figure 42).

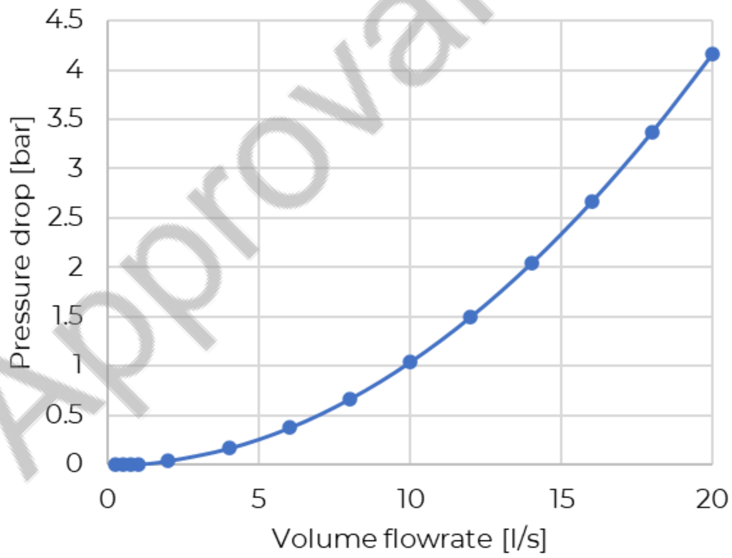

Figure 42: Pressure drop in each level of heat exchange for the Tichelmann design H1.

In a later stage, it was decided to investigate the impact of heat exchange levels on the thermo-hydraulic performance. Figure 43 shows a comparison of the impact of heat exchange levels considering the heat exchange rate – the heat transfer from the heat carrier to the storage medium of sTES. Therein, it is clear that the use of two heat exchange levels with either top and bottom or top and mid shows a close performance to that of three heat exchange levels, whereas the use of mid and bottom heat exchange levels decreases the

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amount of heat exchange rate. As for the hydraulic performance, the pressure drop remains unchanged since the operation boundary conditions are constant.

Later, the number of pipes within each level was also investigated to find out the optimum number. Herein, the general assumptions remain unchanged, while the distance between the pipes increases or decreases following the number of pipes. Figure 44 shows the results for four cases considering several pipes from 25 up to 28. Therein, it can be seen that the increase in pipe numbers results in a marginal increase in the heat exchange rate, while the heat exchange rate becomes almost similar for the flow rate range of 0.25 l/s up to 1 l/s. Therefore, this should be further subject to a techno-economic investigation using transient simulations to allocate the optimal number.

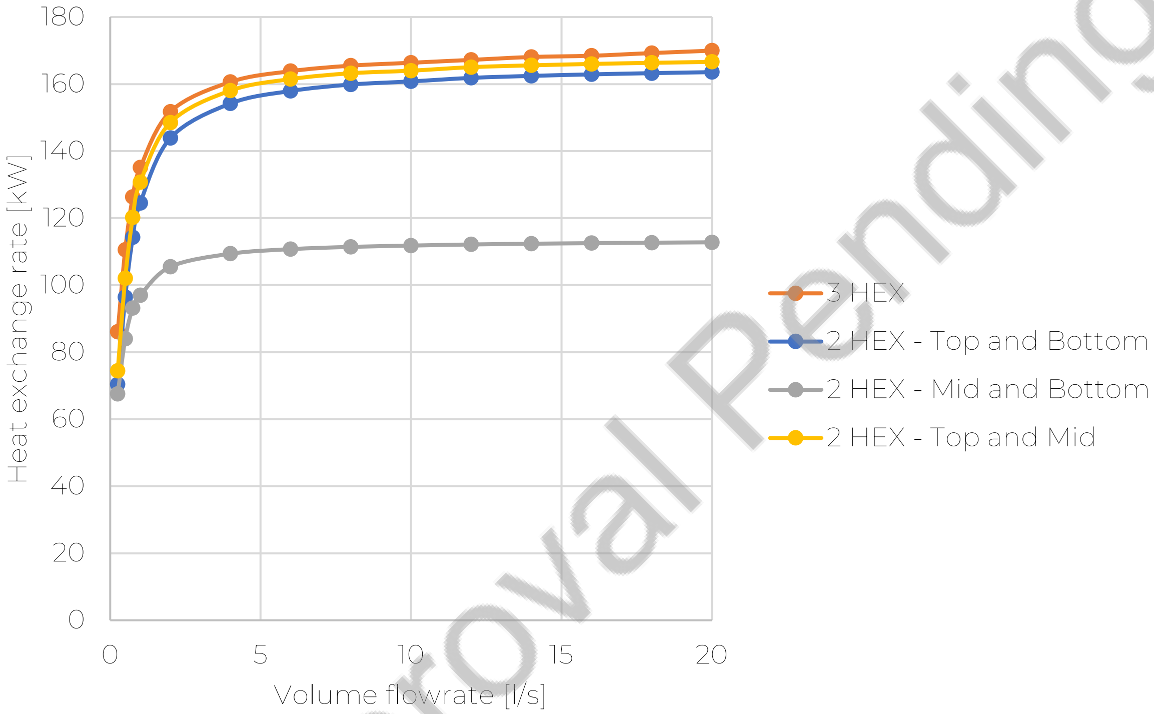

Figure 43: Comparison of heat exchange rate under different numbers of heat exchange levels.

