Solar Heating with Seasonal Storage in Bracht: Construction, Initial Operation and Night-time Cooling against Stagnation

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Abstract

The Bracht solar district heating system is a rural network that supplies an existing village predominantly with solar heat from an 11,640 m² collector field coupled to a seasonal 26,600 m³ pit thermal energy storage, targeting about 98% CO_2 reduction compared to the current situation. The construction challenges posed by groundwater ingress, constrained water supply for filling, and the lack of market-ready submerged temperature measurement were addressed through targeted engineering and a bespoke measurement setup. A comprehensive instrumentation package facilitates closed energy and mass balances, as well as model validation. The primary operational challenge pertains to elevated summer input, a consequence of updated 2030 irradiance statistics. This update leads to a risk of stagnation, particularly when considering limited storage capacity due to economic design of the system. Instead of installing a recooler, an evaluation of night cooling strategies was conducted that utilizes the collector field as a dissipative sink. The results of the simulations indicate that the potential for late-summer cooling is approximately 2–2.5 kWh per m² per night (equivalent to 17–25 MWh). Preliminary results indicate that predictive scheduling can eliminate the risk of stagnation while achieving full seasonal charge, positioning Bracht as a test bed for control strategies in high-solar rural district heating.

Keywords: Solar District Heating, Seasonal Storage, Stagnation Risk and Avoidance, Night Cooling

1. Introduction

The district heating network in Rauschenberg-Bracht (Germany) is designed to supply an existing (rural) village predominantly with solar-derived heat, supported by seasonal thermal heat storage and complementary renewable technologies. The large share of solar thermal energy is achieved with a combination of a large solar thermal collector field and a seasonal pit thermal energy storage. Two large internal heat pumps provide operational flexibility, temperature lift, and resilience under variable ambient conditions. In contrast to most existing heating networks, where solar heat typically accounts for only a minor share, the Bracht system is configured with solar thermal energy as the primary source, making it a demonstrator for high-renewable district heating in dispersed rural settings.

The innovative main component of the system is the PTES. It is essential for achieving high coverage levels and is one of the first of its kind in Germany. Several large-scale pit thermal energy storages (PTES) are currently in operation in Europe, with six located in Denmark and two smaller systems in Germany (IEA Task 39). Additional plants are under construction, such as the PTES in Hyvinkää, Finland, with a planned volume of 380,000 m³ (Hyvinkään Lämpövoima, 2026). Except for the systems in Hyvinkää and Høje-Taastrup, most existing PTES are implemented in small or suburban district heating networks operating at relatively low supply temperatures and typically storing heat from a single dominant source such as solar thermal energy or industrial waste heat (Renne, 2023). In Høje-Taastrup (Copenhagen metropolitan area) a PTES with 70,000 m³ is integrated into a large urban district heating system; however, it is operated as a short-term rather than seasonal storage (Sifnaios et al., 2025). Well-documented reference plants such as Marstal, Dronninglund, and Høje-Taastrup provide extensive monitoring data and form the basis for validation of simulation models (Sifnaios et al., 2023; Sifnaios et al., 2025).

Early experience with seasonal solar thermal energy storage in Germany was gained within the Solarthermie2000 and Solarthermie2000plus programs, where gravel-water, tank, aquifer, borehole, and pit storages were investigated (Adam et al., 2016). These systems were significantly smaller than current PTES concepts, with storage volumes typically between 1,000 m³ and 12,000 m³ (Bauer et al., 2010).

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Within the BMWi project GreenHeat³, the integration of a large-scale PTES of up to 500,000 m³ into the district heating system of Dresden was analyzed, focusing among other points on coupling with solar thermal systems (Weinhold et al., 2019). Although technical feasibility was demonstrated by simulation and feasibility studies, the subsequent demonstration project CityImpuls DD was not realized (Dresden, 2020). Comparable preparatory work for a large seasonal PTES in an urban district heating system was carried out in the ProSaHRO project for the city of Rostock, resulting in a development roadmap for a large-scale PTES project (ProSaHRO). The PTES in Rostock is one of the demonstration plants of the EU project TRESURE (TREASURE). TRESURE builds on earlier theoretical work within gigaTES and addresses material concepts, construction methods, risk management, and implementation strategies in connection with IEA Energy Storage Tasks 39 and 45 (IEA Task 39; IEA Task 45).

