

Article

Experimental Testing of New Concrete-Based, Medium-Temperature Thermal Energy Storage Charged by Both a Thermal and Electrical Power Source

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Abstract

This study aims to explore a new concept for a Power to Heat (P2H) device and demonstrate its effectiveness compared to a thermal heating method. The proposed concept is a medium-temperature system where electro-thermal conversion occurs via the Joule effect in a metallic tube (resistive element). This tube also serves as a heat exchange surface between the heat transfer fluid and the thermal storage medium. The heat storage material here proposed consists of base concrete formulated on purpose to ensure its operation at high temperatures, good performance and prolonged thermal stability. The addition of 10%_{wt} phase change material (i.e., solar salts) stabilized in shape through a diatomite porous matrix allows the energy density stored in the medium itself to increase (hybrid sensible/latent system). Testing of the heat storage module has been conducted within a temperature range of 220–280 °C. An experimental comparison of charging times has demonstrated that electric heating exhibits faster dynamics compared to thermal heating. In both electrical and thermal heating methods, the concrete module has achieved 86% of its theoretical storage capacity, limited by thermal losses. In conclusion, this study successfully demonstrates the viability and efficiency of the proposed hybrid sensible/latent P2H system, highlighting the faster charging dynamics of direct electrical heating compared to conventional thermal methods, while achieving a comparable storage capacity despite thermal losses.

Keywords: thermal energy storage; renewable energy source; thermal–electric energy storage; concrete-based storage



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1. Introduction

The increasing use of renewable energy sources necessitates flexible, affordable, and efficient electrical storage to bridge the gap between energy supply and demand. Carnot battery technology can contribute to addressing this mismatch by buffering electrical energy provided by renewable sources (PV, wind) [1]: it converts electricity into heat and stores it using a resistive heater or heat pump when electricity generation exceeds demand (charging cycle). Conversely, during periods of high electricity demand, it generates power from this stored thermal energy (in its discharging step). Carnot batteries (CBs) are well-suited for medium-to-long duration energy storage (hours to days), making them complementary to short-duration electrochemical batteries. Furthermore, the components are well-established industrial equipment. Finally, the thermal energy storage materials (like molten salt or rocks) are generally inexpensive, making the overall cost of large-scale storage potentially

lower than more conventional technologies. Therefore, this technology can promote the increasingly widespread exploitation of renewable electrical sources and facilitate inter-sectoral integration and energy flexibility [1] by means of robust and conventional processes and equipment.

Charging Carnot batteries can be carried out with different possible heating technologies, such as pumped thermal electricity storage (PTES) [2] systems based on the use of electric heaters, while discharging can be accomplished with various thermal engine technologies, such as Rankine or Brayton thermal engines [3]. Since Carnot batteries are based on heat pumps and thermal engines, they consist of pumps, compressors, expanders, turbines, and heat exchangers, all of which are components that can be easily scaled. For this reason, Carnot batteries could be an alternative for pumped hydro energy storage (PHES) and compressed air energy storage (CAES). Compared to these, Carnot batteries may have lower efficiencies but with the advantage of being installable anywhere, not relying on pre-existing reservoirs or caves. Among network-scale electrical energy storage (EES) technologies, Carnot batteries have the lowest average technology readiness level (TRL), although they are becoming increasingly popular. For this reason, the actual potential of this heterogeneous technological group is not yet clear, despite ongoing research. Recently, a significant number of publications have been dedicated to CB [1,4–16]. Typically, a Carnot battery delivers power ranging from 10 to 1000 MW and has storage capacities of up to 100 GWh [7]. The smaller ones are based on organic Rankine cycle (ORC) and Stirling engines, while the larger ones are generally based on current thermal power plant technologies. The storage duration presently ranges between approximately 4 and 24 h but, with the increasing maturity of these systems and the increasing required storage duration, it may be possible to add further capacity at a relatively low cost. Systems using the heat pump principle for charging are much more addressed by the scientific literature due to their high efficiency.

The reported round-trip efficiencies in the literature span a broad spectrum, from 25% to 80% [3]. Notably, co-fueled systems can surpass this range, reaching even greater efficiencies. High round-trip efficiency is often reported for conceptual systems, typically offering optimistic theoretical results. Therefore, caution is necessary, especially for systems still in conceptual or initial design stages, given the absence of experimental data. Even when demonstration and pilot plants exist, their reported efficiencies are usually theoretical projections for full-scale plants and often remain unverified.

CB systems are seeing rapid development, especially in recent years, with the first large-scale network pilot launched in 2019, and full commercialization of 13 kW modular units in 2021. Further pilot and commercial systems are scheduled for commissioning in 2022 and 2023. Once experience is gained on these systems and renewable energy capacity further increases, even faster development can be expected [16].

Furthermore, there is a significant development of thermal energy storage systems where CB application is specifically suggested as one of the use cases. An interesting trend in these systems, when equipped with high-temperature storage, is a re-adoption of technologies previously considered for concentrated solar power plants and industrial process heat. This confirms that CB are not so much a new technology, but rather a novel combination and application of existing ones. As such, perhaps due to simplicity, electrically heated systems are mostly absent from the scientific literature, although they have the prospect of a low-cost, simple, and robust system. It is worth noticing that the International Energy Agency (IEA) has recently completed, in this sector, the work of Task 36, dedicated to Carnot batteries, within the Technology Collaboration Programme “Energy Storage” (Energy Storage Technology Collaboration Programme—IEA ES TCP ([iea-es.org](https://www.iea-es.org))), and has just launched Task 44 “Hi CBest: Power-to-Heat and Heat integrated

Carnot Batteries for Zero-Carbon (industrial) Heat & Power supply". Finally, it is expected that reducing the cost of the hybrid TES system compared to a traditional one will actively promote this technology and gain investor confidence.

This study specifically focuses on the analysis of electro-thermal conversion (P2H—Power-to-Heat) systems integrated with thermal energy storage (TES), known as thermal electrical energy storage (TEES). The development of these systems requires engineering materials and components for thermal energy storage that can accommodate combined thermal and electrical input. Practically, this means conceptualizing and developing integrated systems for dissipative electricity-to-heat conversion and thermal storage. These systems, while based on existing sensible/latent heat thermal storage technology, demand material reformulation, revised component design, along with experimental characterization and validation. The basic concept of this study is a TEES system operating at a medium temperature (150–350 °C) in which the dissipative electro-thermal conversion (Joule effect) takes place within the metallic tube, which serves as the heat exchange surface between the heat transfer fluid (HTF) and the heat storage medium (HSM) of the TES.