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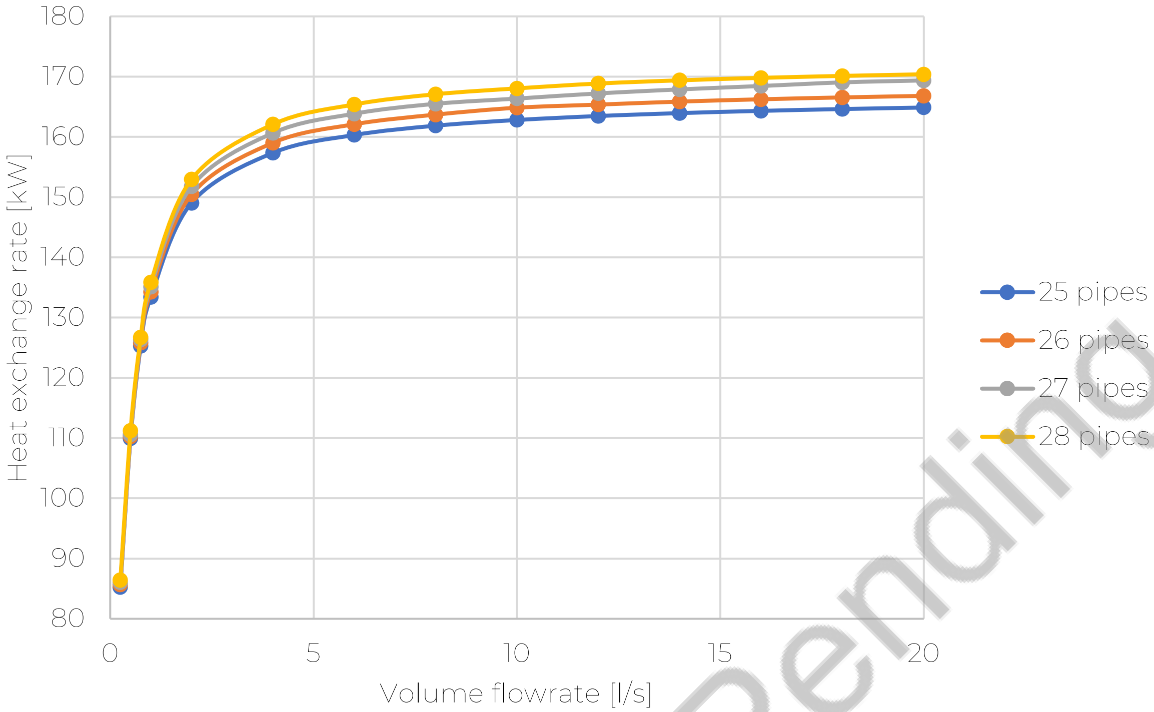

Figure 44: Impact of pipe number on the heat exchange rate.

Further simulation cases focusing on the optimization of the design H1 were conducted. However, the main disadvantage of the H1 design remains highlighted as the damage of a single pipe might lead to the full stop of the entire heat exchange level and high maintenance costs. Therefore, it is important to find an alternative to this design. Subsequently, design H3 emerged as a promising alternative to this design as it allows the operators of sTES to replace a single loop when damaged without a full operation stop for the entire heat exchange level.

In this context, Figure 45 compares the heat exchange rate of Tichelmann's design H1 against Tichelmann's design H3. Therein, design H3 brings more advantages as it allows for more heat exchange rate leading to more effective heat exchange compared to that of design H1. This can be well understood since the total surface area for H3 is 491.44 m^2, whereas the design H1 has a surface area of 319.18 m^2. Moreover, Figure 46 shows a comparison of the pressure drop along the heat exchanger pipes. It can be seen that H3 has more pressure losses compared to H1, which can be attributed to the total equivalent length of heat exchange pipes. In this regard, H1 has a total length of 4,254.6 m, whilst H3 has a total length of 4,798.4 m.

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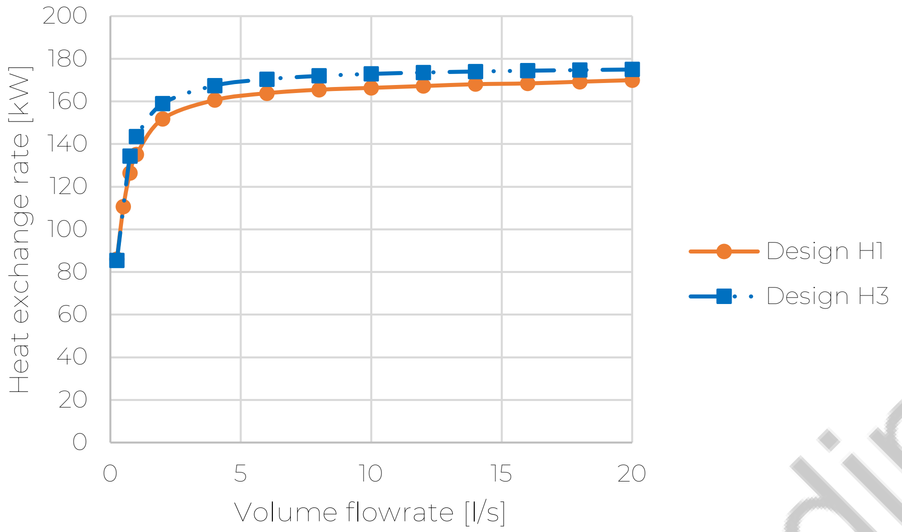

Figure 45: Comparison of heat exchange rate for both Tichelmann's designs H1 and H3.