In Germany, solar district heating networks have so far been implemented only at a comparatively small scale and with moderate solar fractions, especially for existing villages. All realized systems with seasonal storages to date operate with solar shares typically below 50 % (Bauer et al., 2010), other systems which smaller or no storages typically range between 1 and 20 % solar fraction (Sandrock et al., 2020; Leipzig, 2026).

Therefore, the Bracht project represents a significant advancement in technology, as it will provide completely CO2-neutral, solar-based heating to a rural village – already meeting Germany's climate protection targets for 2045.

2. Description of the System

The technical configuration comprises of 11,640 m² flat-plate collectors feeding a 26,600 m³ pit thermal energy storage, a 700 kW thermal wood-fired boiler, and two heat pumps with a combined thermal capacity of about 1.2 MW (see Figure 1). The distribution network extends over roughly 9.7 kilometers and currently connects 193 buildings. Based on the anticipated operating profile and replacement of fossil fuels, the system is expected to reduce carbon dioxide emissions by approximately 98 % relative to conventional individual heating. The seasonal storage enables inter-temporal shifting of solar gains from summer to winter, stabilizing supply during periods of low irradiance and high demand, and thereby allows the collector field to be sized for a high annual coverage without relying on continuous real-time matching between generation and consumption.

The project has been realized through a locally organized cooperative model that achieved a high participation rate among residents, with about sixty percent of houses opting for connection. The solar district heating network reduces the need for extensive renovations to individual buildings, which is particularly beneficial in rural areas where the propensity for retrofitting is often limited due to comparatively low property values. Implementation relied on substantial volunteer engagement and pragmatic engineering solutions, including the temporary use of fire hoses to establish a direct water supply line from a nearby well, which enabled the storage to be filled over a six-month period despite constraints in conventional infrastructure. The system is accompanied by an academic monitoring and research programme (BMWE project "ruralHeat", FKZ: 03EN6031, and additional measurement equipment funded by State of Hesse FKZ: E/611/71690944), positioning Bracht as a real-world test bed for operating strategies and model validation, and as a replicable template for climate-neutral heat supply in similar rural contexts.

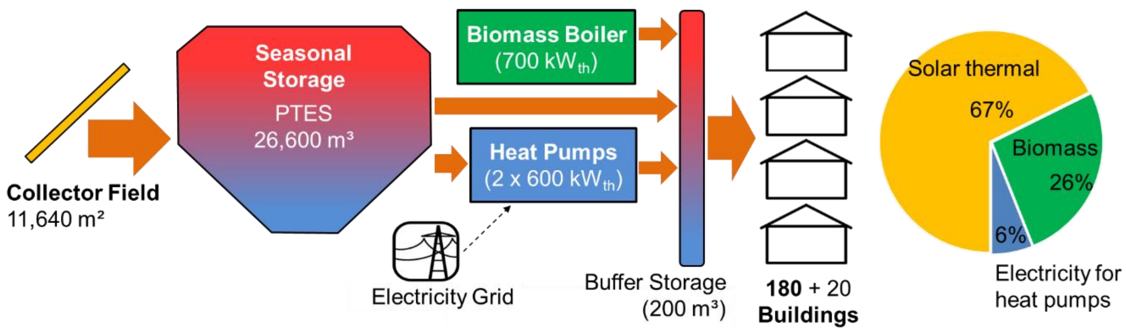


Figure 1: Schematic Component dimensions (left) and share of heat supply (right)

3. Construction Phase and Challenges to be Overcome

During construction, several technical challenges were encountered and resolved through targeted

Figure 2: Water supply system constructed by citizen's cooperative.

engineering measures and pragmatic project management. Heavy rainfall led to groundwater ingress into the excavation, necessitating local stabilization of embankments and walls with concrete to ensure structural integrity and to maintain the required geometry of the pit. Water provision for initial filling of the PTES was constrained by limited on-site supply. To address this, temporary conveyance routes were established, including the partial use of fire hoses and district heating pipes to transport water to the storage (see Figure 2). Commissioning protocols then included extensive flushing of the affected pipe sections to restore hydraulic performance and assure water quality before regular operation.

