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Demonstration of EnergyNest Thermal Energy Storage (TES) Technology

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Abstract. This paper presents the experimental results from the EnergyNest 2 x 500 kWh_{th} thermal energy storage (TES) pilot system installed at Masdar Institute of Science & Technology Solar Platform. Measured data are shown and compared to simulations using a specially developed computer program to verify the stability and performance of the TES. The TES is based on a solid-state concrete storage medium (HEATCRETE®) with integrated steel tube heat exchangers cast into the concrete. The unique concrete recipe used in the TES has been developed in collaboration with Heidelberg Cement; this material has significantly higher thermal conductivity compared to regular concrete implying very effective heat transfer, at the same time being chemically stable up to 450 °C. The demonstrated and measured performance of the TES matches the predictions based on simulations, and proves the operational feasibility of the EnergyNest concrete-based TES. A further case study is analyzed where a large-scale TES system presented in this article is compared to two-tank indirect molten salt technology.

INTRODUCTION

Masdar Institute of Science & Technology and EnergyNest AS have initiated a comprehensive joint research project for building and testing a 2 x 500 kWh_{th} thermal energy storage (TES) pilot. The pilot is based on EnergyNest's unique TES technology using individual TES elements connected in series and parallel. Each element comprises a solid-state storage medium (HEATCRETE®) with integrated steel tube heat exchangers [1]. The system design is modular, and thereby fully scalable to cater to a wide range of TES capacity requirements. Construction of the TES and piping interface was successfully executed within a 6-month period and completed in May 2015. The hot oil-loop at Masdar Institute Solar Platform (MISP) has been upgraded and instrumented to allow operation with synthetic thermal oil up to 393 °C, the same conditions as in most commercial concentrated solar power (CSP) plants. EnergyNest designed, installed and commissioned the entire TES-system by Oct 2015, after which the first thermal cycles were completed by mid-November. After several further improvement upgrades to the oil loop system early 2016, the TES is operated on a 24 hr / 5 days basis with seven full-time Masdar Institute staff under supervision of EnergyNest.

SYSTEM TESTING FACILITY

The section of the hot oil-loop at MISP dedicated to perform research and testing of the TES under controlled conditions using Dowtherm-A heat transfer fluid (HTF) is heated by an electrical heater (100 kW_{el}) to reach max temperature of 393 °C under pressurized conditions [2]. Using the electric oil heater and air-cooled oil cooler, the system allows full flexibility in emulating operation conditions in commercial CSP plants; both charging the TES from a solar field and discharging the TES to a power block with a steam turbine generator. The test facility enables

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validation of developed simulation tools and capabilities in addition to run various specific storage scenarios, and further link results to simulation tools for precise and project-specific system design. A simplified diagram of the MISP oil loop and the EnergyNest TES pilot is shown in Figure 1.

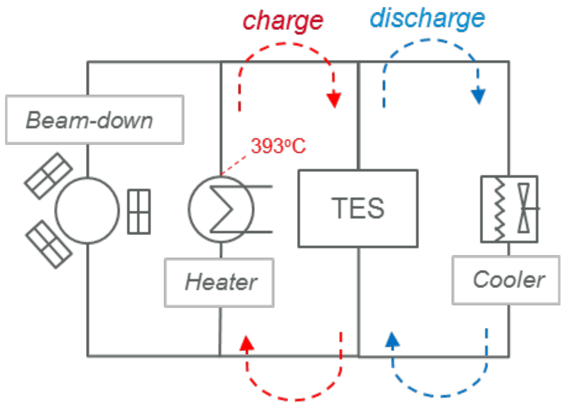
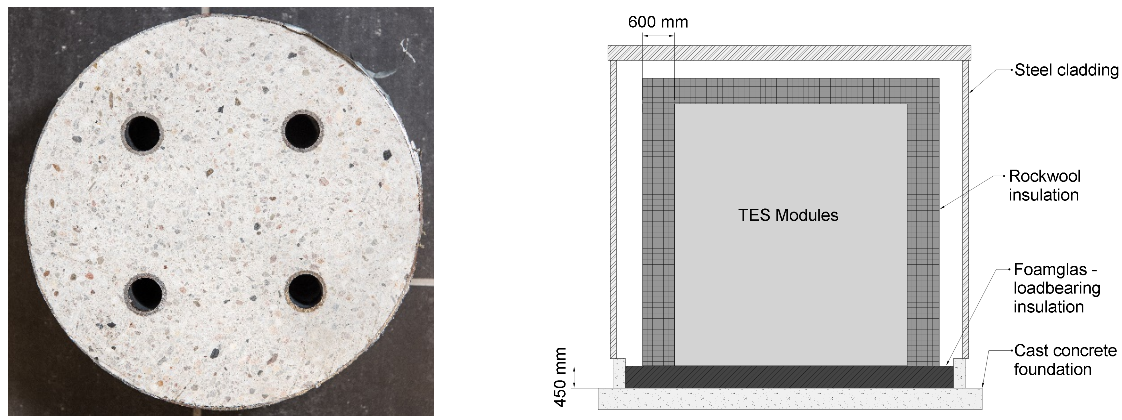