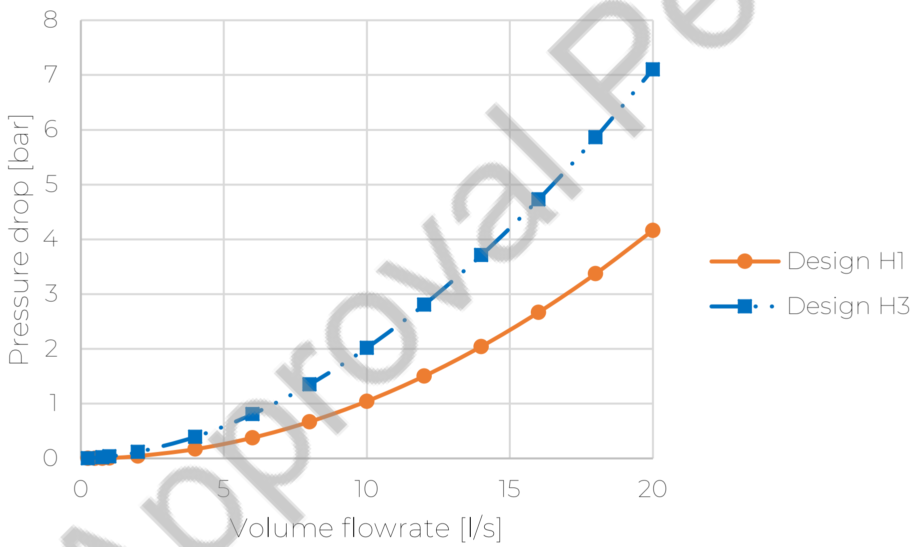

Figure 46: Comparison of pressure drop for both Tichelmann's designs H1 and H3.

3.5.3 Summary Heat exchanger

Value benefit analysis

The evaluation of the design options was carried out using a value-benefit analysis (see Table 7). This analysis helped to objectively compare the advantages and disadvantages of each option and make an informed decision. The criteria for the evaluation included heat transfer efficiency, pressure loss, installation costs, and fast loading and unloading.

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Table 7: Value benefit analysis Heat exchanger (Planungsgruppe M+M AG, 2024b).

Aspects	*Description*	*Weighting factor*	*Option H1 ("Tichelmann double sided")*	*Rating (0-10)*	*Option H2 ("Tichelmann single sided")*	*Rating (0-10)*	*Option H3 ("Loops")*	*Rating (0-10)*
HEX Durability	Durability regarding the durability of materials and regarding in case of emerging of cracks at random locations.	30	A single crack at a random location will corrupt the whole usability of a basin.	1	A single crack at a random location will corrupt the whole usability of a basin.	1	A single crack at a random location will only corrupt a single loop.	10
HEX surface	Capability for fast charge and discharge cycles through maximized HEX- surface.	20	HEX surface 1,440m²	8	acc. D1	8	HEX surface 2,100m²	10
HEX distribution	Capability for fast charge and discharge cycles through even local distribution of HEX within the storage.	20	3 layers with spacing 1 m	10	acc. D1	10	acc. D1	10
Fast loading/ unloading	Capability to handle high volume flow loads (with fixed pressure drop HEX) through minimized pressure drop HEX.	20	2,1 MW/15 K (parallel operation, total)	9	1,5 MW/15 K (parallel operation, total)	7	2,5 MW/15 K (parallel operation, total)	10
Flexibility hydraulic HEX	Hydraulics of heat exchangers can be shifted between parallel and in a row, usage of single HEX layers is possible.	10	Possible	10	acc. D1	10	acc. D1	10
		Usability value		6,70		6,30		10,00
		Capex		100%		38%		50%

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Figure 47 demonstrates that variant H3 performs the best regarding the usability value, as the other variants, H1 and H2, have significant disadvantages due to their design. Variants H1 and H2 are susceptible to interruptions in the event of damage to the loading pipes. A single damaged pipe can cause a complete halt in the loading or unloading process, thereby disrupting the system's functionality. To overcome this limitation, variant H3, with its loop design, is better suited. This design offers greater robustness and the ability to maintain partial operation even in the event of damage. The loop design ensures that if one section is compromised, the rest of the system can continue to function, thereby enhancing overall reliability and reducing maintenance costs. Additionally, the loop design of H3 allows for easier maintenance and repair. In the event of a pipe failure, only the affected loop needs to be disconnected and repaired, rather than shutting down the entire system. This flexibility not only improves operational efficiency but also minimizes downtime and associated costs.

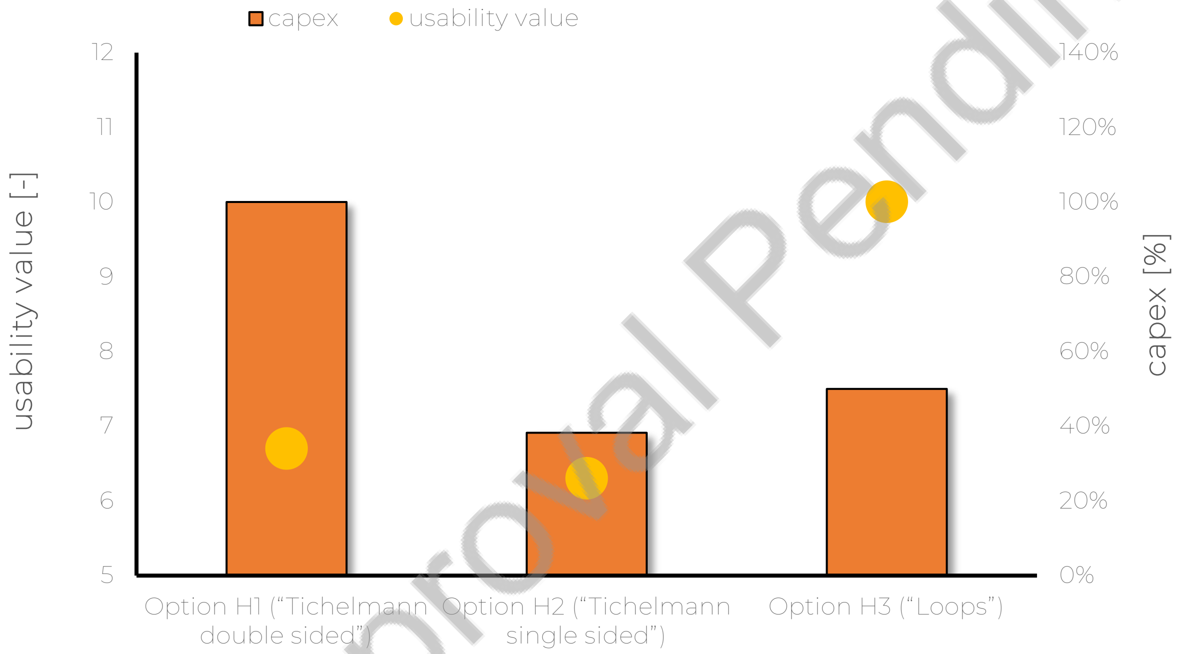

Figure 47: Comparison of capex and usability value of the HEX options H1, H2, and H3 (Planungsgruppe M+M AG, 2024b).