Cost increases of approximately thirty percent emerged during the planning phase, which placed demands on the governance and budgeting capacity of the local citizens' cooperative. The implementation of certain procedures autonomously, such as the installation of the PTES top cover, helped to reduce financial pressure on the cooperative. In total, the construction time was about two years from start to finish, as shown in Figure 3.
Measurement equipment, especially for directly submerged, high-resolution temperature measurement in the PTES, posed a separate challenge, as no off-the-shelf solution was available. Therefore, a measurement system was designed and implemented, with consultation with manufacturers and research partners.

Figure 3: Construction site before the start of construction and after completion of the work.

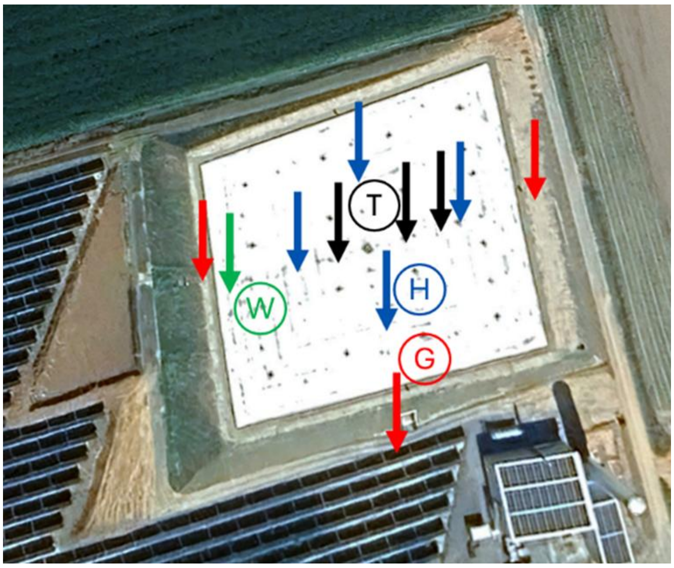
4. Extensive Measurement of the System, esp. PTES

The measurement concept is designed to quantify the dominant loss pathways of the pit thermal energy storage and to resolve its internal thermal state with sufficient spatial detail for model validation. The aerial view of the storage in Figure 4 illustrates the locations and types of the installed sensors. Red markers labeled G (ground) denote temperature measurements in borehole installations in the surrounding soil. These vertical boreholes extend to approximately the storage depth of 14 m and are placed immediately adjacent to the pit to

Figure 4: Sensor types and positions for measuring PTES.

measure the temperature field in the ground and thereby infer conductive heat losses from the side walls. An additional borehole on the southern side at a greater distance captures the far field soil temperature response, which helps distinguish local losses from background seasonal variations and constrains soil thermal properties in the model.

Blue markers labeled H identify four heat flux sensors in the different areas of the top cover. These sensors provide direct measurements of the upward heat flow through the cover assembly and enable an estimation for the top boundary losses of the storage. Moreover, their measurement can be used to detect whether moisture



has penetrated the insulation material. Green markers labeled W indicate sensors at the soil side of the storage wall. This position captures the lateral temperature at the wall interface and supports the estimation of circumferential heat losses in conjunction with the adjacent ground measurements.

Black markers labeled T correspond to three vertical temperature measurement chains within the water volume. These profiles show the stratification of the storage, the effective state of charge to be derived, and provide the top layer temperature required to enforce the operational limit of 85 °C. Together, the external ground measurements, top cover heat flux sensors, wall measurements, and internal temperature chains form a coherent dataset that links boundary heat losses to the evolving internal temperature field. The resulting data will be used to calibrate and validate the PTES model and to support the development of control strategies for charging, discharging, and night cooling.