The TES system, here discussed, mainly uses the sensible heat of cementitious materials enhanced by the addition of shape-stabilized phase change materials (PCMs) for latent heat storage [17–34]. Regarding sensible heat thermal energy storage (SHTES) based on concrete materials, it has a limited thermal storage capacity (Table 1) but offers the great advantage of using widely available, low-cost storage media. However, its application in systems operating up to approximately 400 °C requires a thorough study and evaluation of its mix-design and manufacturing/treatment processes. Furthermore, due to concrete's inherently low thermal diffusivity, these materials must be modified to promote thermal conductivity, along with appropriately sizing the heat exchange system [35].

Table 1. Main thermal properties at 20 °C of some typical SHTES materials [36].

Material	Density (kg/m ³)	Thermal Conductivity (W/(m·°C))	Specific Heat (kJ/(kg·°C))	Thermal Capacity (kWh/(m ³ ·°C))
Aluminum	2700	220	0.93	0.70
Copper	8500	380	0.4	0.94
Cast Iron	7900	44.3	0.67	1.47
Lead	11,340	35.3	0.13	0.41
Brick	1700	0.6	0.84	0.40
Concrete	2400	1.5	1.0	0.67
Granite	2700	2.75	0.8	0.60
Graphite	2250	137	0.5	0.31
Limestone	2500	2.5	0.8	0.56
Sandstone	2400	2.2	0.82	0.55
Sodium chloride	2300	6.7	0.98	0.63
Molten salts	2000	1	1.5	0.83
Mineral oil	800	0.1	2.6	0.58
Synthetic oil	900	0.1	2.2	0.55
Liquid sodium	870	71	1.3	0.31
Water	1000	0.6	4.2	1.17

Past studies on these systems, notably by the German Aerospace Center (DLR) [37–40] and University of Arkansas [41], have consistently highlighted some issues: (i) cementitious materials often exhibit severe cracking and low durability; (ii) ceramic matrix concretes, when used, led to increased costs; and (iii) artifacts, often cast in place, are always significantly large (some tens of m³) and have a strong visual impact. Despite these limitations, commercial initiatives have been launched within the sector. Notably, ENERGYNESTTM

offers commercial solutions using a material called Heatcrete [27]. These solutions provide modular TES sizes up to 4 MWh, declared scalable up to 1000 MWh (IRES 2022 congress, oral presentation by Magnus Mörtberg: “Thermal Storage and Industrial Heat”).

The latent heat thermal energy storage (LHTES) system offers two key advantages for a range of industrial applications:

- i. Compactness (high density of accumulated energy, even 3–5 times that of SHTES), thanks to the exploitation of latent heat.
- ii. Temperature stability of the supplied heat (melting temperature of the PCM) [42].

LHTES systems have already found widespread application at low temperatures but are still in a research and development phase for medium- and high-temperature applications. Above 120 °C, the usable PCMs are generally salts, characterized by low thermal conductivity/diffusivity and a series of characteristics (stability, corrosion) to be appropriately considered. Particular effort has been dedicated in the literature to understanding the physical phenomena related to the phase change, investigating geometries designed to facilitate it, and analyzing systems aimed at promoting heat exchange (e.g., fins) between the piping and the storage medium [43–46]. Among possible methods of promoting conductivity, the development of materials with inherently enhanced properties has also been studied. These materials consist of a base salt to which a small quantity of nanoparticles (Nano Enhanced PCM—NEPCM) is added to improve thermal characteristics, such as conductivity [47,48].

The cementitious material considered in the present study resulted from an iterative optimization work conducted by ENEA, based on compositional modifications. Using standard constituents, this concrete was designed for high-temperature (up to 400 °C) operation, offering durability and excellent heat exchange properties. In the latest formulations, small quantities (5–10% by weight) of micro-encapsulated PCM (mEPCM) were added to increase the concrete’s stored energy density (7–10% [49]), thereby making the TES more compact [27]. It is important to note that the advantage of using microencapsulated PCM is that it effectively prevents any material leakage. Miliozzi et al. observed a 7% energy density increase in their experiments by adding 5%_{wt} of mEPCM (stabilized solar salts) in the cement matrix. Since the material in this application functions solely for thermal storage and not as a structural component, variations in its mechanical properties have theoretically no significant influence, at least up to 10%. Anyway, with the aim of verifying the compression and indirect tensile strength, mechanical tests were conducted on material samples after heating (up to 400 °C) [30]. At 300 °C, the compression strength of concrete without PCM was 25.39 N/mm² compared to 20.08 N/mm² with 10%_{wt} PCM, while the indirect tensile strength was 6.03 N/mm² and 2.35 N/mm², respectively [30].

When considering charging/discharging dynamics, the integration of mEPCM influences heat transport within the material, particularly during mEPCM’s melting/solidification transients. This is because the PCM’s thermal diffusivity is inherently lower than that of concrete, a difference that becomes more pronounced during the phase transition as the PCM’s apparent heat capacity rises due to latent heat absorption/release. As a result, heat transfer within the mEPCM inclusions is slower, extending the charging/discharging phases compared to a standalone cement module. However, since mEPCM constitutes only 10% by weight of the cement matrix, the charging/discharging duration of the overall storage module does not substantially change.

A small-sized thermal storage element (3.00 × 0.22 × 0.22 m) using this newly developed material was studied, designed, and optimized. This element can be considered the base unit for thermal storage modules of flexible dimensions and capacity. These elements were characterized using “ad hoc” equipment, capable of testing the TES modules under operating cycles, like those expected in a hypothetical industrial plant. The results were

in line with preliminary numerical simulations [50]. Research efforts were focused on identifying materials that are low costs, non-toxic, and widely available, and developing solutions that are flexible in terms of size (capacity) and integrability. The ultimate goal is to develop solutions that can be used in the national energy and production system, where the need for flexible and compact systems, including medium–small capacity, is relevant, both for industrial heat supply and for small-scale (distributed) power systems.

The objective of this work is to propose this thermal storage module as a TEES system capable of being powered by both electricity and heat, in the perspective of a cost-effective CB approach. The HSM used is a concrete mixture with the addition of 10%_{wt} of mEPCM. A preliminary experimental analysis of the thermal behavior of this thermal storage module is here presented, in order to verify the technical feasibility of the proposed material for this specific application.

The article is structured to first detail the materials and methods employed, then present the experimental tests and finally comment on the obtained results.