The overall evaluation of usability and investment costs shows that Option H3, despite the higher material costs, offers the best usability among the considered properties. Therefore, Option H3 ("Loop") was chosen for the general design of the heat exchangers in all three basins.

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3.6 Hydraulic Control Room

The hydraulic control room accommodates essential components of the Reno-sTES system and plays a central role in the efficient control and monitoring of energy flows between the storage units and the campus energy infrastructure. Figure 48 illustrates the current planned design of the hydraulic control room.

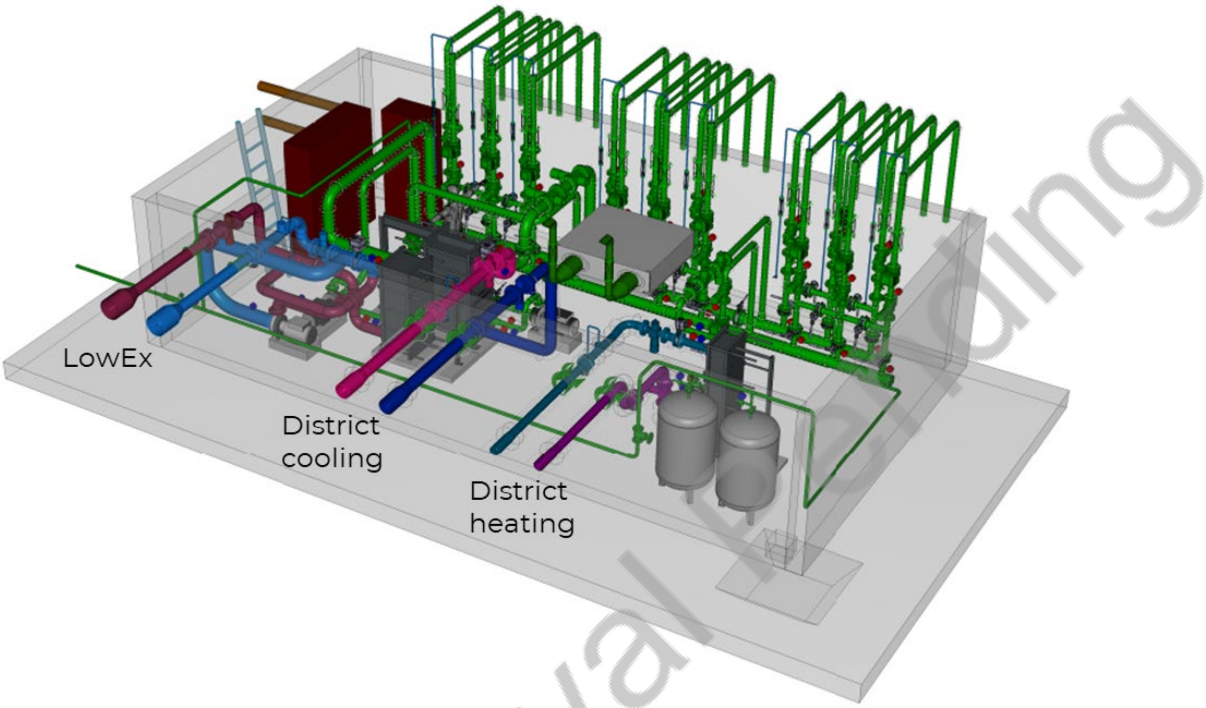

Figure 48: Design of the hydraulic control room. (Planungsgruppe M+M AG, 2024a).

3.6.1 Operation flexibility

Hydraulic connection

The hydraulic connection between the basins and the energy system of the campus can be described in two variations. There are single connections and multiple connections. These allow for a high degree of flexibility in charging and discharging the basins. The following Table 8 lists the possible combinations of connections for the single connection variant.

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Table 8: Variation of single connections (Planungsgruppe M+M AG, 2024b).

Combination	LowEx	District Heating	District Cooling	Valve A	Valve B
1	A	-	-	0	0
2	B	-	-	1	0
3	C	-	-	1	1
4	-	A	-	1	0
5	-	B	-	0	0
6	-	C	-	0	1
7	-	-	A	1	1
8	-	-	B	0	1
9	-	-	C	0	0

A single connection variation means that the basin can only be supplied by one energy source at the same time. For example, if basins A are being charged with LowEx, basins B and C cannot simultaneously be supplied with LowEx, district heating, or district cooling.

The numbering of the valves, where 0 indicates a closed valve and 1 indicates an open valve, is used to manage these connections. Figure 49 shows an example of combination 1 in the hydraulic schematic of the storage system.

Additionally, it is possible to vary which of the three heat exchanger levels (Top, Mid, and Bottom layers) can be charged or discharged. For each basin, there are six possible combinations for how the layers can be supplied.

The variation of multiple connections is further divided into two types of hydraulic connections: Connecting two basins simultaneously and connecting three basins simultaneously. Table 9 lists the possible combinations for these multiple variations.

