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Mine water heat storage with heat pump as a solution for decarbonisation in urban areas

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Abstract

Around 57% of the world's population currently live in cities, with this share exceeding 70% in Europe and 80% in North America. As urbanization continues to rise, energy demand in densely populated areas is growing, while simultaneous decarbonization of heating and cooling remains a major challenge.
One promising approach is the use of abandoned and flooded mines as seasonal heat storage systems in combination with heat pumps. Many cities have developed near former mining areas, making post-mining utilization particularly attractive. In addition to surplus heat from industrial processes or solar thermal systems, excess heat from summer cooling can also be stored. The large water volumes and extensive rock contact surfaces in mines enable significant seasonal energy storage capacity.
In Freiberg, Germany, a pilot-scale storage system was implemented in a former silver mine and operated continuously in test mode for over two years. Storage efficiencies between 45 % and 65 % were achieved, with a heat pump enabling the charge and discharge of the storage system. The mine water temperatures varied between 2 °C and 40 °C.
Based on modelling of three potential districts in Germany, self-sufficiency levels of up to 80 % and storage durations exceeding three months are feasible. Depending on system configuration and existing infrastructure, payback periods between 10 and 15 years are possible — and below 5 years when a district heating network is already in place.
These results demonstrate the technical and economic viability of mine water heat storage as a scalable component for sustainable urban heating and cooling.

Keywords: heat storage, mine water, geothermal energy, urban areas

1. Introduction

The ongoing process of urbanization is one of the defining developments of the 21st century. Currently, more than half of the world's population lives in cities, and this proportion continues to increase. According to United Nations estimates, around 70 % of people in Europe and over 80 % in North America already reside in urban areas [1]. Projections suggest that the global urban population will reach approximately 6.7 billion by 2050 [2]. This demographic shift is fundamentally altering patterns of energy consumption, infrastructure demands, and the environmental footprint of human settlements.

Urban areas are characterized by high population density and concentrated energy demand. They consume more than two-thirds of global energy production and account for over 70 % of worldwide CO_2 emissions. A

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significant share of this energy demand is attributed to heating, cooling, and domestic hot water—sectors that remain heavily dependent on fossil fuels. As urban areas continue to grow and densify, the demand for thermal energy is expected to rise further, particularly in regions with cold winters or increasing cooling requirements during hot summer periods.

Therefore, decarbonizing the heating and cooling supply in cities therefore represents a major technological and systemic challenge. Integrating renewable and locally available heat sources, combined with efficient seasonal storage options, is essential to meet this challenge. In this context, the utilization of abandoned and flooded mines offers a promising opportunity. These subsurface structures contain large volumes of water and extensive rock contact surfaces that can serve as natural thermal reservoirs. Historically, many European cities have developed in close proximity to mining regions, providing favorable conditions for post-mining energy use [3]. In combination with heat pump technology, such mines could play a significant role in the decarbonization of urban energy systems.

To assess under which conditions flooded mines are suitable for seasonal heat and cold storage, it is necessary to determine their potential and achievable efficiency. For this purpose, an experimental storage system was installed in the former silver mine "Reiche Zeche" in Freiberg, Germany. Through cyclic heat charging and discharging experiments, the achievable storage efficiency and operational characteristics were investigated. Based on the boundary parameters derived from these experiments, a larger-scale storage concept was subsequently modelled for three urban areas in Germany to evaluate the broader applicability and potential of this approach.

2. Model storage facility

Experimental storage system and methodology

In the former silver mine "Reiche Zeche" in Freiberg (Germany), a model-scale seasonal heat storage system was established by flooding a basin with approximately 21 m³ of mine water. The storage basin was hydraulically connected to the surrounding mine workings, resulting in a natural throughflow of approximately 1 m/d, depending on external conditions. To capture the thermal evolution of the storage system, more than 80 temperature sensors were installed in the water body and in boreholes extending up to 2 m into the surrounding rock. To reduce convective heat losses to the ambient air, the water surface was covered by a multilayer insulating foil. A detailed description of the experimental setup is provided in Chen et al. (2024) [4], while Oppelt et al. 2025 [5] describe the specific charging and discharging experiments.

The experimental program consisted of cyclic charging and discharging phases. During charging, mine water extracted from another section of the mine at a temperature of approximately 11 °C served as the heat source. The extracted heat was transferred to the storage basin using a heat pump, allowing defined charging temperatures between 25 °C and 50 °C to be achieved. During discharge, the storage was used as the heat source and the heat was extracted by the heat pump in the test rig, where it was heated to between 50 and 60 °C to simulate realistic consumer behaviour. This heat was then transferred to the 11 °C mine water, which was previously used as the heat source.