2. Materials and Methods

The experimental section of the TEES here proposed is composed of two concrete thermal storage devices connected in series. These devices are designed to operate within a temperature range of 200 °C to 280 °C, with a maximum design reference temperature of 350 °C. Each device consists of a metallic tube axially immersed in a cylindrical concrete shell (storage medium) in a “shell and tube” configuration. The metallic tube, which acts as the heat exchange surface, is made of AISI 304 stainless steel with a length of 1 m, an outer diameter of 21.3 mm, and a thickness of 1.65 mm. The cylindrical shell has a length of 0.7 m and an outer diameter of 120 mm.

The heat storage medium is a specially formulated base concrete designed for high-temperature operation and good and stable thermal performance. To this, 10% by weight of a PCM [51,52], specifically solar salts (a 60/40%_{wt} mixture of sodium and potassium nitrates) stabilized in a porous matrix (mEPCM) [53–58], has been added. The PCM is encapsulated in diatomite [59,60], a highly porous fossil flour, at a weight ratio of 80–20%.

The test section was realized by connecting the two devices in series, leaving the heat exchange tube uncovered at its ends and in the central part. This configuration allows, during the electrical charging phase, the connection of the positive pole of a DC current generator to the uncovered central area and the connection of the negative pole to both the ends of the metallic tube. This way, the initial and final parts of the tube are at the same potential.

More specifically, the electro-thermal conversion is accomplished through the Joule effect [61] generated by a current passing through the metallic tube. The metallic tube simultaneously serves as the conduit for oil flow and the medium for electricity, which enables the Joule effect for heating. This effectively makes the tube an electric heater (rod). This is added to the text. The current I flowing through the tube generates heat in the tube itself with a power P that can be calculated using the well-known relation:

$$P = R \cdot I^2 = V \cdot I \quad (1)$$

where R represents the electrical resistance of the metal tube, V the voltage and I the electric current intensity. The resistance is given by the relationship:

$$R = \rho_{el} \cdot \frac{L}{A_{tube}} \quad (2)$$

with ρ_{el} being the electrical resistivity at operative temperature, L being the distance between the poles, and A_{tube} being the area of the cross-section of the exchange tube (in this case, the metallic section of the tube). Furthermore, the tube has four metal clamps capable of handling the calculated maximum amperage of 630 A per connection with the power supply. These clamps are located at the ends and in the central part (Figure 1a). This solution ensures that only the exchanger is energized, isolating it from the rest of the system.

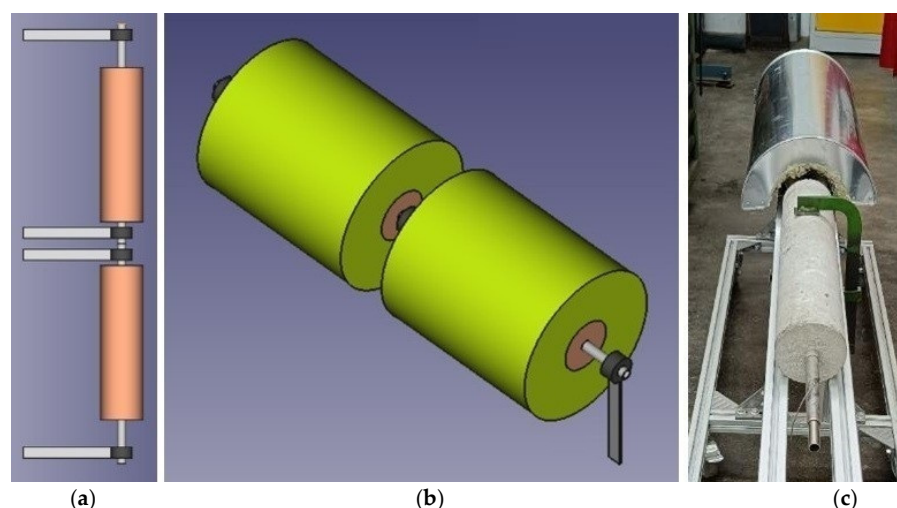


Figure 1. Experimental TEES section with two devices connected in series: (a) schematic, (b) three-dimensional schematic, and (c) realized devices.

The TEES element (Figure 1b) has been thermally insulated to have a surface temperature compliant with regulations and to prevent excessive heat loss. Rock wool with a thickness of 100 mm was used. All the insulation is protected by an aluminum sheet (Figure 1c).

Driven by environmental concerns and the ongoing phase-out of some commercial cements (i.e., Portland cement), new concrete formulations were studied by ENEA. Furthermore, in adherence to circular economy principles, a series of materials (fibers and aggregates) derived from industrial waste (steel slag, carbon fibers extracted from filters, etc.) were identified and incorporated as fibers and aggregates. After a comprehensive assessment of various potential materials, the composition ultimately selected for the thermal storage module is reported in Table 2.

Table 2. Composition of the mixture for the energy storage module.

Component	Mix
Water	7.12% _{wt}
Cement (CEM II 42.5R-B/(P-LL))	18.02% _{wt}
Sand (0–4)	34.19% _{wt}
Small gravel (5–15)	12.57% _{wt}
Gravel (15–30)	17.97% _{wt}
Nylon fiber (Meralflex)	0.05% _{wt}
Carbon fiber	0.24% _{wt}
Fibermix	0.68% _{wt}
Super-plasticizing additive	0.20% _{wt}
mEPCM	8.96% _{wt}
Water/Cement rate	0.4
Volumic mass (kg/m ³)	2220

This formula, which is derived from previous studies on fires in tunnels and nuclear accidents [62], allows energy to be stored both as sensible and latent heat, with a high thermal capacity and increased stored energy density compared to conventional concrete mixtures. In addition this material can operate effectively at medium–high temperatures (150–400 °C), by combining concrete materials with metal and polymer fibers, while retaining structural properties suitable for HSM.

The developed storage module was installed on the ENEA ATES (Advanced Thermal Energy Storage System) test plant to carry out its thermal characterization (Figure 2). The ATES infrastructure consists of an oil circuit, provided with a heating/cooling system (Julabo—HT30-M1 C.U., JULABO GmbH, Seelbach, Germany), capable of operating at temperatures up to 350 °C. This system is meant to be directly connected to the storage module under testing. The maximum heating power is about 3 kW, whereas the cooling power is 15 kW; the oil flow does not exceed 18 L/min. Through 4 electrically actuated valves, the experimental facility can generate a clockwise, anticlockwise or by-pass oil circulation; the latter allows rapid heating or cooling of the thermal fluid to enable the charging/discharging of the storage modules. The facility is also equipped with a control and data acquisition system, developed in the LabView® environment, which allows remote control and real-time monitoring of operating parameters (Figure 3).