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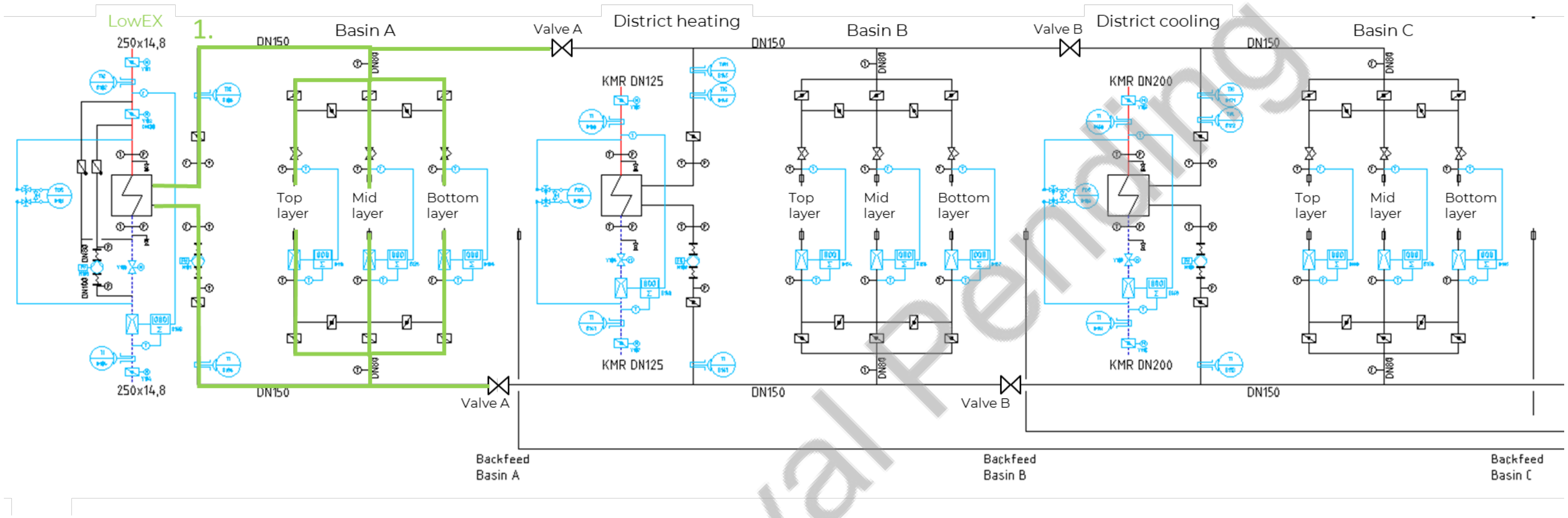

Figure 49: Variation of single connections: Control scheme storage system (LowEx, district heating & district cooling for Basin A, B, and C) (Planungsgruppe M+M AG, 2024a; IN-Campus GmbH).

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Table 9: Variation of multiple connections (Planungsgruppe M+M AG, 2024b).

Combination	*LowEx*	*District Heating*	*District Cooling*	*Valve A*	*Valve B*
connection of 2 basins at the same time					
10	A, B	-	-	1	0
11	A, C	-	-	1	1
12	B, C	-	-	1	1
13	-	A, B	-	1	0
14	-	A, C	-	1	1
15	-	B, C	-	0	1
16	-	-	A, B	1	1
17	-	-	A, C	1	1
18	-	-	B, C	0	1
connection of 3 basins at the same time					
19	A, B, C	-	-	1	1
20	A, B	-	C	1	0
21	-	A, B, C	-	1	1
22	-	A, B	C	1	0
23	-	-	A, B, C	1	1
24	-	A	B, C	1	1
25	A	-	B, C	0	1
26	A	B	C	0	0

Figure 50 and Figure 51 show an example of combinations 13 and 25 in the hydraulic schematic of the storage system. As mentioned in the single connection in this variation is also, a variety of heat exchanger layers can be charged and discharged.

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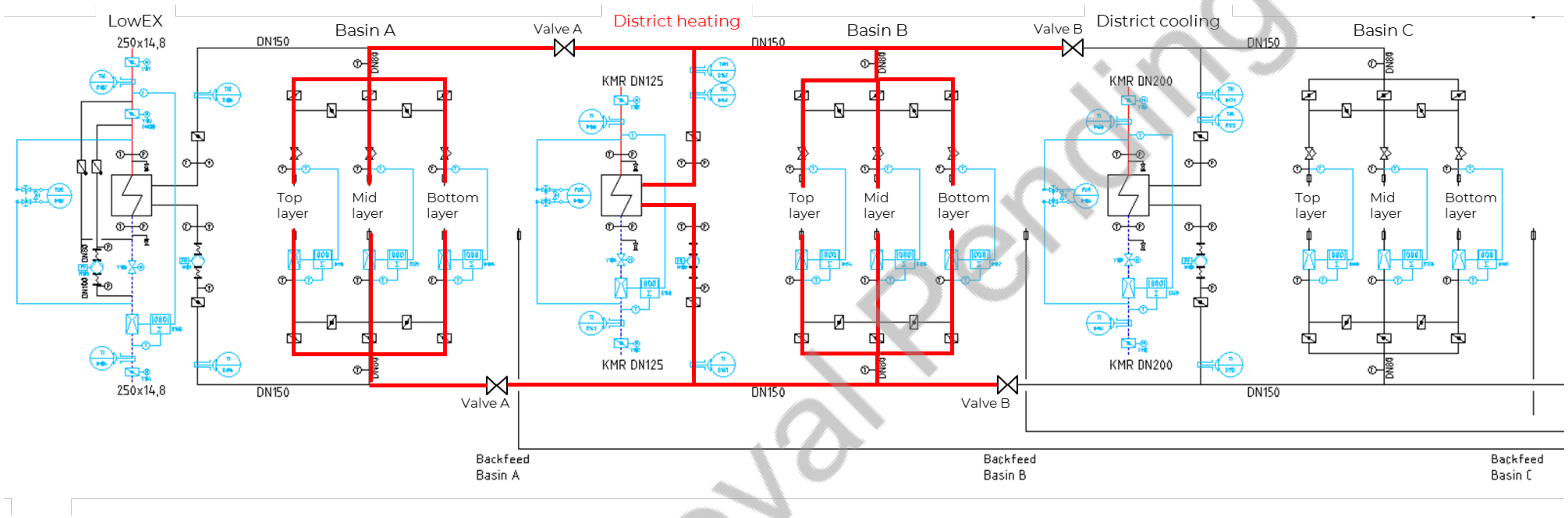

Figure 50: Variation of multiple connections: Control scheme (MSR – drawing) storage system (LowEx, district heating & district cooling for Basin A, B, and C (Planungsgruppe M+M AG, 2024a; IN-Campus GmbH). A legend of the symbols can be seen in Figure 52.

