Experimental and Numerical Assessment of Sand-Based Sensible Heat Storage for Seasonal Thermal Energy Storage

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Abstract:
The growing penetration of renewable energy sources, such as photovoltaics and wind turbines, has heightened the need for effective energy storage solutions to balance supply and demand fluctuations. While direct electricity storage technologies - including batteries, supercapacitors, compressed-air energy storage, and pumped-hydro storage - are widely explored, the integration of Power-to-Heat technologies with thermal energy storage presents a promising alternative for large-scale applications. Among various thermal storage concepts, sensible heat storage remains particularly attractive due to its simplicity, robustness, and cost-effectiveness. This study examines the potential of sand-based high-temperature e heat storage for seasonal thermal energy storage. Experimental and numerical investigations were conducted to evaluate different charging and discharging strategies for a sand storage bed. Two heating approaches were analyzed: direct electrical heating with embedded heating elements and indirect heating via air channels supplied with hot air from an external heater. The heating and cooling dynamics of the storage bed were characterized, and the thermal power absorbed during charging and released during discharging was quantified. Furthermore, several charging scenarios were considered, involving renewable electricity sources – photovoltaic systems and wind turbines – as well as grid support to assess the possibility of using a sand-based reservoir as a seasonal heating storage for residential buildings or other objects. The results demonstrate the strong potential of sand-based thermal energy storage for long-term heat retention, space heating applications, and enhancing power system flexibility by improving the stability and dispatchability of renewable energy generation.

Keywords:
Seasonal thermal energy storage; energy storage; sensible heat storage.

1. Introduction

The rapid growth of global energy demand and the ongoing depletion of fossil fuel resources underscore the urgent need for sustainable and resilient energy solutions. Meeting the future energy requirements of a growing global population necessitates a transformation toward low-carbon and environmentally responsible energy systems. Although considerable progress has been made in deploying renewable electricity and heat generation technologies, the large-scale transition to low-carbon systems also depends on the development and integration of advanced energy storage technologies. Within this context, Power-to-Heat (P2H) and Seasonal Thermal Energy Storage (STES) systems offer promising pathways to integrate variable renewable energy (VRE) sources into both individual and district heating systems that traditionally rely on fossil fuels [1]. Their relevance is particularly pronounced in the residential sector, which remains a major contributor to final energy consumption and greenhouse gas (GHG) emissions. In 2023, households accounted for 26.2% of the EU's final energy consumption, with space heating and domestic hot water preparation representing 62.5% and 15.1% of this demand, respectively. Although building energy codes and minimum performance standards are becoming increasingly stringent, and the adoption of efficient and renewable building technologies is accelerating, the pace of change remains insufficient to align with the Net Zero Emissions by 2050 (NZE) scenario [2].

High-quality nearly zero-energy buildings (NZEBs) maximize passive design strategies, energy-efficient technologies, and on-site renewable energy resources. However, decarbonizing urban environments requires expanding this concept to the district scale, giving rise to nearly zero-energy districts (NZEDs). NZEDs typically integrate multiple renewable energy technologies, such as photovoltaic systems, solar thermal collectors, shallow and deep geothermal energy, biomass, and small-scale wind turbines, within low-temperature district heating and cooling networks that enable efficient energy distribution and multi-source integration [3,4]. To address the temporal mismatch between renewable energy availability and heating/cooling demand, NZEDs employ both short- and long-term storage solutions. Battery systems provide short-term balancing, while STES enables seasonal shifting of thermal energy, enhancing the flexibility and resilience of district-level heat supply [5]. Furthermore, sector-coupling strategies – including Power-to-Gas (P2G), Power-to-Heat (P2H), and Power-to-Hydrogen ($P2H_2$) technologies – are increasingly incorporated to convert surplus renewable electricity into thermal or chemical energy carriers, thereby supporting grid stability and enabling cross-sector decarbonization. Smart grids and demand-response mechanisms further enhance district-level self-sufficiency, facilitate energy sharing, and strengthen the integration of distributed renewable resources at the urban scale [6].