Beyond the PTES-specific instrumentation, the plant is equipped with extensive measurement equipment across heat generation, storage, and distribution to enable closed energy and mass balances. Measurements include irradiance and collector field temperatures, mass flows and pressures at collector and storage inlets and outlets, supply and return temperatures and volume flows in the district network, electrical power consumption of pumps, heat pumps, and auxiliary equipment, heat pump operating parameters for COP determination, biomass boiler thermal output, and outdoor ambient temperature. All sensors are integrated into a common data acquisition system and are subject to calibration and plausibility checks. This ensures that charging and discharging capacities, cover and ground losses, distribution losses, and end-use delivery can be compared, providing a reliable basis for model validation and for the assessment of control strategies.

To draw on existing experience, several meetings were held with Danish Technological University (DTU) during the planning of the measuring points. As DTU manages several PTES in Denmark, they were able to provide valuable input on how to measure the earth basin storage facility effectively.

5. Stagnation and Night Cooling

4.1 Effects of Increased Irradiance Forecast for 2030

As previously outlined, the Bracht system can supply a substantial share of winter heat demand from solar energy by utilizing irradiance captured in summer in conjunction with seasonal storage. For economic reasons, the dimensioning of the PTES in Bracht is relatively small compared to the collector field size. That brings the risk, that under summer conditions when solar gains peak and demand is limited, the large solar thermal system is vulnerable to stagnation due to a fixed maximum storage temperature. According to the manufacturer, stagnation should be avoided, if possible, since the thermal stress would eventually destroy components or cause leakages, which in turn entails high repair and maintenance costs. To ascertain the risk of stagnation, a critical prerequisite is an accurate description of site-specific solar irradiance. The update of the Meteonorm dataset for 2030, specifically the revised irradiance statistics, worsened the problem examined here.

Figure 5 contrasts global irradiance derived from the dataset used for the original system dimensioning with values from the updated Meteonorm version for 2030 and shows systematic increases in annual totals and a greater incidence of prolonged high irradiance episodes. This revision leads to substantially higher input energy than previously assumed when the system was dimensioned using Meteonorm 7 data and raises the risk of stagnation unless control measures are adapted accordingly. For that reason, weather data from a P10 year was used to assess the risks and to guide the selection of suitable avoidance measures. This choice provides a defensible worst-case envelope and allows the system to be evaluated against conditions that are likely to occur only several times over the service life.

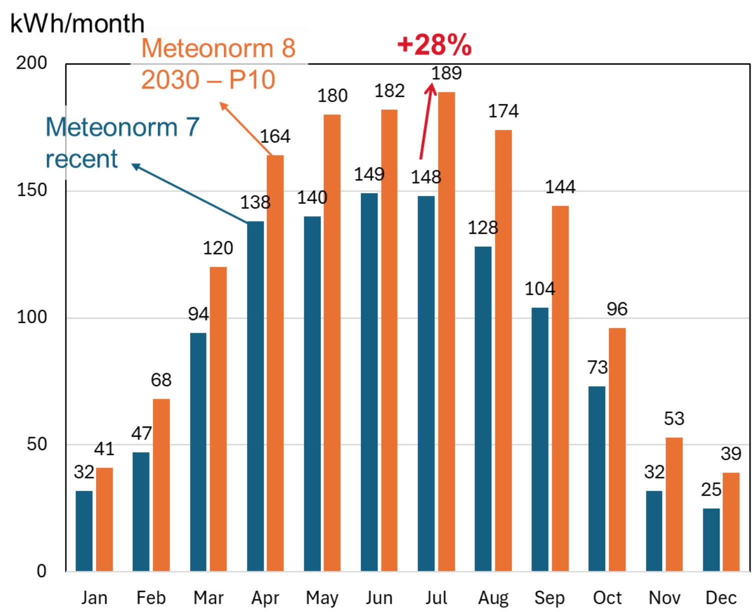
4.2 Possible Measures Against Stagnation:

The technical standard solution for dismissing excess heat during extended periods of high irradiance is the deployment of a dedicated recooler with the capacity of the whole collector field (here approx. 7 MW). This measure is expected to prevent stagnation altogether as the recooler can be in operation in parallel without impeding the functionality of the overall system or even single components. Nevertheless, this solution would require an additional invest of approximately 250 k€. Furthermore, it would necessitate space, integration and auxiliary power requirements.