The heat pump was used exclusively to provide controlled charging temperatures within the experimental setup. In a real-scale implementation, the required charging temperatures would instead be supplied directly by external heat sources such as solar thermal systems or industrial waste heat.

The thermal balance of the storage system was calculated based on measured temperature changes in the water and surrounding rock. Heat quantities were derived from the temperature differences before and after charging and discharging phases. The calculations were performed using the material properties listed in Table 1, based on Chen et al. (2024) [4] and Oppelt et al. 2025 [5].

Table 1. Assumed thermal properties used for energy balance calculations

Parameter	Value		
	Water	Rock	Insulating foil
Density in kg/m³	997	2,700	Not relevant
Specific heat capacity in J/(kg·K)	4,186	1,000	
Heat conductivity in W/mK	0.6	3	0.2

Experimental results and conclusions for large-scale plants

Figure 1 shows the experimentally derived thermal balance of the charging–discharging cycle conducted between June and October 2024. The figure summarizes the heat stored in the water body, the heat transferred to the surrounding rock, and the heat losses associated with throughflow and surface heat exchange.
Due to the limited sensor depth of 2 m, heat propagation into deeper rock zones could not be measured directly and was therefore estimated, resulting in the uncertainty ranges indicated in Figure 1.

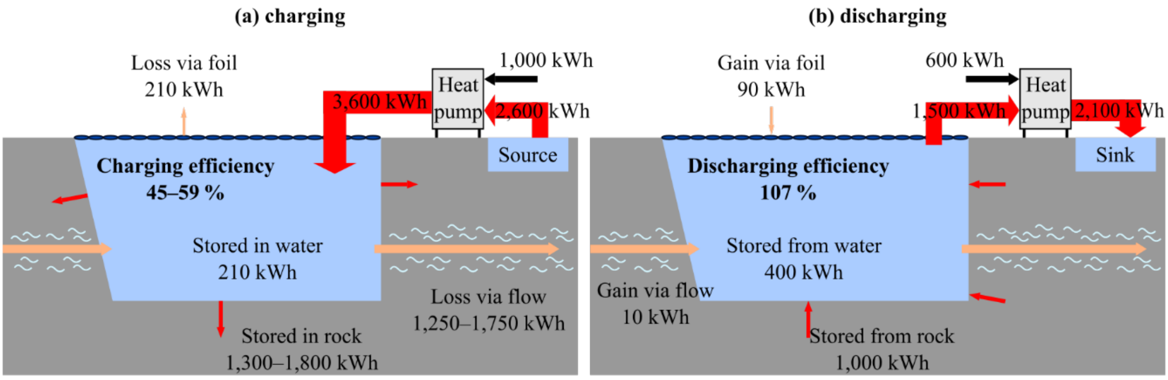

Figure 1. Schematic overview of the thermal balance of the results if the storage cycle in the Reiche Zeche real-world laboratory (June–October 2024)

However, Figure 1 also reveals that during the discharge phase (b), this throughflow contributed to a net thermal gain. As the stored water and surrounding rock cooled below the ambient temperature, the inflowing water became an additional heat source. When the storage temperature dropped below 11 °C, inflow added heat to the system; above that threshold, it caused heat losses. Overall, this effect resulted in a net gain of approximately 10 kWh. A further gain of around 90 kWh was attributed to interactions between the surface and surrounding air via the insulation foil. To calculate efficiency, the heat dissipation from water and rock as indicated by the measured values is compared to the heat actually extracted from the test rig. Due to the gains via the foil and the inflows, this results in a calculated discharge efficiency slightly above 100 %. Nevertheless, due to one week of free cooling between the first and second cooling cycles, the discharged heat energy (1,500 kWh) cannot be directly compared to the charged energy (3,600 kWh), since part of the stored heat was lost during the passive cooling period. For this reason, the 2,100 kWh ultimately transferred to the heat sink cannot be compared with the total electrical consumption of 1,600 kWh (charging and discharging) when calculating storage efficiency. Due to the experimental modifications made and the subsequent free cooling to the environment, not all of the stored energy was available at the start of the discharge process.