Figure 2. ATES system with the module installed and details of the power supply.

In particular, the system is equipped with 16 thermocouples and 2 resistance temperature detectors (RTDs) to detect the following operating temperatures:

- Temperature inside the tank(s) volume;
- Temperature of the outer surface of the tube;
- Temperature of the internal and external walls of the tank itself;
- Temperature at the inlet and outlet of the tank and the inlet and outlet of the heater/cooler.

The experimental tests for the thermal characterization of the TEES system were designed and programmed to perform a series of thermal charging/discharging cycles of the storage modules. In these cycles, the thermal charging phase was powered electrically and/or thermally, while the thermal discharging phase was accomplished through cooling by HTF. Before starting the planned tests, it was necessary to degas the storage modules (to eliminate free water present in the concrete) by circulating diathermic oil at a flow rate of

18 L/min and a temperature of 140 °C for 24 h. Subsequently, two charging/discharging tests of the storage modules were performed: one with electrical charging and the other one with thermal charging through the heat transfer fluid. In both tests, the discharging phase was always accomplished through the heat transfer fluid (Table 3).

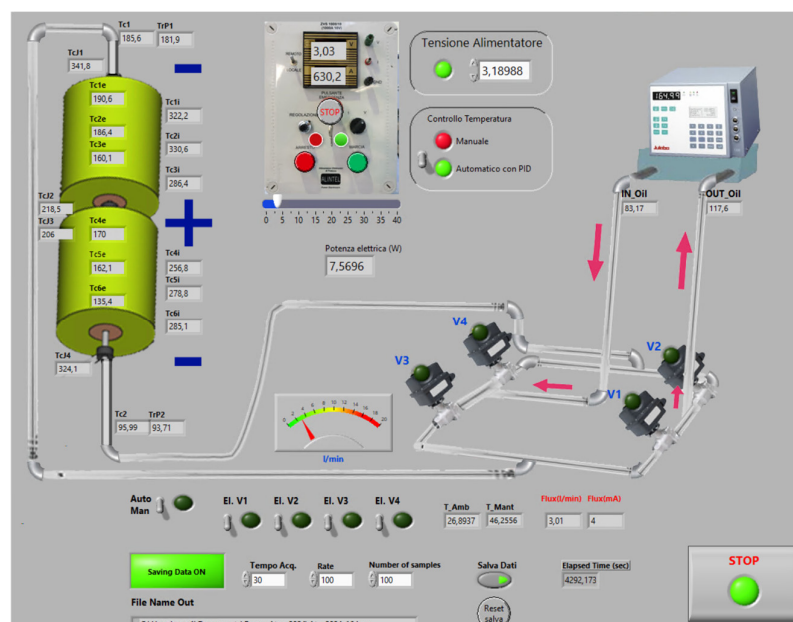


Figure 3. ATES control interface.

Table 3. Charging/discharging test of the TEES system.

Step	Method: Conversion P2H	Method: Heating by HTF
charging	Duration: 10 h Target temperature: 320 °C	Duration: 30 h Thermal oil flow: 18 L/min Thermal oil inlet temperature: 320 °C
discharging	Duration: 4.5 h Thermal oil flow: 18 L/min Thermal oil inlet temperature: 150 °C	Duration: 3 h Thermal oil flow: 13.5 L/min Thermal oil inlet temperature: 150 °C

Afterward, a partial load test was performed. In this test, a charging/discharging cycle with electric heating (P2H) was repeated, where the charging and discharging time was reduced to 5 and 2.5 h, respectively. Finally, a cyclic functional test of the system was performed, completing a total of 4 cycles (Table 4).

Table 4. Cyclic test (4 cycles) TEES system.

Step	
charging	Duration: 2 h Target temperature: 260 °C
discharging	Duration: 1 h Thermal oil flow: 14 L/min Inlet thermal oil temperature: 180 °C

As previously mentioned, these preliminary tests are aimed at verifying the feasibility of a system combining several innovative aspects. An analysis was conducted on the measurement uncertainty of the instrumentation installed on the ATES experimental plant. Specifically, during electric heating, temperature measurements collected by Class 1 K

thermocouples have a tolerance of $\pm 1.5\text{ }^{\circ}\text{C}$ at $250\text{ }^{\circ}\text{C}$. This results in a standard uncertainty of 0.35%, including the rest of the measurement chain. Conversely, during heating or cooling by the HTF, errors arise not only from temperature measurement (using RTD/Pt100 Class A thermo-resistors with a tolerance of $\pm 0.65\text{ }^{\circ}\text{C}$ at $250\text{ }^{\circ}\text{C}$ and a standard uncertainty of 0.11%) but also from flow measurements (KEM HMP 09 flowmeter, with an error of 1.42% and a standard uncertainty of 1.67%). The supplied/extracted power, which is a combination of these two measurements, is characterized by a standard uncertainty of approximately 12% for a temperature difference of $10\text{ }^{\circ}\text{C}$.

3. Results and Discussion

3.1. Charging/Discharging Test

As mentioned above, the charging/discharging cycles (Table 3) of the thermal storage system were repeated twice to verify the behavior of the storage module under thermal and electric heating (P2H conversion method).

3.1.1. P2H Conversion Method

During the charging phase, the tube's Joule heating continues until the target temperature is reached and maintained, and the HTF flow rate is kept at zero. The voltage remains between 2.5 and 3 V (maximum value), while the maximum current is 630 A. This results in a maximum delivered electrical power of 1.9 kWe. The electrical resistance of the tube was estimated to be $4.76\text{ m}\Omega$, a value consistent with theoretical calculations.

These units behave like two resistors powered in parallel. The electrical resistance of each unit was calculated using Equation (2) and considering only the metal tube's properties (length: 0.9 m, section: 127 mm^2 , electrical resistivity: $1.3\text{ Ohm}\cdot\text{mm}^2/\text{m}$ at $300\text{ }^{\circ}\text{C}$): the resulting calculated electrical resistance is about $9.2\text{ m}\Omega$. Consequently, the equivalent electrical resistance of the system is $4.6\text{ m}\Omega$. Therefore, the difference between the measured and calculated electrical resistance is only about 3.5%. This minimal discrepancy suggests that no significant unaccounted electrical resistances are present.