A solution based (almost) only on the already existing components is night cooling. Here, the PTES is cooled through the collector field by operating the pumps when there is no irradiance and the ambient temperature is lower than the respective storage temperature. This process serves to restore thermal headroom in the storage system, thereby ensuring sufficient capacity for the following day's operation. Night cooling is widely known and used in smaller solar thermal systems, often declared as a “vacation function” for times when no heat demand is present. Since almost no additional components have to be installed, night cooling presents itself as a cost-effective alternative.

For night cooling the main challenge can be delineated by two primary objectives: the complete avoidance of stagnation during daytime operation and the overarching goal of a fully charged PTES by the end of summer.

Figure 5: Differnce in Global irradiation from weather data first used for system design and a high irradiation y(p10) year for 2030.



It is imperative that night-time cooling is scheduled and sized in a manner that ensures a sufficient buffer prior to the occurrence of high irradiance days. The Bracht installation is being used to develop and validate a suitable control strategy for large-scale night cooling.

4.3 Description of night cooling strategy:

Figure 6 illustrates the maximum for the incoming solar heat and the dissipative capacity for night cooling in the summer months. The upper (blue) curve shows the clear sky irradiance multiplied with a factor 0.5, which is a very conservative upper envelope for the maximum heat gain. This maximum possible input declines over the season as day length and solar elevation decrease. The pink curve represents the daily night cooling potential, calculated with a mean collector temperature of 70 °C, the mean daily ambient temperature and an assumed night cooling operation from sunset to sunrise. Since the ambient temperature is used as a daily mean, this potential also represents a conservative estimation. The night cooling potential rises from July onward because nights become longer and ambient temperatures drop. The two curves intersect around the end of September. This intersection marks the point, where the night cooling potential exceeds the maximum possible solar heat gain. Thus, after the intersection, no storage capacity is needed to avoid stagnation, the daily yield can be dissipated during the respective night.

The area between the blue and pink curves up to the intersection marks the storage capacity that must be reserved to avoid stagnation, since only the energy under the night cooling curve can be removed per night. Simulations indicate a high late summer cooling potential of about 2 to 2.5 kWh/m² per night.

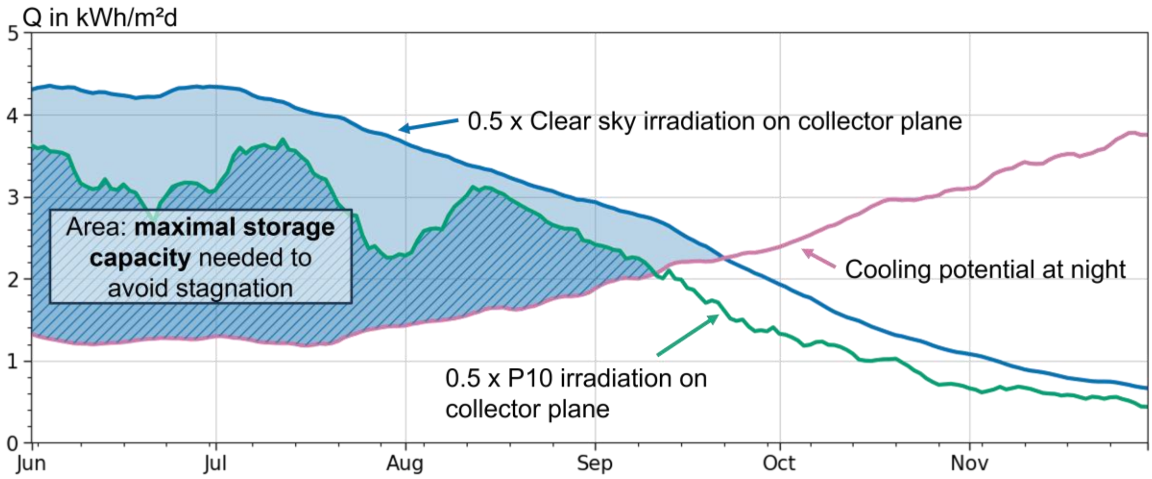


Figure 6: Night cooling potential and radiation on collector plane for clear sky conditions and a P10 weather year for 2030.