In total, three complete charge–discharge cycles were performed. Approximately 38,000 kWh of heat were introduced into the storage system. Considering the initial storage temperature of 11 °C and the final temperature of 4 °C, an additional initial thermal content of about 1,000 kWh was present. Roughly 16,900 kWh were discharged or remained as residual heat in the rock at the end of the experiments, corresponding to an overall storage efficiency of around 45 % (Comparison of the amount of energy charged via the test rig with the amount of energy discharged via the test bench). For the first two cycles, with lower maximum storage temperatures of 30 °C, efficiencies of nearly 60 % were achieved—significantly higher than the average across all cycles (Comparison of the energy charged via the test rig with the energy available in water and rock at the end of the charging period). In the third cycle, with a target temperature of 50 °C, greater losses occurred due to increased heat transfer to the surrounding rock, throughflow, and ambient air, resulting in an efficiency of approximately 35 to 45 %. Here, the loss or gain via the foil must be taken into account. This would not be the case if such a system were implemented on a larger scale, since an entire section of the route would normally be flooded, resulting in the complete enclosure of the water basin by rock. A comparative calculation, assuming the model basin is completely surrounded by rock but otherwise exhibiting the same behaviour, shows the efficiency could be increased by up to 5%. At low storage temperatures (below 30 °C), the effect would be closer to one percent. This is because, as described above, additional gains are achieved in the experiment via the foil at temperatures below the initial temperature (11 °C), which would also be lost if the basin were completely submerged.

Based on the results from the Reiche Zeche experiments, the storage efficiency of a mine-water-based seasonal heat storage system can be assumed to range between 35 % and 60 %. For subsequent modelling and theoretical analyses, an average efficiency of 50 % was adopted. Extrapolation to multi-year operation assumes stable boundary conditions and consistent charging potential, which should be verified in future studies.

3. Potential assessment for sample districts

Objective and modeling framework

To evaluate the potential contribution of mine-water-based seasonal thermal storage systems to the decarbonization of urban heat supply, three representative districts in Saxony (Germany, Fig. 2) were selected as case studies. The districts differ in size, heat demand density, and availability of local heat sources, allowing the influence of these parameters on storage performance to be assessed.
The modeling approach aims to quantify (i) the achievable storage utilization, (ii) the resulting degree of thermal self-sufficiency, and (iii) the interaction between storage temperature and heat pump performance at the district level.

The conceptual system layout assumes the integration of a mine-water thermal storage into a low-temperature, decentralized district heating network. The storage system supplies heat to the network, while individual buildings use heat pumps to raise the temperature to a required supply level of 55 °C. The mine-water storage is charged during periods of excess heat availability, primarily in summer, and discharged during the heating season. If neither storage nor renewable heat sources can meet demand, a backup supply based on natural gas is assumed.

The simulations were performed using an hourly time step over a full year. Storage temperatures, charging and discharging power, heat pump operation, and district heat demand were calculated dynamically.
The key model assumptions and boundary conditions are summarized below and are primarily derived from the experimental results presented in Section 2.

Model assumptions used for all districts:

- Storage temperature 2 °C to 40 °C (based on experimental results from Section 2)
- Storage efficiency: 50 % (based on experimental results from Section 2)
- Storage volume (constrained by mine geometry):
  - Small district: 5,000 m² mine water
  - Medium and large district: 10,000 m³
- Storage geometry: fully surrounded by rock (experimental surface effects excluded)
- Mine water parameters: density: 997 kg/m³, specific heat capacity: 4.186 J((kg·K) (as in section 2)
- Rock parameters: density: 2.700 J((kg·K), specific heat capacity: 1.000 J((kg·K) (as in section 2)
- Heat pump target temperature: 55 °C (resulting from district data)
- Seasonal performance factor heat pump: 2 to 5
  (variable in the model, depending on storage temperature)
- Backup heat supply: natural gas

Potential heat sources for charging the mine-water storage include solar thermal systems on rooftops and former mining areas, industrial waste heat, and excess heat from building cooling during summer.
Only heat sources that are either already available or could realistically be implemented within the district boundaries were considered. Surplus electricity-based heating options were excluded due to strong competition with other applications and limited feasibility for exclusive use in thermal storage systems.
Solar thermal potential was calculated based on the work of Wenzel et al. [13] and Heinrich et al. [14], while industrial waste heat was calculated based on companies' energy requirements. Depending on the type of operation (e.g. metal processing or the food industry), different degrees of waste heat availability were assumed. The model assumes a constant level of waste heat availability during the operating hours of individual companies. Availability parameters according to Hausl [15] were used to calculate cooling requirements.