1.1. Power-to-Heat technologies

Power-to-Heat systems convert electrical energy into thermal energy for use in buildings, industrial processes, and other sectors. These solutions transform surplus electricity into heat through well-established principles, enabling rapid integration with existing district heating infrastructure. When coupled with thermal energy storage, P2H allows controlled heat utilization, improving overall energy efficiency and facilitating the integration of renewable energy sources [7]. A wide range of P2H technologies is currently deployed, including electric boilers, heat pumps, radio-frequency and microwave heaters, mechanical vapor recompression units, infrared heaters, resistance furnaces, induction furnaces, and electric arc furnaces [8]. Among these options, electric boilers and heat pumps are the most widely used in the building sector. Electric boilers offer a key advantage in their high conversion efficiency, typically 95–99%, and electrical capacities range from a few kilowatts to more than 70 MW [9]. Heat pumps, in contrast, represent an alternative electrification pathway with even higher efficiency. Large-scale heat pumps can be centrally integrated into district heating networks, utilizing low-grade environmental heat sources such as ambient air, groundwater, or industrial waste heat. When fossil-based post-heaters are not used, the system must be capable of supplying temperatures of at least 90 °C. Alternatively, decentralized heat pumps can be installed at the building level. In low-energy buildings, domestic hot water (DHW) typically requires temperatures around 60 °C, while space heating can be supplied at typically 35–45 °C [10]. Commercially available heat pumps exhibit coefficients of performance (COP) between 2.4 and 5.8 and heating capacities ranging from 2 kW to 20 MW [11]. Both electric boilers and heat pumps constitute clean and efficient alternatives to fossil-fuel-based systems such as gas- and coal-fired boilers.

1.2. Thermal energy storage systems

Within P2H applications, thermal energy storage plays a central role in providing system flexibility. TES technologies are commonly classified into three categories based on their underlying physical mechanisms: sensible heat storage (SHS), latent heat storage (LHS), and thermochemical heat storage (TCS). SHS is the most mature and widely deployed TES technology due to its simplicity, reliability, and cost-effectiveness. Its storage capacity depends directly on the specific heat capacity of the medium and the operational temperature difference. Suitable SHS materials must exhibit high thermal stability, durability over repeated cycles, and limited volumetric expansion. Typical storage media include liquids such as water and thermal oils, as well as solid materials such as concrete, ceramics, molten salts, and sand or rock beds [12]. Although SHS systems are robust and scalable, their relatively low energy density compared to other TES types often necessitates large storage volumes. In contrast to SHS, LHS systems store energy through the enthalpy of phase change – most commonly the solid–liquid transition. Phase Change Materials (PCMs) offer significantly higher energy densities than SHS, enabling more compact storage designs. A major advantage of LHS is its nearly isothermal charging and discharging behavior: during phase transition, the heat transfer fluid maintains an almost constant outlet temperature, ensuring stable thermal performance for downstream applications [13]. Thermochemical Heat Storage (TCS) represents the highest theoretical energy density among TES technologies. It relies on reversible endothermic and exothermic reactions – such as the hydration and dehydration of salts or hydroxides – to store and release heat [3]. During charging, thermal energy drives the decomposition of the reactant (e.g., dehydration of salt), effectively storing energy in chemical form. TCS offers two major advantages: exceptionally high storage density and the ability to retain energy for long periods without thermal losses. However, the technology remains complex, requiring precise control of pressure, reactant handling, and gas flows, and is currently hindered by high capital costs that limit large-scale deployment.

As TES technologies expand into residential and industrial heating applications, Seasonal Thermal Energy Storage has become essential for bridging the gap between summer renewable energy surpluses and winter heating demand. The suitability of a given STES technology depends strongly on its ability to retain energy over extended periods. TCS offers the best theoretical long-term performance because energy is stored chemically with negligible thermal losses. However, auxiliary energy requirements for reactant conditioning and system operation must be considered. LHS and SHS experience continuous thermal losses to the environment. Although LHS benefits from higher energy density and smaller surface-to-volume ratios, large-scale SHS – particularly packed-bed thermal energy storage (PBTES) – often remains the most practical option due to its simplicity and the low cost of bulk materials such as rock or sand. Several STES configurations are currently in use, each adapted to specific geological, spatial, and economic conditions. These include Aquifer (ATES), Borehole (BTES), Tank (TTES), and Pit (PTES) storage, as well as more specialized latent-heat (LHTES) and thermochemical (TCSS) systems. Each configuration presents distinct trade-offs among efficiency, scalability, and site requirements [1]. The TES configurations listed above offer considerable flexibility for integration into district heating networks, particularly their ability to capture and store energy from diverse sources, such as industrial waste heat, solar surpluses, and P2H systems. However, their performance is fundamentally constrained by operating temperature limits. Most conventional storage media cannot exceed approximately 95 °C without encountering issues related to phase instability, elevated pressure, or material degradation. PBTES emerges as the only practical option for high-temperature applications. By employing solid filler materials in combination with gaseous heat transfer fluids, PBTES avoids the thermodynamic limitations associated with liquid-based storage. This configuration enables operation at substantially higher temperatures, thereby increasing the achievable energy density and meeting the requirements of high-grade industrial processes and advanced district heating systems. The PBTES system typically consists of an insulated vessel filled with a granular or structured solid material that serves as the primary storage medium. Research has identified a wide range of suitable materials for such systems, including silica sand, crushed rock, alumina beads, steel slag, ceramics, and perforated concrete blocks. In PBTES systems, thermal energy is transferred by a heat transfer fluid that flows through the interstitial voids of the packed bed. In the conventional operating mode, the heat transfer fluid flows directly through the porous medium, promoting thermal stratification. When liquid heat transfer fluids are used, both the fluid and the solid medium contribute to the overall storage capacity [14,15]. PBTES systems offer several important advantages, foremost among them their capability to operate across an exceptionally wide temperature range. Because the storage medium contains no water, the tank can safely reach much higher charging temperatures than conventional water-based systems. Depending on the selected filler material, operating temperatures may reach 1000 °C, substantially enhancing the achievable volumetric energy density and overall storage performance [16].