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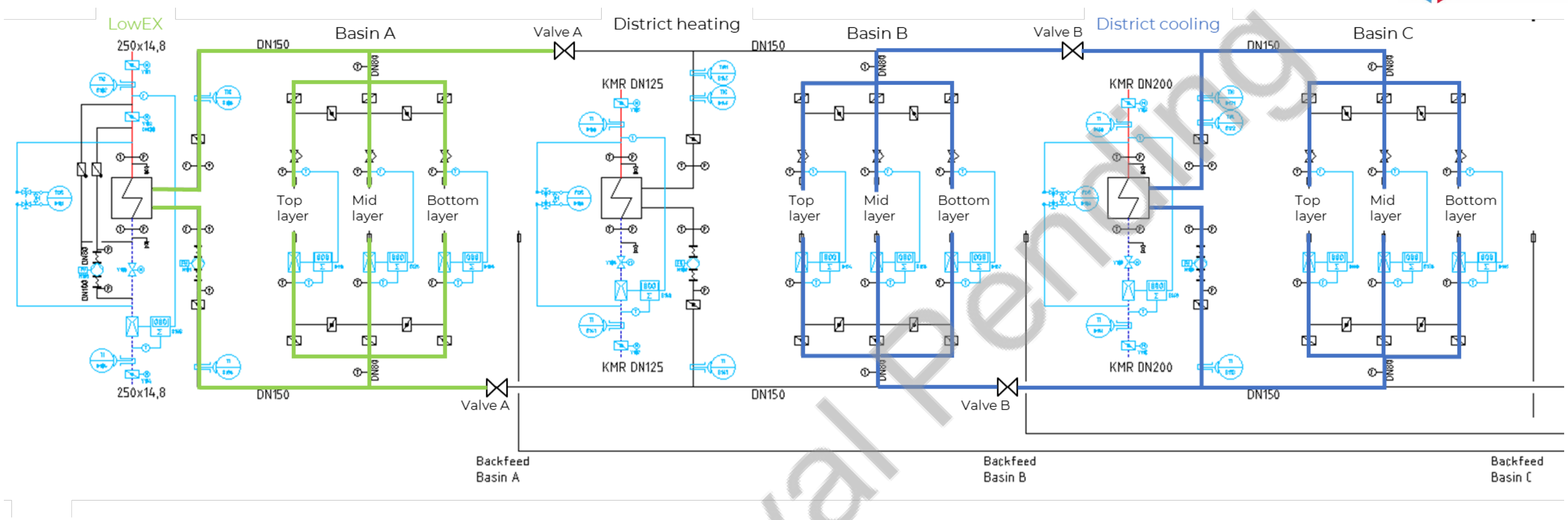

Figure 51: Variation of multiple connections: Control scheme (MSR – drawing) storage system (LowEx, district heating & district cooling for Basin A, B, and C) (Planungsgruppe M+M AG, 2024a; IN-Campus GmbH). A legend of the symbols can be seen in Figure 52.

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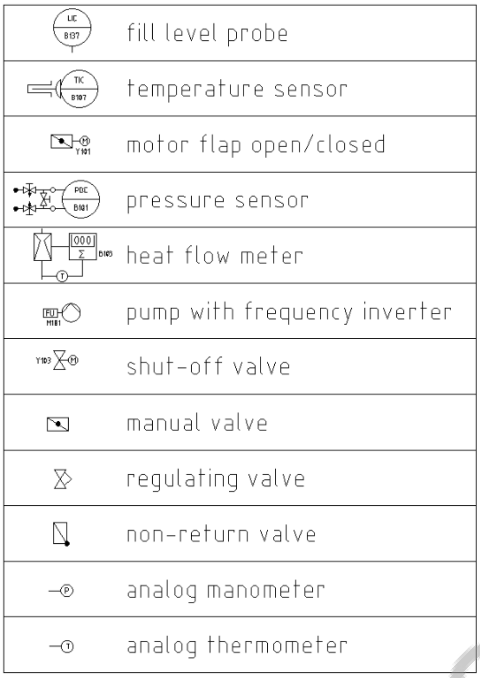

Figure 52: Legend of hydraulic symbols (Planungsgruppe M+M AG, 2024a).

The various hydraulic connections between the basin and the energy system offer a total of 26 possible combinations. This highlights the high degree of flexibility and adaptability of the hydraulic configuration. This diversity allows for solutions to be developed for different requirements and conditions, significantly enhancing the efficiency and effectiveness of the entire system.

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3.7 Current Status

The chapter provides an overview of the current status of the implementation of the Reno-sTES system at the incampus and the progress made up to the reporting date (January - October 2024). It includes both ongoing and outstanding work on the various system components, such as the inspection of the sealing sheet of the basins, the hydraulic control unit, and the integration of the infrastructure into the campus energy system.

3.7.1 Basin Construction

During the last inspection, 3 holes were identified in the sealing sheet of basin A. These defects were documented, and a plan was developed to carry out the necessary repairs and adjustments. However, due to the cold weather conditions that occurred during the planned repair period, the work had to be postponed initially. Figure 53 shows the holes in the sealing sheet.