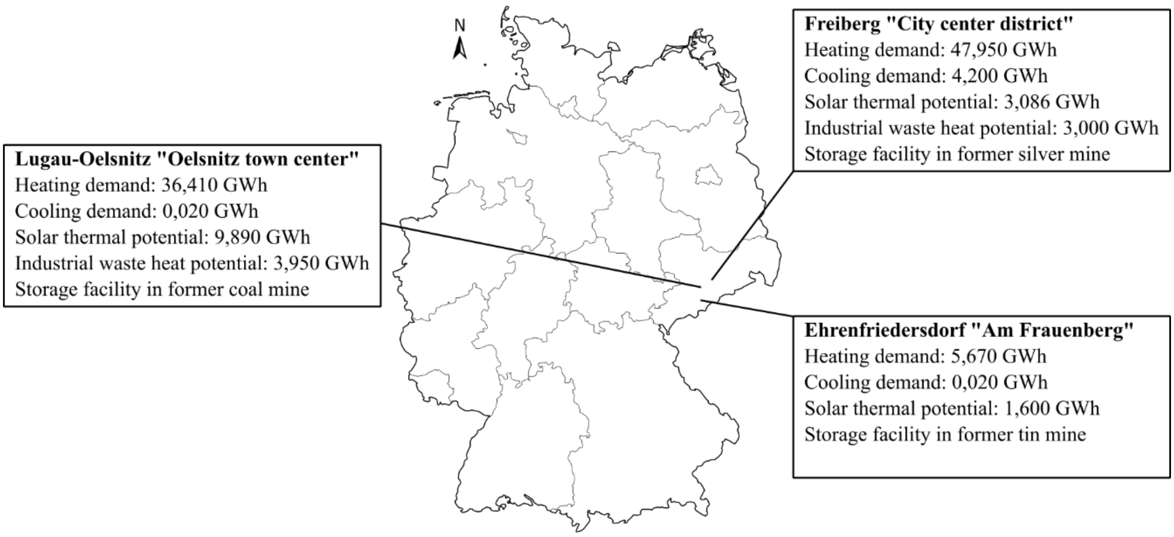

Figure 2. Overview of the districts under consideration and their demand and potential data.

At the beginning of each simulation year, the storage temperature was initialized at its minimum value of 2 °C. The model calculates hourly charging and discharging operation based on the availability of excess heat, district demand, and storage temperature.
The heat pump seasonal performance factors (SPF) vary dynamically as a function of storage temperature, linking storage utilization directly to overall system efficiency. Key output parameters include storage temperature evolution, charging and discharging power, heat source shares, and the resulting degree of district self-sufficiency.

Case study results overview

The modeling results for the three districts are presented in Figures 3 to 5 and discussed in detail in the following subsection. Each case study highlights different limiting factors, including heat source availability, storage utilization, and heat pump efficiency.
For the district in Freiberg, a mine-water storage volume of 10,000 m³ was assumed, with a storage efficiency of 50 % as derived in Section 2. At the beginning of each simulation year, the storage temperature was set to its minimum value of 2 °C. The heat pumps operated in average with a SPF of 3.2. Hourly simulations were performed to calculate the thermal mix, storage temperature evolution, and the district's overall degree of energy self-sufficiency. The results for the inner-city district of Freiberg are presented in Figure 3.

The model indicates that during summer months, surplus heat from industrial processes and potential solar thermal installations on rooftops could be used to charge the storage system. As shown by the modeled charging and discharging power, the system operates predominantly in charging mode until late August, followed by discharging until mid-October. Under the given boundary conditions, the storage capacity would be sufficient to supply the district for approximately six weeks. However, the storage potential is not fully utilized: despite allowing for charging up to 40 °C, the maximum temperature reached was only 19 °C. The limited availability of excess heat restricts the storage operation and consequently the renewable energy share of the district. Waste heat from building cooling contributes minimally—about 4,000 MWh/a, primarily from a single shopping center in the city center. This situation could change in the future if, due to rising summer temperatures, more buildings integrate cooling systems. Under the present assumptions, the self-sufficiency rate of the district amounts to 23 %, meaning that 77 % of the thermal demand would still need to be supplied externally. The Integration of an additional industrial waste heat source (with a potential of 39,600 MWh/a) would increase the self-sufficiency to 78 %, allowing storage-supported operation until the end of December.