The clear sky example demonstrates that a purely operational night cooling strategy can be sufficient even in an exceptionally, unrealistically sunny scenario. The green line illustrates the P10 weather data (Meteonorm) for the year 2030, which predict more realistically maximal solar radiation and consequently sufficient nighttime cooling earlier in the year.

Operationally, the required free storage capacity at any time depends on the anticipated solar thermal yield, estimated from weather forecasts or a clear sky reference, and on the expected night cooling capacity, which is determined by ambient temperature and the number of night hours without irradiation. An intelligent control strategy must schedule night cooling so that adequate headroom is created ahead of forecasted high input days, while ensuring that the cumulative surplus between the two curves can be buffered until they cross. This implies adaptive planning of discharge during nights and continuous updating of targets as forecasts and measured ambient conditions evolve. In practice, night cooling should be terminated as early as practicable in late summer to preserve charging opportunities and to enable a fully charged PTES by the start of the heating season. Preliminary simulations for the Bracht system indicate that, with such predictive scheduling, complete avoidance of stagnation can be achieved while still reaching a full state of charge by fall.

6. Summary and Conclusion

In summary, the Bracht system has progressed to completion despite several setbacks during planning and installation, and first heat delivery is planned for fall/winter 2025. As the first climate-neutral heat supply for an existing village in Germany based on solar energy, it provides a blueprint for renewable heat supply in rural areas without the extensive use of biomass. The PTES volume of 26,600 m³ reflects an economic sizing that is relatively small in relation to the collector field, and this constraint, together with higher irradiance estimates for 2030 and 2045, elevates the likelihood of summer generation–storage mismatch. Prolonged stagnation must be avoided to protect both the collector field and the storage, while still achieving a fully charged PTES by the end of the season. The analyses conducted to date indicate that the practical capacity for night cooling is substantially larger than commonly communicated by industry, suggesting that an operational strategy based on night cooling is feasible if it is managed intelligently. A predictive control approach that calculates and maintains the necessary free storage capacity, informed by forecasted solar yield and ambient conditions, will be tested in Bracht. To enable rigorous evaluation and model improvement, extensive sensor equipment has been installed for in-depth analysis. The resulting data will be used to further develop and validate the PTES model, with the aim of translating site-specific experience into robust guidance for large-scale solar thermal systems facing similar constraints.

7. Acknowledgement

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8. Declaration of Generative AI and AI-assisted technologies

During the preparation of this work the authors used "DeepL" and "DeepL-Write" for translation and in order to check grammar and improve readability of the text. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the content.

9. References

M. Adam, H. P. Wirth, F. Ille und J. Gottschald, 2016. ST2000-LangEff Schlussbericht: "Langzeitstudie zum Betrieb und zur Leistungsfähigkeit großer Solaranlagen aus dem Solarthermie-2000 und Solarthermie2000plus Programm" ST2000-LangEff Schlussbericht, doi: 10.2314/GBV:895457717.

D. Bauer, R. Marx, J. Nußbicker-Lux, F. Ochs, W. Heidemann und H. Müller-Steinhagen, 2010. German central solar heating plants with seasonal heat storage, Solar Energy, Jg. 84, Nr. 4, S. 612–623, 2010. doi: 10.1016/j.solener.2009.05.013. [Online]. https://www.sciencedirect.com/science/article/pii/S0038092X09001224

D. Renne, 2023, Proceedings of Solar World Congress 2023. Freiburg, Germany: International Solar Energy Society, Oct. 2023 - Nov. 2023, doi:10.18086/swc.2023.