Figure 4 shows the trends of the internal and external temperatures of the two devices, alongside the ambient temperature and the external mantle temperature of one of the devices. It is worth noting that Tc5e exhibited weird behavior, probably due to a partial detachment of the thermocouple during the test. The room temperature, maintained between 25 and $30\text{ }^{\circ}\text{C}$, confirms that the test was conducted at a sufficiently stable temperature despite its duration. However, the mantle temperature rises to approximately $60\text{ }^{\circ}\text{C}$, significantly exceeding the design specification of $35\text{ }^{\circ}\text{C}$, indicating that the insulation's performance was below expectations.

During the charging phase, the internal temperature of the concrete module rapidly reaches the target temperature, evidencing the high efficiency of the Joule effect. An exception is observed in the temperatures of the outermost thermocouples (top and bottom), which are more susceptible to thermal losses. Conversely, during the discharging phase, the internal temperature rapidly decreases to around $170\text{ }^{\circ}\text{C}$, then declines more slowly towards $150\text{ }^{\circ}\text{C}$. The discharging time is estimated to be approximately two hours.

During the charging phase, external temperatures of the concrete module slowly increase due to the material's diffusivity, asymptotically approaching temperatures between 220 and $250\text{ }^{\circ}\text{C}$. These values are lower than the target ones, due to heat losses toward the environment. In the discharging phase, the concrete module's external temperature behavior is like its internal temperature, though characterized by a slower rate and lower temperature values resulting from the same factors previously mentioned. Figure 5 shows the estimated energy stored in the medium, relative to its energy content at $20\text{ }^{\circ}\text{C}$. As shown, approximately 1.69 kWh of thermal energy was stored after about 10 h, under near

steady-state conditions. The charging time, reaching to the initial temperature plateau time ($t = 5$ h), was approximately 3 h, when reaching 98% of charging capacity. The discharging phase at $150\text{ }^{\circ}\text{C}$, occurring between 10 and 14.5 h, does not reach a true steady state, the duration of which should be around 5–6 h.

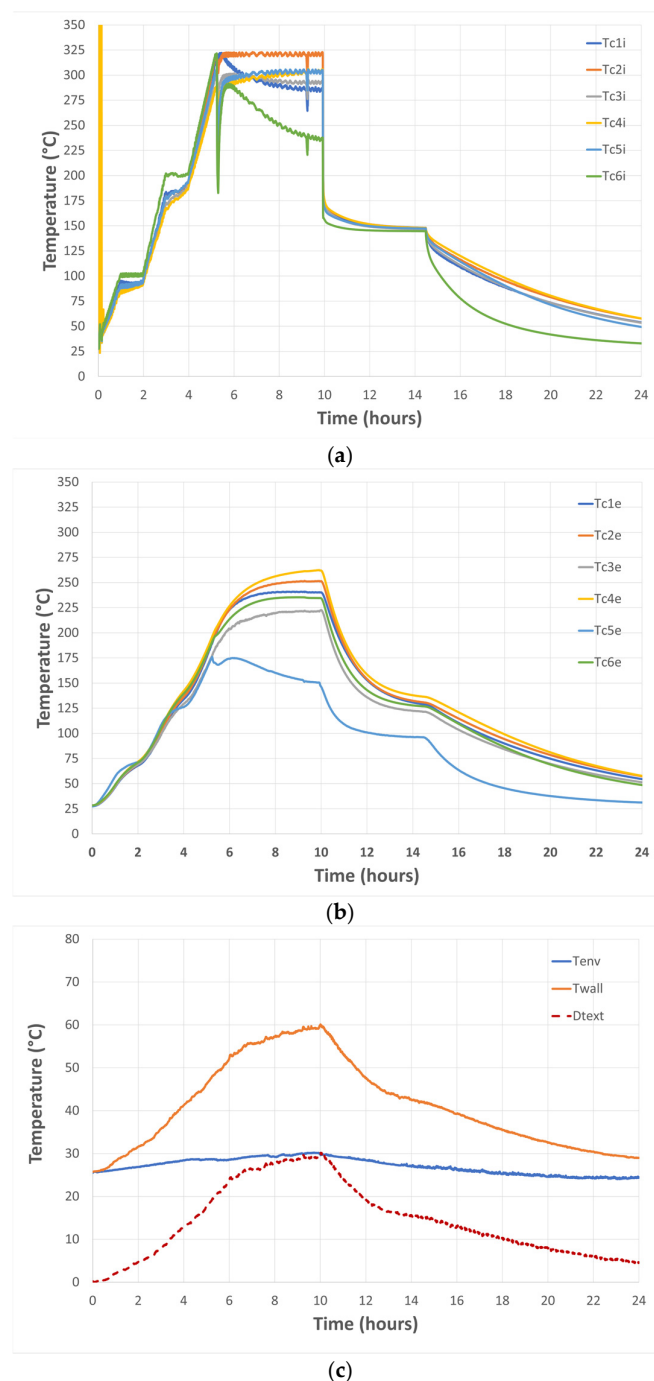


Figure 4. P2H Conversion Method: trends of the internal (a) and external (b) temperatures of the two devices, the room temperature, and the external mantle temperature of one of the devices (c).

The module was initially fully insulated to limit thermal losses, but during testing, the metallic connection terminals to the power supply experienced excessive temperature increases. For safety reasons, it was necessary to de-insulate that part. For future tests, a higher thickness of the connection terminals will be applied. The thermal losses, estimated to exceed 300 W in the temperature range $120\text{--}140\text{ }^{\circ}\text{C}$ and 1700 W in the range

280–290 °C, substantially condition the charging/discharging dynamics, alongside the material's thermal diffusivity.

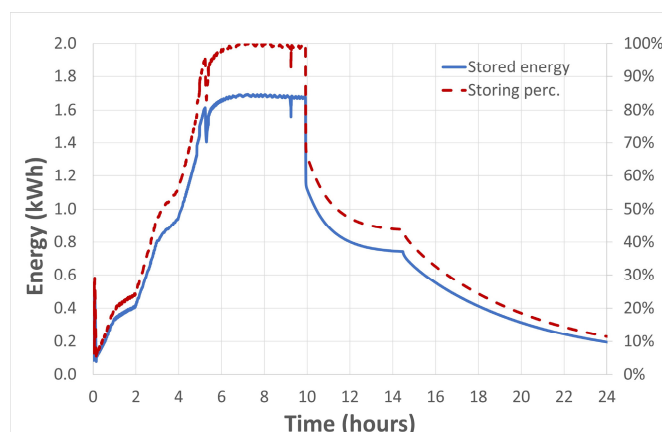


Figure 5. P2H Conversion Method: estimated energy stored in the storage medium compared to that at 20 °C.