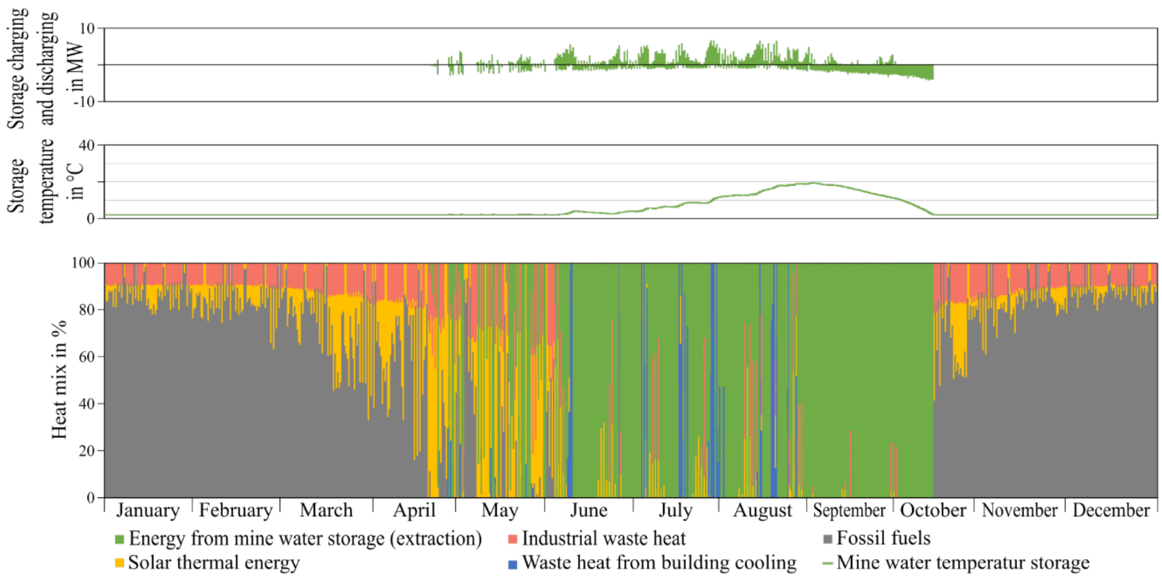

Figure 3. Results of modeling the storage operation of the district in Freiberg over one year, with hourly charging and discharging capacity (top), storage temperature (middle), and heat mix (bottom). (Assumptions: heat storage volume 10,000 m³, max. discharge capacity = 10 MW, minimum/maximum temperature = 2°C, 40°C, storage efficiency = 50%)

For the small-town district of Ehrenfriedersdorf, characterized by lower energy demand, a mine-water storage volume of 5,000 m³ was assumed. As shown in Figure 4, the maximum storage level would occur between late August and early September, with a peak temperature of around 30 °C. The heat pumps would operate at an average SPF of 4.0. Despite incomplete storage utilization, the stored energy would be sufficient to cover nearly the entire annual demand, with external (fossil) backup required only from early January to mid-March. The model results in a self-sufficiency rate of 67 %. A key factor in this scenario is the inclusion of a potential solar-thermal field on the former mine tailings area. However, the economic viability of such high-investment renewable sources is addressed separately in Section 4.

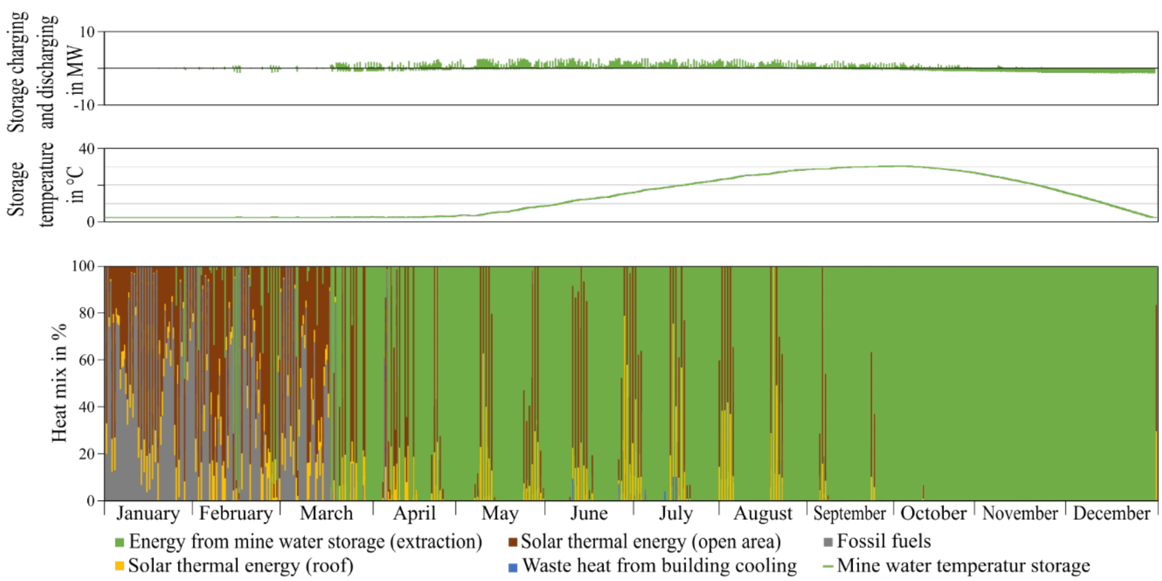

Figure 4. Results of modeling the storage operation of district Ehrenfriedersdorf over one year, with hourly charging and discharging capacity (top), storage temperature (middle), and heat mix (bottom). (assumptions: heat storage volume 5,000 m³, max. discharge capacity = 10 MW, minimum/maximum temperature = 2°C, 40°C, storage efficiency = 50%)