Dresden, 2020. Klimaschutz in der Landeshauptstadt Dresden: Neunte Berichterstattung zum Beschluss „V2021/12 Integriertes Energie- und Klimaschutzkonzept Dresden 2030 vom 20.06.2013" Dec. 2020. [Online]. https://www.dresden.de/media/pdf/umwelt/klimaschutz/neue-seiten-2020/Beschlusskontrolle_IEuKK_2020.pdf

M. Sandrock, C. Maaß, S. Weisleder, C. Baisch, G. Löschan, H. Kreuter, D. Reyer, D. Mangold, M. Riegger, C. Köhler, 2020. Ein neuer Weg zu effizienten Wärmenetzen mit Niedertemperaturwärmeströmen, German Environment Agency, December 2020

I. Sifnaios, G. Gauthier, D. Trier, J. Fan, and A. Jensen, 2022. Dronninglund water pit thermal energy storage dataset, Solar Energy, Jg. 251, S. 68–76, 2023. doi: 10.1016/j.solener.2022.12.046. [Online]. Verfügbar unter: https://www.sciencedirect.com/science/article/pii/S0038092X22009252

I. Sifnaios, A. Jensen, S. Furbo, and J. Fan, 2023. Heat losses in water pit thermal energy storage systems in the presence of groundwater, Applied Thermal Engineering, Jg. 235, S. 121382, 2023. doi:

10.1016/j.applthermaleng.2023.121382. [Online]. Verfügbar unter: https://www.sciencedirect.com/science/article/pii/S1359431123014114

I. Sifnaios, S. Furbo, and A. Jensen, 2025. Monitoring data of the Høje Taastrup water pit thermal energy storage, Data in Brief, Jg. 58, S. 111305, 2025. doi: 10.1016/j.dib.2025.111305. [Online] https://www.sciencedirect.com/science/article/pii/S235234092500037X

K. Weinhold et al., 2019. Green Heat³ : Entwicklung innovativer Energieversorgungstechniken und -strukturen mit den Kernkomponenten modularer Großwärmespeicher und Maxianlage Solarthermie : koordinierter Schlussbericht zum BMWi-Verbundvorhaben FKZ 0325872 : Teilprojekt: Technisch-wirtschaftliche Systemuntersuchung (0325872 A); Teilprojekt: Wissenschaftliche Modellierung Komponenten und System (0325872 B); Teilprojekt: Baugrundseitige Aspekte Großwärmespeicher (0325872 C) : Laufzeit des Vorhabens:01.12.2016 bis 31.03.2019 (in de), 16082019. Aufl. Dresden: DREWAG Stadtwerke Dresden GmbH, doi: 10.2314/KXP:1821595823.

References for research projects

GeoSpeicherBerlin: EnArgus database. Last accessed February 2026. [Online] https://www.enargus.de/detail/?id=31411276

Hyvinkään Lämpövoima. "Hyvinkäästä edelläkävijä uusiutuvan energian varastoinnissa - Hyvinkään Lämpövoima." Last accessed: 9. February 2026. [Online.] https://hlv.fi/ajankohtaista/maailman-suurin-lampovarasto-hyvinkaalle/

IEA Energy Storage Task 39. "Deliverables." Last accessed: 9. February 2026. [Online] https://iea-es.org/task-39/deliverables/

IEA Energy Storage Task 45. " Accelerating the Uptake of Large Thermal Energy Storages" Last accessed: February 2026. [Online.] https://iea-es.org/task-45/

Leipzig: Die neue Solarthermie Leipzig West. Last accessed March 2026 [Online] https://zukunft-fernwaerme.de/solarthermie-leipzig-west/

ProSaHRO: EnArgus database. Last accessed February 2026. [Online] https://www.enargus.de/pub/bscw.cgi/?op=enargus.eps2&q=HIR%20Hamburg%20Institut%20Research%20gGmbH&v=10&id=26094928

ruralHeat: EnArgus database. Last accessed February 2026. [Online] https://www.enargus.de/detail/?id=27519505

TREASURE. Last accessed February 2026. [Online.] https://www.treasure-project.eu/