1.3. Integration of Power-to-Heat technologies with thermal energy storage systems and various renewable energy

The potential for integrating different generation and storage technologies clearly demonstrates the strong compatibility between VRE sources (such as photovoltaic systems and wind turbines), P2H systems, and STES solutions. Together, these technologies form an essential pathway for deep decarbonization, as they enable the effective use of intermittent renewable electricity within the thermal sector. By converting surplus renewable power into heat, P2H systems reduce fossil fuel consumption, limit curtailment, and provide valuable operational flexibility to the broader energy system. Their technological maturity, cost-effectiveness, and scalability make P2H solutions particularly well-suited for deployment in low-temperature district heating and cooling networks, which are increasingly central to NZED strategies. When combined with STES, these systems can shift substantial amounts of renewable energy over extended periods, enabling seasonal balancing and more efficient utilization of distributed generation. Beyond improving energy efficiency, P2H technologies coupled with STES systems also contribute to power system stability. By absorbing excess renewable electricity during periods of high generation, they help maintain grid balance while simultaneously reducing dependence on fossil-based heat production. Consequently, the coordinated deployment of VRE, P2H, and STES is emerging as a cornerstone of future integrated energy systems that can support a low-carbon, resilient, and flexible energy transition. The general idea of integrating VRE, STES, and P2H solutions into the district network is shown in Figure 1.

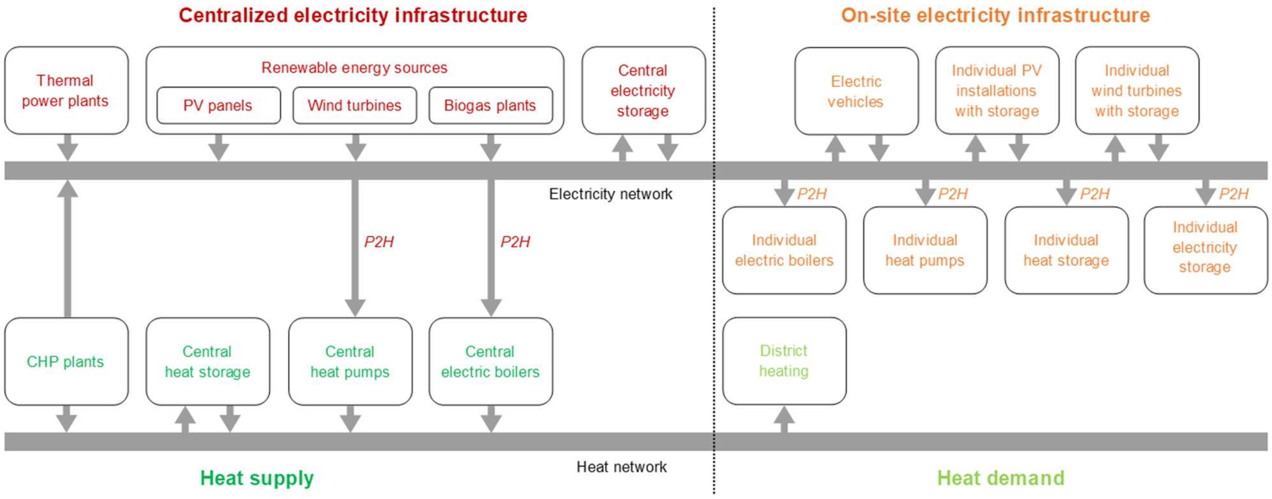


Figure. 1. *The concept of integrating VRE, STES, and P2H solutions into the district network (adopted from Ref. [17]).*

Given the current state of research, PBTES technology has emerged as a highly promising storage option due to several advantageous thermophysical and practical properties. Considering sand, as a medium, its relatively high specific heat capacity enables substantial energy accumulation within a compact volume, improving the overall effectiveness of the storage system. Moreover, sand is abundant, inexpensive, non-toxic, and widely available, making it a cost-efficient and environmentally benign alternative to many conventional storage materials [18]. Despite the progress achieved to date, several aspects of sand-based thermal storage still require further investigation. This study contributes new insights in the following areas:

- Development of a hybrid charging strategy, enabling the storage system to utilize energy from multiple sources, including electric heaters and air channels.
- Introduction of a numerical analysis framework incorporating targeted simplifications that enable long-duration, multivariate simulations of sand-based TES systems to be performed with significantly reduced computational effort.
- Enhancing the effective thermal conductivity of the sand bed by incorporating aluminum metal foams, thereby increasing the storage capacity and reducing both charging and discharging times.