FIGURE 1. Simplified diagram of MISP HTF oil-loop (left) which is upgraded and instrumented to perform research and testing of TES systems under emulated solar conditions using a controllable electric oil heater. Photograph of fully commissioned EnergyNest thermal energy storage with 2 x 500 kWh_{th} capacity installed at MISP.

PILOT STORAGE SYSTEM DESIGN

As mentioned earlier, the TES pilot has an estimated total energy storage capacity of 2 x 500 kWh_{th} and consists of four separate thermal modules (250 kWh_{th} each) using two different heat exchanger designs, all enclosed in thermal insulation. Multiple cylindrical heat exchanger elements are placed inside a steel frame (termed “cassette”) which is manufactured, assembled and pressure tested in a workshop before shipment to site. The cassettes are dimensioned to fit inside a standard 20” or 40” container for easy transport. Upon arriving to the construction site the cassettes are casted with HEATCRETE®. Once casted they are termed modules, which are then assembled onto a thermally insulated loadbearing foundation. These modules can be stacked vertically and horizontally, allowing for a very efficient system with low footprint and minimal heat losses. In the TES pilot at MISP each module comprises 24 five-meter-long elements connected in series. A cross-section of one such element with carbon steel tubes cast in HEATCRETE® is shown in Fig. 2a. For the 250 kWh_{th} nominal capacity modules, the specific capacity of the elements (including HEATCRETE®, carbon steel tubes and HTF inside the tubes) is 43.3 kWh/m^3. The tubes in each element are configured so that the HTF flows in and out of one element through two parallel U-shaped tubes. This design ensures minimal thermal stress in the axial direction of the elements since the dominating temperature gradient is in the radial direction. The thin steel cylindrical casting form remains in place after casting, as it represents an optimum geometry for reinforcement and support of the TES element.

Inside the TES pilot, the modules rest on a 450 mm thick loadbearing insulation constructed using Foamglas®, with temperature sensors strategically located for monitoring the heat loss to the cast concrete foundation. Around the modules, including the top, a layer of 600 mm thick Rockwool is used for thermal insulation. The entire assembly is protected from the elements by a steel cladding attached to a super-structure mounted on a casted concrete foundation, as shown in Fig. 2b. To control and monitor the performance of the TES pilot, there are 98 temperature sensors inside the TES modules and at various levels of the loadbearing insulation, 32 temperature sensors on the external HTF pipes combined with pressure and mass flow instrumentation. The K-type thermocouples used have an accuracy in line with the specification of ±2 °C absolute or better, whereas the Coriolis flow meter has a measurement accuracy of 0.1%. All data is collected through a data acquisition setup directly in the SCADA control system and through an external data logger. For research purposes and convenience, additional accessibility to sensor cabling/connectors inside the external cladding was included in the design of the superstructure, in addition to a removable roof structure for future access and inspection of the modules. In summary, the complete TES comprises of the following main components: carbon steel tubes/pipes, HEATCRETE®, steel cassette frames, insulation material together with the concrete foundation and steel cladding; all which have a high expected lifetime and represent materials that can be easily sourced and recycled.



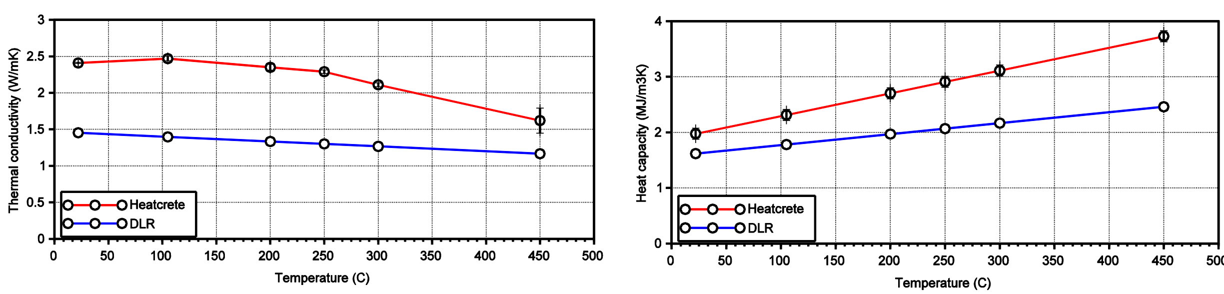
(a) (b)

FIGURE 2. (a) Photograph of a cross-sectioned cylindrical heat exchanger element showing the steel tubes cast in HEATCRETE®. (b) Illustration of EnergyNest thermal energy storage pilot, with insulation surrounding the modules.