For the example district in the former Lugau–Oelsnitz mining area, again a storage volume of 10,000 m³ was assumed. As shown in Figure 5, no significant long-term storage effect develops in this case. The mine-water reservoir would primarily function as a short-term buffer, balancing daily fluctuations—for instance, between daytime solar thermal generation and nighttime demand. The maximum storage temperature reaches only 3 °C, resulting in a relatively low average SPF of 2.5 for the heat pumps. Waste heat from building cooling again contributes negligibly, with only 13 MWh/a available under current conditions. Despite the lack of long-term storage, the self-sufficiency rate reaches 45 %, as most of the available renewable heat is used directly rather than stored. A reduction of the storage volume to 5,000 m³ would have little impact on performance, as the storage temperature would remain nearly constant at 3 °C.

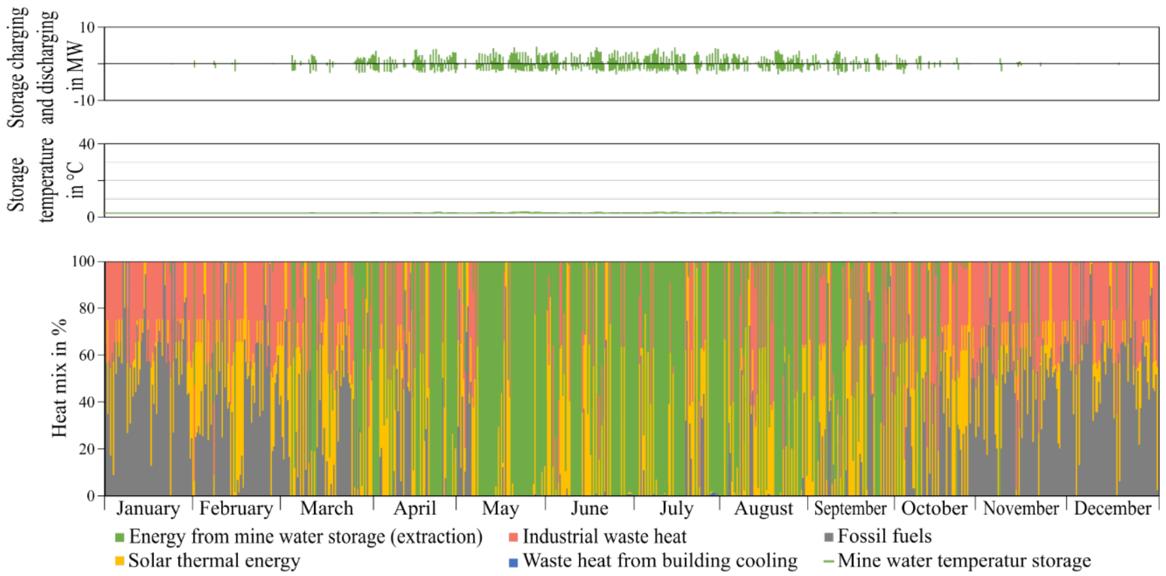

Figure 5. Results of modeling the storage operation of district Lugau-Oelsnitz over one year, with hourly charging and discharging capacity (top), storage charge status (middle), and heat mix (bottom). (assumptions: heat storage volume 10,000 m³, max. discharge capacity = 10 MW, minimum/maximum temperature = 2°C, 40°C, storage efficiency = 50%)

Across all three case studies, a key challenge becomes evident: securing sufficient heat for seasonal storage charging. Particularly in the larger districts of Freiberg and Lugau–Oelsnitz, integrating industrial waste heat is essential to achieve storage durations of several weeks. Moreover, storage utilization is closely linked to the efficiency of the heat pumps. As demonstrated in the Lugau–Oelsnitz scenario, low storage temperatures reduce the heat pump SPF and consequently the overall system efficiency. The economic implications of these findings are discussed in the following section.

Role of heat pumps

The overall efficiency and applicability of mine-water-based seasonal thermal storage systems is largely determined by heat pumps. They are the key interface between the storage temperature and the temperature requirements of the district heating network and end users. As demonstrated by district-scale simulations, the storage temperature directly affects the SPF of the heat pumps and consequently the utilisation of stored thermal energy.