2. Materials and methods

This section presents descriptions of the experimental rigs used to validate mathematical models and the basic assumptions underlying the numerical work.

2.1. Experimental rigs

In the experimental part of the study, two test rigs were used, each representing a different method of charging and discharging a sand-based thermal storage bed. Both laboratory setups were constructed around a steel cylindrical tank with a total volume of 205 dm³. The tank was pre-insulated with a 10 cm layer of mineral wool and filled with approximately 300-350 kg of quartz sand. In the first configuration (rig 1), five electric heaters, each rated at 1400 W, were inserted directly into the sand bed to provide internal heating. On the other hand, a corrugated steel DN50 pipe was implemented to extract heat. In the second configuration (rig 2), a DN50 pipe heat exchanger with a constant circular cross-section and a total length of 4.75 m was embedded within the bed. Air was used as the working fluid and flowed through the exchanger, enabling both charging and discharging of the storage system. On the inlet side, the duct was insulated with high-temperature ceramic wool and connected to an air heater. The heater featured a simple design consisting of a cylindrical channel equipped with three spiral electric heating elements, each with a nominal power of 2000 W. Airflow through both the heater and the heat exchanger was provided by a centrifugal fan. An illustration of the developed experimental rigs is presented in Figure 2.

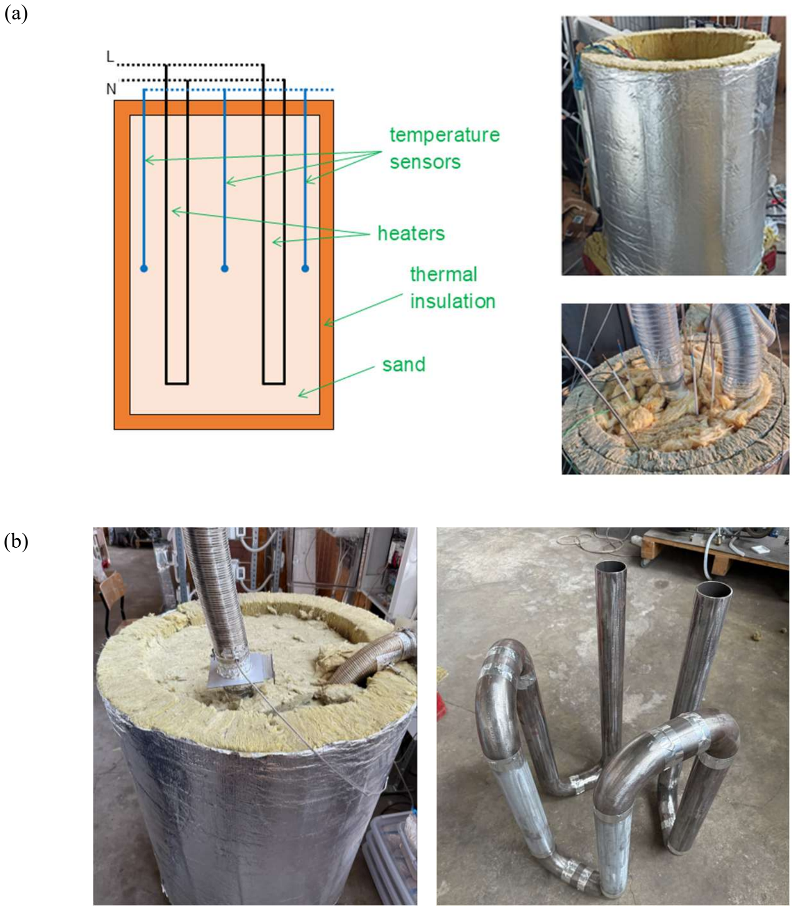


Figure. 2. *View of the experimental rigs: (a) experimental rig 1 and (b) experimental rig 2.*

The system operation was monitored using a dedicated control and measurement setup based on a modular programmable logic controller (PLC). The heaters (both in rig 1 and rig 2) were operated via relay modules that switched them on and off according to a predefined time schedule. The main parameters of the experimental system are summarized in Table 1.