Figure 53: Holes in a sealing sheet of the Basins (Planungsgruppe M+M AG, 2024a).

Due to the defects, the construction process (filling and Insulation) is delayed. Watertightness of the basins is a prerequisite for the next steps in basin construction.

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3.7.2 Hydraulic Control Room

What is already implemented

The demolition work of the old pump station has been successfully completed. The construction of the new hydraulic center has now begun. Currently, the formwork for the floor plate and the exterior walls is largely completed. The formwork for the ceiling is still pending. Figure 54 shows the current state of the hydraulic control room.

Figure 54: Hydraulic control room: Formwork of the floor plate and exterior walls (Planungsgruppe M+M AG, 2024a).

3.7.3 What's Coming Up Next

Connection to the Infrastructure (planned in November 2024):

- Completion of the connection of the energy system to the central hydraulic room

Patching the holes in the basins and leakage test:

- Planned next year 2025, because of the cold weather conditions

Start Construction Basin A, B, and C (next year 2025):

- After patching the holes, starting with the construction of insulation and filling

DTS-cable layout:

- Laying of the Distributed Temperature Sensing (DTS) cables for monitoring the temperature curves in the basins, planned for 2025.
- The installation is being carried out by Martin Luther University Halle-Wittenberg (MLU).

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- The installation will be carried out at the same time as the filling.

Making the construction site winter-proof:

- The pipes of the infrastructure connections must be covered

Finalizing of tender process (controls + pipework).

3.8 Insights and Conclusions

Challenges

- The construction site and the research project started almost simultaneously. Managing the ten on-site working companies in an ongoing project with dynamic design decisions is challenging and time-consuming.
- Ensuring the flow of information, results, and changes with the construction partners and project partners is demanding and hard to ensure.
- The condition of the brownfield poses scheduling and cost risks.
- Weather conditions present a risk, as both the installation of the foils and the laying of the heat exchanger pipes can only be carried out above a temperature of 8°C.

Achievements

- Through the optimization process, the project was successfully brought within the budget with minimal functional compromises.
- Two important milestones of the project will be achieved by the end of the year:
  - the completion of the construction work of the hydraulic control room
  - the completion of the infrastructure connections such as electrical power connection, connection to water supply, connection to data system, connection to LowEx-System, district heat system, and district cooling system.

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4 Varanto (Giga-CTES) – Implementation, Results, and Evaluation

4.1 Varanto plans

The overall plans for the cavern thermal energy storage (CTES) Varanto were described in Chapter 2.2, and this chapter provides more technical details about the implementation and more concrete material concerning the status of the project. The chapter concludes with insights and conclusions at this point of the project.

The main technical parameters of the Varanto unit are listed in Table 10.

Table 10. Main technical parameters describing the Varanto storage unit.

Parameter	Description
Storage capacity	90 GWh (thermal energy)
Volume	1,100,000 m^3 total volume (including process space), water volume 930,000 m^3
Structure	Three underground, connected caverns, each 300 m long, 40 m high and 20 m wide
Depth	140 m below the ground level
Temperature	45 °C (cold) - 140 °C (hot)

The storage is planned to be loaded by using a combination of district heating and electric boilers. The target is to raise the temperature of the storage medium up to 90°C by district heating and to utilize the electric boilers (2 x 60 MW) to raise the temperature to 145°C. The boilers are used to heat district heating water, allowing the same heat exchangers to be used for loading the storage. This also enables the use of the electric boilers directly as a heat supply for the district heating system.

Figure 55 shows an indicative 3D model of the planned storage along with its main dimensions. The connection points (right-hand side of the main volume) are the diffusors for inlet/outlet flow.

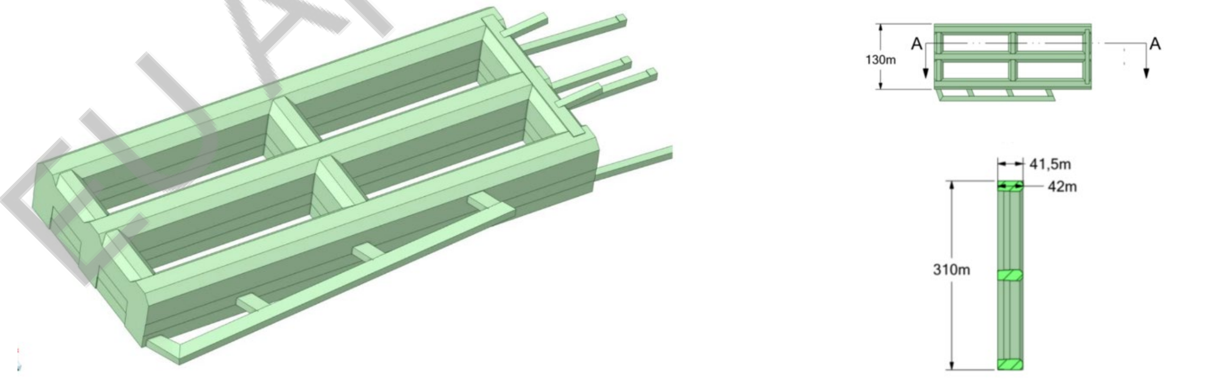

Figure 55: An indicative 3D model of the Varanto storage with the main dimensions given.

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Figure 56 illustrates the placement of the diffusors in more detail. Upper (1 and 2) and lower (5 and 6) diffusors are naturally at the top and bottom of the storage volume. The middle diffusors 3 and 4 are located 25 m and 10 m from the bottom of the storage, respectively.