When there is sufficient excess heat available to raise storage temperatures above 20 °C for extended periods, the SPF of heat pumps is high (>3.5), enabling an efficient heat supply and high degrees of district self-sufficiency. Conversely, in cases with limited charging potential, such as in the Lugau–Oelsnitz district, storage temperatures remain close to the minimum operating level. This results in significantly reduced heat pump efficiency and limits the benefits of long-term storage.

These findings emphasise that mine-water storage systems must be evaluated in conjunction with heat pump performance. Instead, storage design, charging strategy and heat pump operation must be considered together as an integrated system. From a planning perspective, ensuring sufficient seasonal charging potential is therefore at least as important as the storage volume itself. Without adequate storage temperatures, the mine-water reservoir primarily functions as a short-term buffer rather than a seasonal storage system.

4. Economic efficiency of the sample districts

The implementation of mine-water thermal storage systems is only feasible if economically viable operation can be ensured. Therefore, the three sample districts were subjected to an economic assessment following VDI 2067 [9]. Full-cost calculations were performed based on payback relative to an alternative supply with natural gas. All other assumptions are summarized in Table 2. The results for payback periods and net present value (NPV) are presented in Figure 6, where the NPV is indicated by colored circles and the payback period by the position on the grid. The economic efficiency calculation is carried out with the aim of achieving pure cost coverage compared to a natural gas solution without profit. This means that the NPV for a mine water storage system is calculated, whereby the profits represent the savings achieved when heat is provided from the storage facility or renewable sources instead of natural gas. Three variants were evaluated for each district:

- **Variant A – Storage only, no network, no additional heat sources:** Economic assessment includes only the investment costs for the storage system, heat pump, and heat exchanger, excluding costs for a district heating network or additional heat sources, such as solar thermal systems or industrial waste heat.
- **Variant B – Storage with network, without additional heat sources:** Variant A plus the costs for construction and operation of a district heating network.
- **Variant C – Storage with network and additional heat sources:** Variant B plus the costs for construction and operation of the heat sources feeding the storage system (solar thermal + industrial waste heat).

For each variant, calculations were performed both without subsidies (yellow) and with subsidies (green). Subsidies were assumed according to the Federal Funding Program for Efficient District Heating Networks [10,11]. Additionally, fouling in the heat exchangers between mine water and the district heating network was considered, reducing heat transfer efficiency over time. For further details on this assumption, see Oppelt et al., 2025 [12]. The assumptions regarding the economic conditions are summarized in Table 2 below.

Table 2. Assumed economic conditions

Parameter	Value	Base for assumption	Parameter	Value	Base for assumption
Energy prices in €/kWh			Price changes per year in %		
Electricity price	0.32	[13]	Discount rate	2.75	[16]
Electricity price (heat pump)	0.25	[14]	Deposit/consumption-related costs	6.27	Average cost development from 2020 to 2025
Natural gas price	0.17	[15]	Operating-related costs	2.53	
			Maintenance costs	7.04	

The results clearly indicate that for the Freiberg district, all variants achieve payback. Even when including the costs of a district heating network and all potential heat sources, the payback period is approximately 14 years. The storage system alone would reach payback in just over 3 years, and with subsidies, in only 2 years.

These results could not be achieved at the other two sites. In Ehrenfriedersdorf, the concept is economically feasible only with subsidies when all components are included, resulting in a payback of about 14.5 years and an NPV of approximately €4.5 million. In the same scenario, Freiberg achieves an NPV exceeding €60 million. In Lugau–Oelsnitz, the mine-water storage system alone is only economically viable if the network and all heat sources are already available. This highlights, as discussed in Section 5, that significantly more heat sources would be required in Lugau–Oelsnitz to achieve an effective and economically viable concept.

The underlying reason is a poor heat availability-to-consumer ratio: for the district size, only limited storable heat is available from solar thermal systems, cooling, and industrial waste heat. While this ratio exceeds 20,000 kWh per consumer in Freiberg and Ehrenfriedersdorf, it is only 13,800 kWh per consumer in Lugau–Oelsnitz. Reducing the district size while maintaining industrial waste heat potential could lead to an economically feasible solution.

In summary, the economic assessment demonstrates that profitability is strongly site-dependent. In the best-case scenario, as in Freiberg, strong seasonal charging potential exists from solar thermal and, in particular, industrial and building cooling waste heat, combined with a locally concentrated winter heat demand. This confirms that mine-water thermal storage can provide a viable solution for urban areas in former mining regions, where potential heat sources and sinks are located in close proximity to abandoned and flooded mines.