Table 1. *The main elements of the test rig used during the tests.*

Element	Description	
	Experimental rig 1	Experimental rig 2
Sand container	Cylindrical steel vessel with a diameter of 56 cm and a height of 90 cm, insulated with a 10 cm layer of mineral wool.	
Electric heaters	Five 1 400 W electric heaters located directly in the sand bed	Three 2 000 W electric heaters located in the air channel
Heat exchanger	DN50 steel pipes for discharging the sand bed	DN50 steel pipes for charging and discharging the sand bed
Air fan	MPLUSM WPA X6, maximum flow rate: 245 m^3/h	
Temperature sensors	K-type thermocouple sensors (NiCr-NiAl) with a measuring range from 0 °C to 1100 °C and tolerance ±2.0 °C or ±0.0075 × [t], where t is the measured temperature in °C	
Controller	The modular unit WAGO PFC200 with a set of input and output modules	
Software	CoDeSys in version 2.9	

2.2. Numerical works

Numerical simulations were conducted using the ANSYS Workbench environment. The computational domain included a cylindrical sand bed (mass approx. 300 kg) contained within an insulated steel tank. To reduce computational time for long-term transient simulations, the sand bed was assumed to behave as a solid body with effective thermodynamic parameters, rather than as a complex porous medium. For variant no. 1, the model exploited axial symmetry, allowing for calculations on one-fifth of the total volume to further optimize resource usage. In variant no. 2, the geometry included a 4.75 m-long pipe heat exchanger embedded in the sand.

The thermodynamic properties of the sand were implemented as temperature-dependent functions (except for density, which was assumed constant). Specific heat (C_p) and thermal conductivity (λ) were defined as linear functions based on experimental and literature data to account for the behavior of quartz sand across a wide temperature range (up to 1073 K):

- Density: ρ = 1617 kg/m^3,
- Specific Heat: C_p = 1.2099 · T + 498.56 J/(kgK),
- Thermal Conductivity: λ = 0.0006 · T - 0.0102 W/(mK) [19].

For the performance enhancement study, aluminum metal foams with high porosity (ε = 0.95) were integrated. Their effective properties within the sand-foam domain were determined using the Local Thermal Equilibrium (LTE) approach for specific heat and the Bhattacharya et al. [20] correlation for effective thermal conductivity. This modification resulted in an effective thermal conductivity up to 14 times higher than that of pure sand.

The numerical grids consisted of polyhedral cells (approx. 0.82 million cells for the symmetry-based model), with significant refinement near heat sources (heaters or pipe surfaces) to capture high-temperature gradients. A sensitivity analysis was carried out to select the optimal cell size of the numerical grid. The final mesh settings that were implemented into the model assumed a global cell size of 0.05 m and a local sizing of 0.0005 m on heater surface. In variant no. 1, electric heaters were modeled as heat-flux sources (Q_h) with control logic to prevent sand sintering above 1073 K. In variant no. 2, storage was charged by hot air flow through the exchanger. The discharge process used the same exchanger but assumed cold air on the inlet. Airflow was modeled using the k-ω SST turbulence model. All models were validated against experimental data from laboratory prototypes, showing strong agreement, with mean absolute deviations in sand temperature ranging from 2.9 K to 3.5 K.

To ensure the accuracy and comparability of results across both storage configurations, the numerical models were developed with consistent thermodynamic assumptions. Table 2 summarizes the key numerical parameters used in the study. As shown, the numerical approach for variant no. 1 focused on long-term thermal behavior (up to 21 days) and utilized symmetry to optimize computational efficiency. In contrast, the variant no. 2 (with and without metal foams) focused on a single charging and discharging cycle with a pipe heat exchanger. In both cases, the properties of the sand were treated as temperature-dependent functions.