3.1.2. HTF Heating Method

The programmed charging/discharging cycles (Table 3) have identical target temperature values (320 °C and 150 °C), although the duration of the plateaus at a constant temperature differs slightly. Figure 6 shows the inlet and outlet temperatures from the heating/cooling system, as well as the power supplied/absorbed: during the charging phase, the heating thermal power is approximately 2.6 kW.

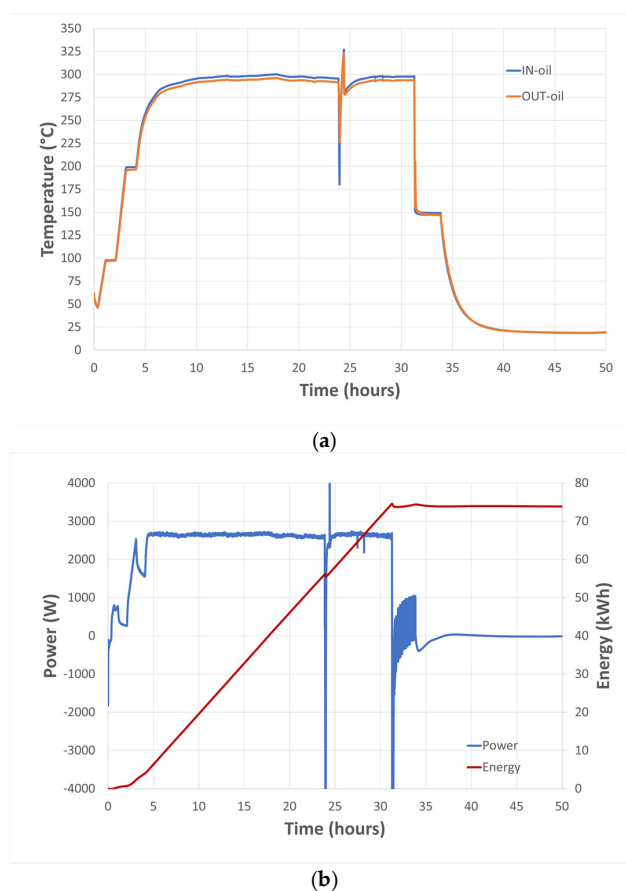


Figure 6. Trends of heating/cooling system inlet and outlet temperatures (a) and power output/absorption and energy (b).

Figure 7 shows the trends of the internal and external temperatures of the two devices, the ambient temperature, and the external mantle temperature of one of the devices. The ambient temperature, maintained between 19 and 23 °C, demonstrates that the test was conducted at a sufficiently stable temperature despite its duration. In this case as well, the mantle temperature rises to approximately 53 °C, exceeding the design temperature (35 °C). This indicates that the insulation performs below expectations. During the charging phase, the internal temperatures stabilize after about 12 h at a temperature level lower than the target (280–290 °C). It indicates non-negligible heat losses from the HTF circuit, between the electric heater and the TEES. The discharging phase is very similar to that recorded in the previous test, although the duration is shorter.

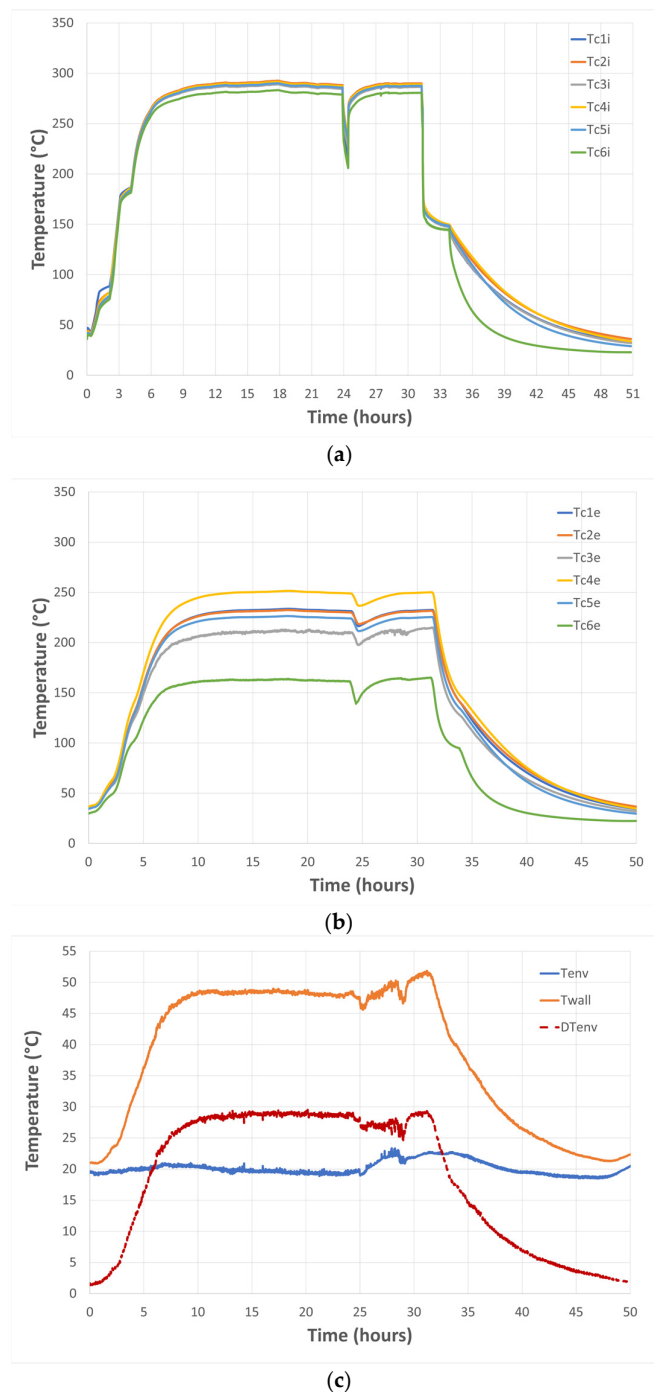


Figure 7. HTF Heating Method: trends of the internal (a) and external temperatures (b) of the two devices, the room temperature and the external mantle temperature of one of the devices (c).

Throughout the charging phase, the external temperatures of the concrete module increase slowly due to the material's low diffusivity, asymptotically reaching temperatures between 220 and 250 °C. These values are lower than the target ones, due to heat losses. The concrete module's external temperature behavior is similar to its internal temperatures, though characterized by a slower rate and lower temperature values resulting from the same factors previously mentioned.