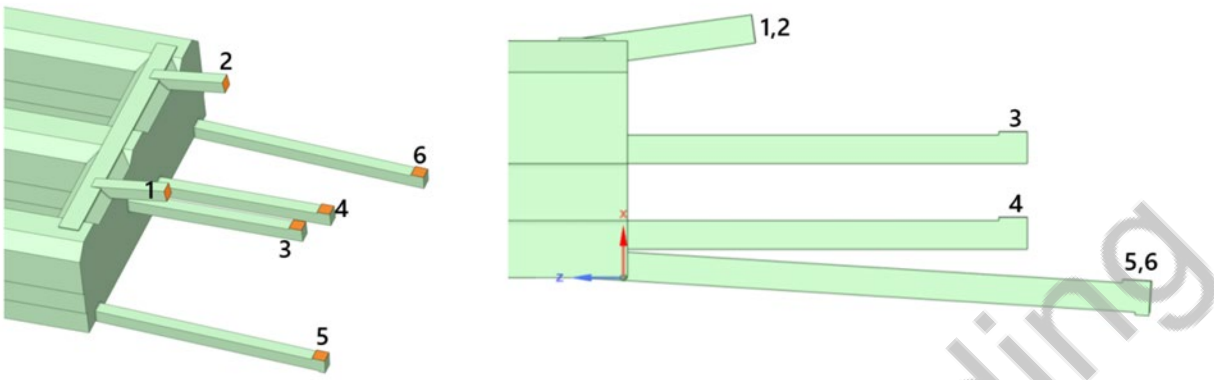

Figure 56: Current plan for the location of the diffusors (inlet and outlet) in the storage.

The number of diffusors is linked to the storage loading arrangement due to the role of district heating and electric boilers. The planned operation can create three separate, stratified water volumes within the storage, roughly at 45 °C, 90 °C and 140 °C.

The final design and dimensions of the storage volume are still being refined, but the illustrations presented here are close to what will be constructed.

The operation of the electric boilers and thus the loading process in general will be influenced by the market conditions within the electricity market, i.e., loading will occur when it is most economical – or at least when it is not particularly expensive. Thus, the share between district heating and electricity as a heat source may vary.

4.2 What's already implemented

The system into which the storage is to be integrated already exists (i.e. Vantaa district heating system), but the storage represents a new and significant component.

The initial screening, feasibility assessment, and planning and design phase of the project have been completed, although some details are still being refined. The actual implementation has begun, but setting up the monitoring systems for wells and groundwater level and quality can be marked as a completed task.

4.3 What is planned

The construction phase will continue as planned, and the activity within the site is expected to increase due to the start of the excavation work.

The final decision on specific material selection is to be made during 2025, as early as possible.

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4.4 Current Status

The current activities and the status of the construction effort are outlined in Chapter 2.2.6. In summary, the preliminary design phase has been completed and construction is starting. Excavation is expected to begin in early 2025. Refining the plans and final material selections are still being worked out in 2025.

Figures 57 and 58 show how the construction site looked like during Autumn 2024.

Figure 57: Above-ground construction work at the service entrance for the Varanto storage.

Figure 58: A closer view of the construction at the service entrance.

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4.5 Insights and Conclusions

The main insight into the project is based on its status as a novel undertaking. Many engineering challenges have already been recognized and solved during the Varanto project, and the INTERSTORES project is also contributing to finding solutions for the current and future challenges.

Due to the novelty, the involvement of the researchers can be seen as a concrete benefit for the Varanto project. It also represents an environment that potentially accelerates the adoption of the findings within the INTERSTORES project.

One specific issue outside the technical engineering challenges is the integration of the system into the surrounding district heating system. This has shaped the specific design of the storage (e.g. the role and expected operation of the electric boilers). As the surrounding energy system and landscape is changing faster than ever, the modelling work on potential future developments is highly significant. In the end, the success of the project is decided by a combination of 1) technical implementation and 2) operational benefit during its lifetime. The challenge lies in enabling flexible and future-proof design that is robust considering the uncertainties related to the energy sector.

As a recognition of the potential benefits of Varanto, the board of Vantaan Energia is already taking steps in preparation for a second thermal energy storage of a similar scale to Varanto, and naturally also connected to the district heating network.

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5 Summary and Outlook

5.1 Incampus

The Reno-sTES system at the incampus in Ingolstadt represents a showcase project for sustainable energy storage and the innovative use of existing infrastructures. With three storage basins (A, B, and C) a total storage capacity of 680 MWh (thermal energy) at a thermal range of 30 Kelvin, and a volume of 18,000 m^3 water equivalent, the system offers an efficient option for the seasonal storage of heat and cold.

So far, construction work has begun and the most important design decisions have been made. Milestones such as the infrastructure and the hydraulic control room on the construction site will be reached by the end of 2024. Some detailed decisions, such as the exact plan for the arrangement of the heat exchangers or the method of laying the DTS cables in the basins, still have to be made with the help of the INTERSTORES project partners.

The next step on the construction site will be the leak test of the basins. Once this test has been successfully completed, the installation of the basins, including insulation, filling, heat exchangers, and laying the DTS cables, can be completed by the middle of next year.

5.2 Varanto

Varanto project aims for a large-scale, seasonal thermal energy storage with a capacity of 90 GWh. The storage will be implemented as a cavern thermal energy storage (total excavated volume of 1,100,000 m^3), and kept under hydrostatic pressure, enabling the targeted temperature of 140 °C. The storage will be loaded by a combination of district heating and electric boilers and unloaded into the city-wide district heating network of the city of Vantaa.

The preparation phase for the construction project is completed, and the construction effort has begun. Currently, the above-ground works are ongoing. The excavation work is expected to begin in early 2025 and last approximately 2.5 years.

Final design issues and materials selection are to be done during 2025, parallel with the start of the excavation work.

The INTERSTORES project (research) will support the Varanto project (implementation) by working on materials, design concepts, and energy system integration modelling and studies. Lessons learned can be applied to Varanto, its continuation (2nd storage of a similar design being prepared by Vantaan Energia), and potential replication opportunities.

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