Table 2. *Summary of numerical modeling parameters.*

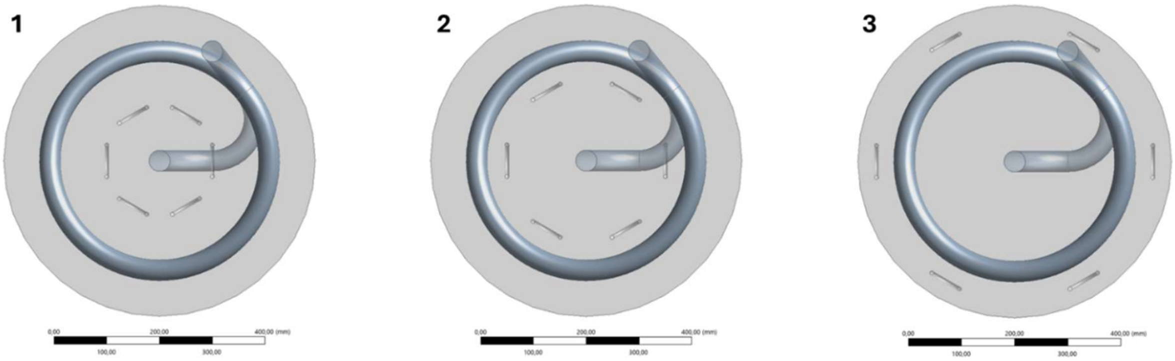
Element	Description	
	Variant no. 1	Variant no. 2
Software	ANSYS Fluent 2024 R2	ANSYS Fluent 2025 R1
Space Claim	3D / 1/5 Symmetry (72° Sector)	Full 3D Domain
Mesh Type	Polyhedral (approx. 0.82 M cells)	Polyhedral (approx. 0.74 M cells) with Inflation Layers
Sand Model	Solid zone (effective properties from literature)	Solid zone (effective properties from experiments and literature)
Sand - Metal foam model	N/A	Solid zone (effective properties from literature)
Turbulence Model	N/A	k-omega SST
Heat Source	Volumetric Heat Generation (Heaters)	Energy Transfer from Fluid (Air)
Time Step	60 s (transient)	60 s (transient)
Convergence Criteria	10^{-6} for energy, 10^{-3} for others	10^{-6} for energy, 10^{-3} for others

3. Results and discussion

This section includes the results obtained during the discussed studies, including assessing the performance of the charging sand bed using electric heaters (section 3.1), assessing the performance of the charging sand bed using an air channel (section 3.2), performance enhancement with metal foams (section 3.3), and Comparison of Various Operating Scenarios (section 3.4).

3.1. Assessing the performance of the charging sand bed using electric heaters

The initial phase of the numerical investigation focused on identifying the optimal spatial distribution of electric heaters within the sand bed (experimental rig 1). Three geometric configurations were evaluated to determine their impact on thermal uniformity and storage efficiency. The necessity for this optimization stems directly from the thermophysical properties of the storage medium. Unlike water or molten salts, where natural convection rapidly homogenizes the temperature field, the packed sand bed operates purely on conduction. Given the inherently low thermal conductivity of the sand, heat injected by the electric elements propagates slowly, resulting in steep thermal gradients and localized heat accumulation near the heat sources. The geometries of the analyzed heater distributions within the sand bed are shown in Figure 3.



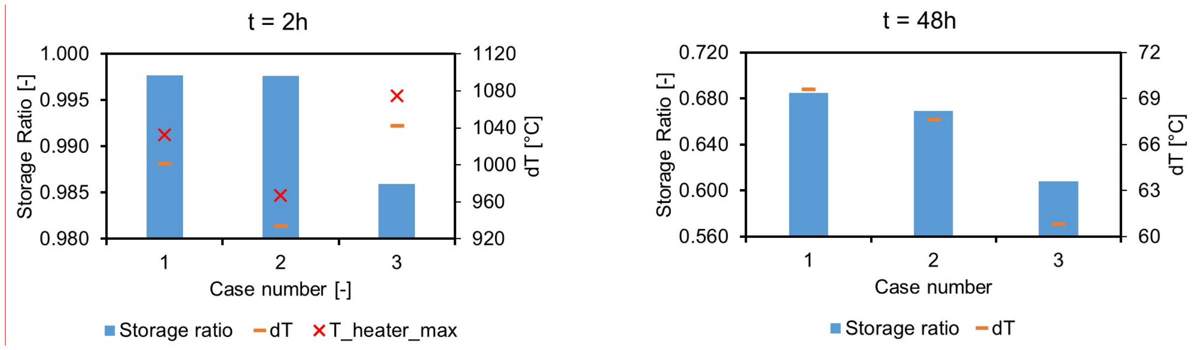
(a) (b) (c)

Figure. 3. *Geometries of analyzed variants of heater distribution inside the sand bed.*

The performance of each variant was benchmarked using a comprehensive set of thermal indicators evaluated at specific time points from 2 to 48 h. These metrics included the minimum (T_{min}), maximum (T_{max}), and average (T_{av}) sand temperatures, as well as the overall spatial temperature difference (ΔT). Furthermore, the net energy stored in the bed, E_{net} [MJ], and the Storage Ratio, *SR*, were calculated. The *SR* parameter was introduced to show the efficiency of the storage operation for the analyzed time. Its value was calculated according to the following equation:

$$SR = \frac{E_{net}}{Energy\ input} \tag{1}$$

Energy input for the analyzed case was related only to the operation of electric heaters, i.e., it was constant at 43.2 MJ. The selection of the optimal variant was not based solely on thermodynamic efficiency, but also on physical safety constraints. The peak surface temperature of the heater at the end of the charging phase served as the primary limiting criterion. By analyzing the intersection of the maximum retained energy and the safe operational limits ($T_{h,max}$), the study identified the geometric layout that maximizes the sand bed's P2H capabilities without compromising its structural integrity. Simulation results were collected at two selected simulation times: t = 2 h (at the end of heating) and *t* = 48 h. All data are summarized in Figure 4.