Figure 8 shows the estimated energy stored in the medium, relative to its energy content at 20 °C. As can be seen, after approximately 15 h, under quasi-steady state conditions, about 1.68 kWh of thermal energy was stored, with a charging time of approximately 6 h, when reaching 98% of charging capacity, reading to the initial temperature plateau time ($t = 9$ h). The discharging phase at 150 °C, between hours 31 and 34, is still far from steady state condition, the duration of which is expected to be around 5–6 h. In this case as well, the dynamics of the charging/discharging processes are substantially influenced not only by the thermal diffusivity of the material but also by the high level of thermal losses, estimated to be more than 300 W at 120–140 °C and 1700 W at 280–290 °C.

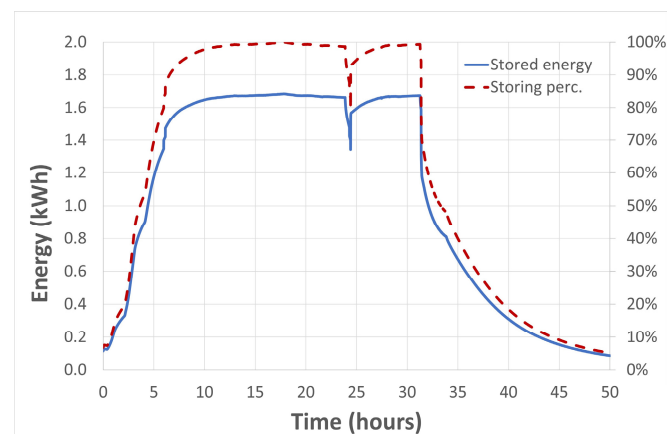


Figure 8. HTF Heating Method: estimated energy stored in the storage medium compared to that at 20 °C.

3.1.3. Comparison of Methods

The following points can be highlighted from the comparison of the behavior of the two storage modules under electric and thermal charging:

- Joule effect electric heating allows for the generation of heat at the target temperature directly within the heat exchange tube in a very effective manner. In the case of heating via heat transfer fluid, neglecting heat losses along the HTF circuit, heat transfer between the fluid and the heat exchange tube occurs through convection, which appears less effective than the former.
- The heating method significantly impacts charging time: electric heating achieves charging in approximately 3 h from the start of the test, while in the second case the charging time is almost double (6 h). In fact, since the heat transfer within the storage medium is strictly connected to its thermal diffusivity, the possibility of having a high and stable internal temperature on the tube's wall favors the charging speed.
- In both cases, the concrete accumulated a maximum thermal energy of 1.68 kWh, which is 86% of its theoretical storage capacity (1.96 kWh). This limitation can be attributed to the high level of recorded thermal losses, ranging from 300 W at 150 °C up to approximately 1700 W at 290 °C.

3.2. Cyclical Test

During the charging phase of each cycle, the tube is heated through the Joule effect to its target temperature, which is then maintained. The HTF flow rate is kept at zero. The system delivers a maximum electrical power of 1.7 kW_e, with a maximum voltage of approximately 2.8 V and a maximum current of 630 A. Figure 9 shows the temperature trends of the two devices, specifically including their internal and external temperatures, in addition to the ambient temperature and the external mantle temperature of one of the devices. The ambient temperature, maintained between 15 and 20 °C, is sufficiently stable throughout the test. The mantle temperature rises above 40 °C (slightly higher than the design temperature of 35 °C). During the charging phase, the internal temperatures of the concrete module quickly reach the target, demonstrating the high effectiveness of the Joule effect. In contrast, the outermost thermocouples (top and bottom) exhibit temperatures affected by significant heat losses. In the discharging phase, internal temperatures within the concrete module rapidly drop to about 200 °C and then undergo a slower reduction to around 190 °C.

Regarding the concrete module's external temperatures, during the charging phase, they slowly increase due to the material's diffusivity, reaching 170–210 °C. These temperatures are lower than the target because of inherent thermal dispersions, which prevent the outer zones from utilizing the latent heat of the mEPCM. Conversely, during the discharging phase, the external temperature behavior of the concrete module is very similar to its internal temperatures, though characterized by a slower rate and lower values originating from the same factors previously mentioned.

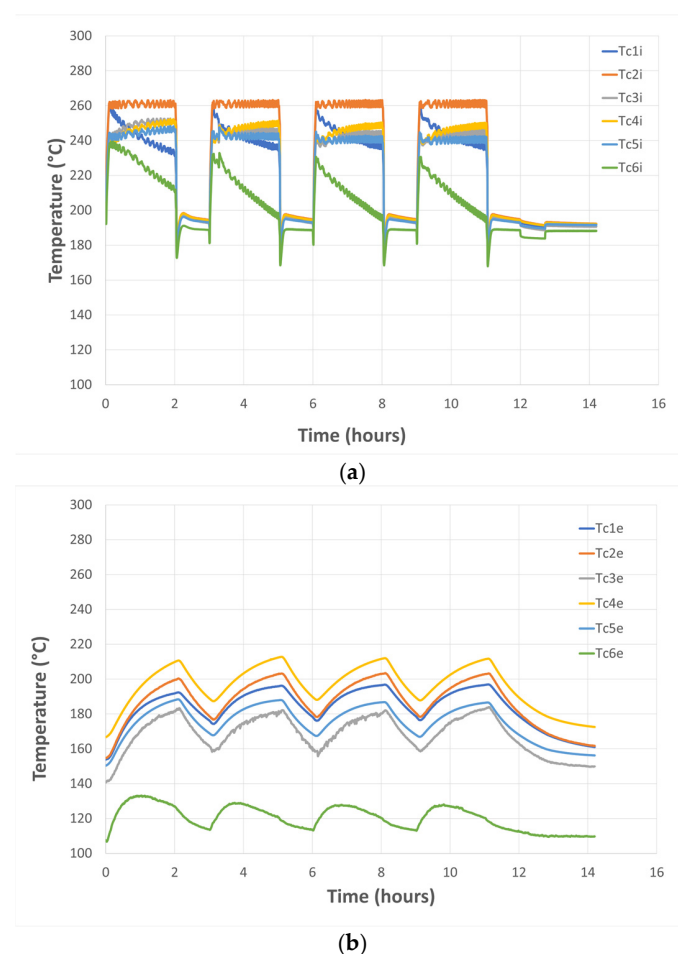


Figure 9. Cont.