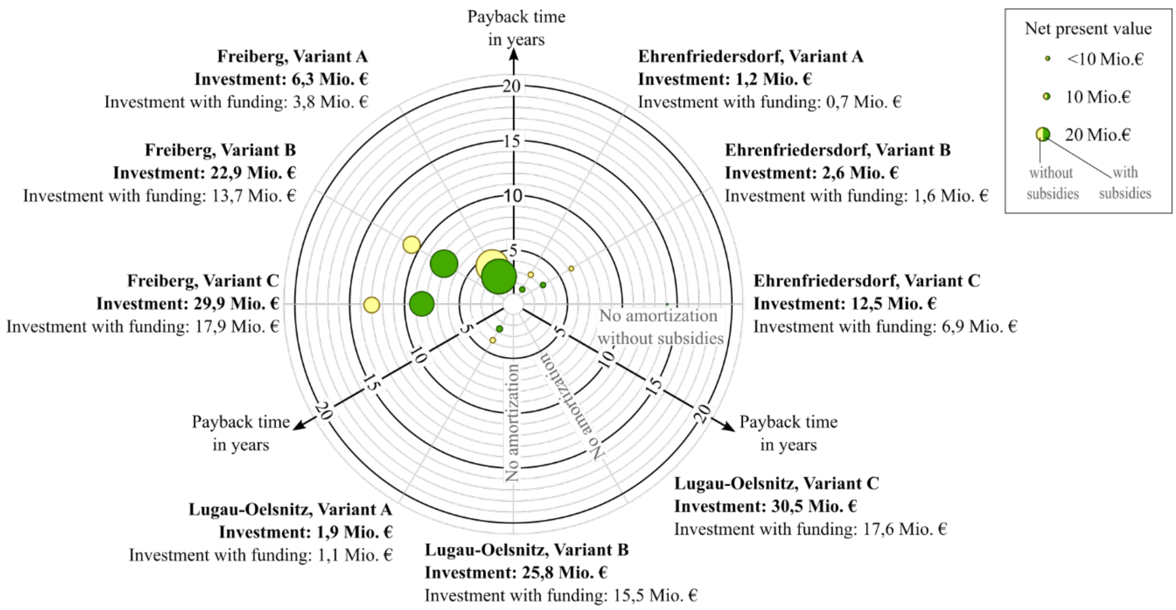

Figure 6. Results of the economic efficiency calculation for the districts under consideration

5. Conclusion

This study investigates the potential of mine-water thermal storage systems for the decarbonization of urban heating in former mining regions. Based on a model-scale experimental facility at the former silver mine “Reiche Zeche” in Freiberg, key insights into the efficiency and thermal behavior of mine-water storage systems were obtained. The experiments demonstrated that storage efficiencies between 35 % and 60 % are achievable, depending on maximum storage temperature, throughflow losses, and the availability of external heat sources.

Using the experimental results as boundary conditions, three representative districts in Saxony were modeled to assess the potential of seasonal energy storage at the district scale. The analysis showed that the availability of excess heat—particularly from industrial waste heat and solar thermal installations—and the density of heat demand are critical for achieving high self-sufficiency rates. In Freiberg, a high degree of autonomy could be reached, whereas smaller districts or those with limited heat supply, such as Lugau–Oelsnitz, demonstrated only partial benefits from this technology. If there is insufficient heat available for storage and the mine water heat storage therefore only reach low temperatures, the SPFs of the heat pumps at the consumer end also suffer. It is therefore advisable to ensure that the seasonal storage tank is very well equipped, i.e. with periods of temperatures > 20 °C lasting as long as possible.

The economic assessment highlights that profitability is highly site-dependent. While the storage system in Freiberg achieves payback within a few years, other districts require additional heat sources or adjustments to district size to reach economic viability. This once again demonstrates that mine water heat storage systems are particularly well-suited to urban areas. Subsidies significantly improve the economic outcome and are often essential for locations with limited heat availability. Sensitivity to variations in industrial waste heat, solar thermal potential, and heat pump performance should be considered in future planning to ensure robust and reliable operation.

Overall, the study demonstrates that mine-water thermal storage systems offer a promising solution for seasonal thermal energy storage in urban areas of former mining regions. The combination of locally available heat sources, appropriately sized storage, and efficient heat pumps is crucial to achieve both technical efficiency and economic feasibility. Future research should further investigate long-term performance, seasonal variability, and sensitivities to different heat sources and operational configurations to support transferability to other regions.

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