(a) (b)

Figure. 4. *Geometries of analyzed variants of heater distribution inside the sand bed.*

As can be concluded comparing the analyzed variants, concentrating the heaters near the central axis of the tank forces a massive amount of thermal energy into a small volume of sand, drastically increasing local temperatures. Conversely, distributing the heaters closer to the outer perimeter ensures a more uniform heat distribution and engages a larger volume of the bed during the active charging phase. Consequently, the second variant was chosen for its best parameters. It was characterized by one of the highest Storage Ratio values, the lowest heater temperature, and one of the most stable temperature distributions.

3.2. Assessing the performance of the charging sand bed using an air channel

As an alternative to charging the sand bed using electric heaters, a system with an air channel (experimental rig 2) was tested. To thoroughly investigate both the charging and discharging processes, their durations were significantly extended. In the simulations presented below, the complete operating cycle lasted 102 h, consisting of 48 h of charging, 6 h of idle operation, and 48 h of discharging. To assess the operating parameters of the analyzed sand bed, a set of performance indicators was defined. These include: maximum stored thermal energy (the amount of energy stored at the end of the charging process, i.e., after 48 h), losses to the ambient environment (the total energy lost from storage during the idle period), time required to charge the storage by 50 MJ (the moment during charging when the stored energy exceeds 50 MJ), and time required to discharge the storage by 50 MJ (the moment during discharging when the stored energy decreases by 50 MJ). The illustration of the analyzed sand bed with an air channel is shown in Figure 5.

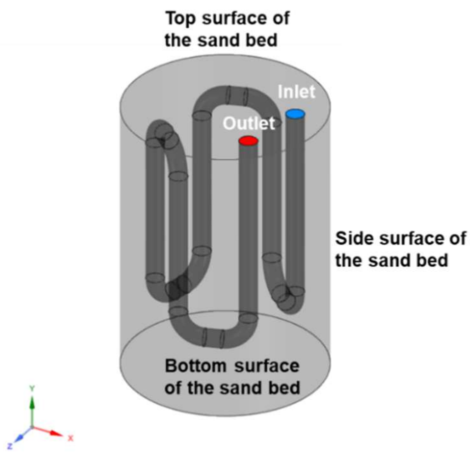


Figure. 5. *The illustration of the analyzed sand bed with an air channel.*

In the presented variant, the maximum stored thermal energy (ΔE_{st}) was 73.3 MJ, the losses to the ambient environment (E_{loss}) amounted to 6.8 MJ, the time required to charge the storage by 50 MJ ($t_{50,charge}$) was 19.1 h, and the time required to discharge the storage by 50 MJ ($t_{50,discharge}$) was 26.0 h. In the next stage of the study, the possibility of improving the thermal storage performance of the analyzed system was evaluated by introducing metal foams to enhance heat transfer within the bed.

3.3. Performance Enhancement with Metal Foams

The low thermal conductivity of sand was identified as one of the factors limiting the optimal performance of the thermal storage system. Porous structures – specifically, metal foam – were employed as one method to increase its effective thermal conductivity. Placing these structures within the bed and allowing the sand to fill their pores can increase effective thermal conductivity by as much as several times. A series of analyses were conducted to identify a variant that would maximize the positive impact of metal foam on the storage facility's performance (energy stored over the study period) while minimizing the volume of the porous structure.

The best option was to cover the heat exchanger with a 1-cm-thick layer of metal foam. This increased the storable energy by 20% using only 0.0086 m³ of porous material. Other variants involved placing the metal foam within the storage tank to form a cylindrical shape along the heat storage system's axis. These did not allow for such a significant increase in energy storage capacity while simultaneously requiring much larger volumes of porous material.