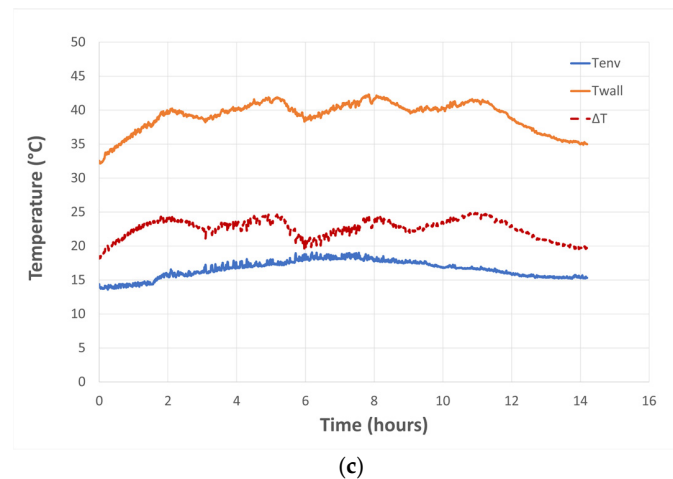


Figure 9. Trends of the internal (a) and external (b) temperatures of the two devices, the room temperature, and the external mantle temperature of one of the devices (c) for the four cycles performed.

Figure 10 shows the estimated energy stored in the storage medium, relative to its energy content at 20 °C. As can be seen, upon completion of the 2-h charging cycle, the maximum energy stored at 260 °C is approximately 1.31 kWh, with a filling factor of about 68%. However, the discharging phase, lasting 1 h, does not reach a steady state at 180 °C, indicating that the devices are not able to fully release their stored energy.

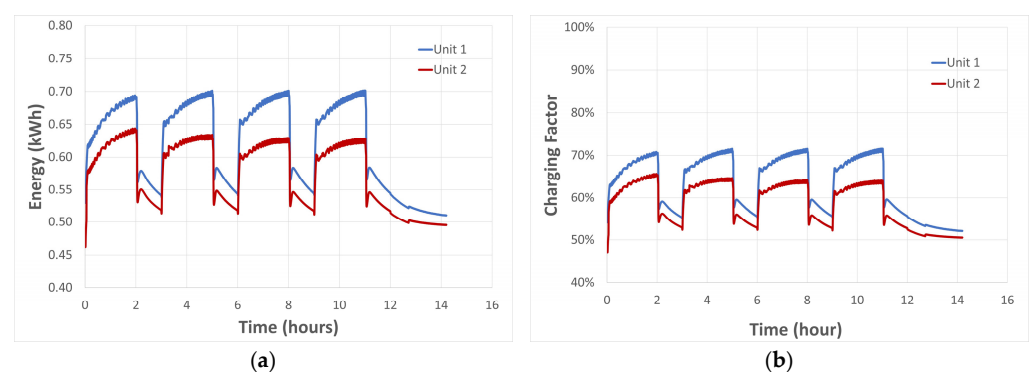


Figure 10. Estimated energy accumulated in the storage medium relative to its energy content at 20 °C (a) and charging factor for the four cycles (b).

Therefore, the results demonstrate that, while the thermal behavior of the system stabilizes after the second cycle, the chosen durations for the charging and discharging phases are currently insufficient for an effective system operation. The installation of larger-sized modules could minimize thermal losses, while the use of finned tubes could rise the thermal exchange efficiency.

4. Conclusions

This work effectively demonstrates the promising performance of the proposed TEES (thermal energy electrical storage) concept. Key findings and future research directions are below reported.

4.1. Key Findings

- **Reliable and Efficient Electrical Charging:** The TEES concept operates reliably and efficiently during its electrical charging phase. The measured electrical resistance of the exchange tube aligns with theoretical values, indicating minimal current leakage or additional electrical resistance.

- **Effective Internal Electro-Thermal Conversion:** The internal electro-thermal conversion, based on the Joule effect, ensures stable heat generation within the tube at the target temperature. This heat is then effectively transferred to the concrete storage medium via conduction, differentiating it from heat transfer fluid convection.
- **Limiting Factors Identified:** Despite the effective heat generation and transfer, the thermal diffusivity of the storage medium (concrete) remains a limiting factor in quickly and fully utilizing the storage capacity. Additionally, significant thermal losses were observed (300 W at 120–140 °C and 1700 W at 280–290 °C), which hinder system charging and reduce recovered thermal energy.
- **Crucial for Future Devices:** Reducing these thermal losses is paramount for future laboratory-scale devices to allow for a more accurate assessment of the concept's performance.
- **Cyclic Operation Stability:** In cyclic operation, the system's thermal behavior stabilizes after the second cycle. The duration of both charging and discharging phases is crucial for effective utilization of the storage medium's capacity.

4.2. Future Research Directions

- **Larger Modules and Optimization:** Future efforts will focus on developing and testing larger-sized modules to optimize their thermal performance by minimizing thermal losses. This will simultaneously accelerate the progress of the technology readiness level (TRL) of this compact and reliable TEES system concept, and will also allow its costs and performance to be evaluated.
- **Multi-Arrayed Configurations:** As a next step, a series of modules will be created and integrated into multi-arrayed configurations (combining series and parallel layouts). This will facilitate the testing of operational strategies to optimize the simultaneous charging of these modules with both electricity and heat. The use of larger modules is desirable to minimize thermal losses and increase the TRL of this innovative TEES system concept.

In conclusion, the successful demonstration of the TEES concept's reliable electrical charging and effective internal electro-thermal conversion lays a strong foundation for its future development, with ongoing research focused on optimizing module size, minimizing thermal losses, and exploring multi-arrayed configurations to advance its Technology Readiness Level and assess its overall performance.

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Abbreviations

The following abbreviations are used in this manuscript:

CAES	Compressed-Air Energy Storage
CB	Carnot Battery

HSM	Heat Storage Medium
HTF	Heat Transfer Fluid
LHTES	Latent Heat Thermal Energy Storage
mEPCM	micro-Encapsuled Phase Change Material
NEPCM	Nano Enhanced Phase Change Material
ORC	Organic Rankine Cycle
P2H	Power to Heat
PCM	Phase Change Material
PHES	Pumped Hydro Energy Storage
PTES	Pumped Thermal Electricity Storage
SHTES	Sensible Heat Thermal Energy Storage
TEES	Thermal Electrical Energy Storage
TES	Thermal Energy Storage
TRL	Technology Readiness Level

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