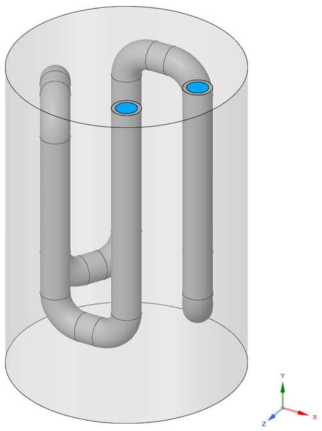


Figure. 6. *Best variant assuming metal foam coating on the heat exchanger*

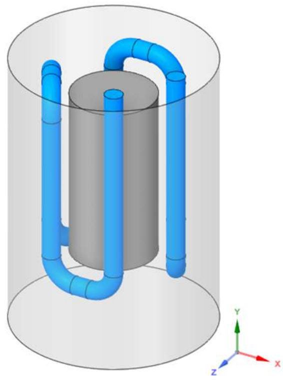


Figure. 7. *The variant assuming cylindrical-shaped metal foam in a sand bed*

3.4. Comparison of Various Operating Scenarios

Regardless of the charging system applied to the sand bed, an important aspect is the analysis of charging scenarios, which may be based, among others, on energy from renewable sources (e.g., photovoltaics) as well as on electricity drawn from the power grid during so-called night tariffs. The analysis discussed in this section focuses on verifying the feasibility of supplying energy to the sand heat storage under different heating schedules. Four cases were considered: continuous charging, charging based on the G12 tariff, charging using photovoltaic energy on a reference summer day, and charging using photovoltaic energy on a reference winter day. The G12 variant refers to an electricity purchase tariff offered by Polish energy distributors. This tariff is based on two or three different electricity price levels, depending on the time of day. Variations of average sand bed temperature for different charging schedule options are shown in Figure 8. Furthermore, the comparison of the different schedules in terms of the time required to heat the sand bed to selected temperature levels is included in Table 3.

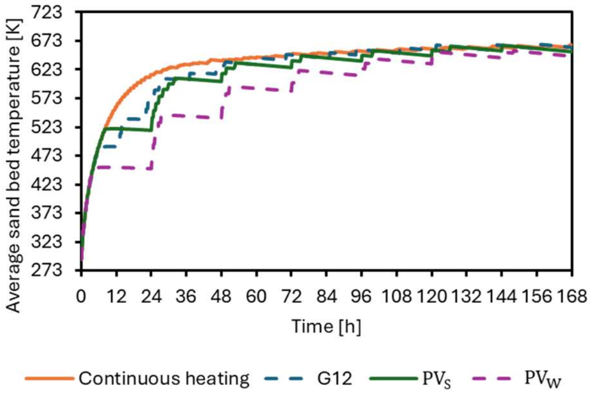


Figure. 8. *Variations of average sand bed temperature for different charging schedule options.*

__Table 3.__ Comparison of the different schedules in terms of the time required to heat the sand bed to a given temperature value.

Temperature [K]	Time to reach a given temperature [h]			
	Continuous charging	G12 tariff charging	PV_S charging	PV_W charging
450	4.0	4.0	4.0	24.0
550	10.8	22.2	24.8	48.1
650	71.0	91.0	113.5	130.1

As shown in Table 3, each proposed charging schedule can raise the sand-bed temperature to approximately 650 K or higher within 7 days. The schedule with longer intervals between charging cycles limits the heater's ability to recover toward the minimum set-point temperature, primarily due to increased heat loss to the surroundings. Moreover, the analyzed schedules exhibit clearly differentiated charging dynamics. Due to the implemented control logic, the operation of the storage system can be closely linked to the heater temperature (to avoid potential heater damage). This imposes certain limitations on the maximum amount of energy that can be stored within a single day. Future research should therefore focus on identifying optimal intervals between charging cycles. One possible solution to this issue could be the use of an array of smaller thermal storage units charged sequentially. Such an approach would allow continuous intake of excess energy while preventing overheating of the heater.

4. Conclusions

This study investigated the performance of a sand-based sensible heat storage system for high-temperature seasonal thermal energy storage using both experimental measurements and numerical simulations. Two different approaches to charging and discharging the sand bed were analyzed and discussed. In the case of implementing electric heaters, the results showed that the spatial arrangement of the heaters strongly affects the temperature distribution within the sand bed. Locating the heaters closer to the tank perimeter improves thermal uniformity, increases the effective utilization of the storage volume, and reduces the risk of local overheating. The air-channel charging configuration also demonstrated good performance, enabling the storage of approximately 73 MJ of thermal energy with relatively low heat losses. To address the limited thermal conductivity of sand, the introduction of aluminum metal foam near the heat exchanger proved effective, increasing the stored energy by about 20 % while requiring only a small volume of additional material. Finally, the analysis of different charging schedules showed that the analyzed prototype storage system can reach temperatures above 650 K within approximately one week under various operating conditions, including renewable-energy-based charging. Overall, the results confirm that sand-based packed-bed thermal energy storage is a technically feasible and cost-effective solution for integrating Power-to-Heat technologies with renewable energy sources. They also highlight the strong potential of sand-based thermal energy storage as a scalable, low-cost technology for renewable energy integration and seasonal heat storage applications.

Acknowledgments

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