Storage Medium Performance

The unique HEATCRETE® concrete recipe used in the TES is developed in collaboration with HeidelbergCement and differs significantly from regular structural concrete; it has a higher thermal conductivity compared to regular concrete for effective heat transfer, at the same time being chemically stable for operation up to 450 °C, and with sufficient strength to withstand repeated thermal stress cycles. All parameters relevant to the performance of the material have been thoroughly tested and characterized in parallel with the construction of the TES. The mechanical strength (compressive strength at elevated temperatures) and thermal properties (TPS method [3]) of the concrete were measured by independent lab facilities at NTNU in Trondheim, Norway and The Fire Research lab at SP Technical Research Institute of Sweden.

Normal concretes have rather poor thermal conductivity; in fact, in most applications such as in buildings one prefers concrete to be as thermally insulating as possible. Comparing the thermal performance to earlier demonstrations of concrete-based TES by DLR [4] (Fig. 3a & b) HEATCRETE® has both significantly higher thermal conductivity and heat capacity. The experience from the test lab is an accuracy of 2-5% for thermal conductivity and 5-10 % for diffusivity up to 500 °C given that the thermal contact between sample and material is good. High heat capacity is desirable since it reduces the storage volume, and high thermal conductivity enhances the heat transfer dynamics in the system [4]. The results shown in Figure 3a & 3b clearly show that for a given thermal energy storage capacity, less concrete will be required using the current HEATCRETE® than by previously available concretes.



(a) (b)

FIGURE 3. Measured thermal conductivity (a) and heat capacity (b) of HEATCRETE® after thermal conditioning over a temperature range from 20 to 450 °C (compared to DLR demonstrated concrete [4]).

When the HEATCRETE® is first heated, free water and some chemically bound water will evaporate, diffuse and escape. Losing water by evaporation does not affect porosity, however, as the temperature increases, dehydration creates additional pore space and shrinkage. In the case of HEATCRETE® the water-cement ratio is very low by design, and hence the porosity remains very low ensuring good heat transfer capability and suitability for thermal energy storage applications. During the thermal conditioning process (first start-up), the TES is heated in a slow and controlled way to limit the build-up of vapor pressure inside the concrete. Density measurements by SP shows a mass loss of 4.3% for samples heated to 200 °C in accordance with this prescribed heating process. Further heating to 550 °C only marginally reduces density (0.39 %) proving that nearly all the free water has been removed at 200 °C, and that the additional loss is probably due to the release of some chemically bound water. Similar results were also reported in [5] by thermal stability analysis performed on small non-conditioned HEATCRETE® samples.

Furthermore, from compression testing at temperature, HEATCRETE® attains twice the strength of normal structural concrete at 200 °C, increasing from 45 MPa as cast and cured up to 84 MPa at the higher temperature. The strength also remains high at further elevated temperatures (>70 MPa at 400 °C); this is an important result since it implies that the HEATCRETE® has strong mechanical integrity at operational temperatures.

PILOT STORAGE SYSTEM RESULTS

When the TES is operated, the individual elements in the modules exchange energy by means of the HTF flowing through the serially connected elements. As typical for sensible TES systems this results in a "hot-side" and "cold-side" with a difference in temperature ($\Delta T = T_{in}$-T_{out}) over the storage. The ΔT decreases as the TES is being charged, subsequently discharged, and the rate of change depends on the HTF mass flow and duration of charge and discharge. The HTF inlet temperatures and mass flow for the charge/discharge cycles during testing of the pilot TES is chosen based on a prescribed set of conditions emulating a solar field and a power block in a typical parabolic trough CSP plant. In such plants the steam generator is typically operated in a sliding pressure and temperature mode following a decrease in HTF temperature. This results in a decreasing outlet temperature (thus decreasing inlet temperature to the TES) as the TES outlet temperature decreases during discharge. Figure 4 shows the measured HTF temperature and mass flow from one week of continuous operation. The HTF is heated to 390 °C in the installation by the electrical heater; however, thermal losses in the oil loop facility reduces the inlet temperature delivered to the TES modules to about 375 °C. These thermal losses mainly arise from using small-diameter piping (3/4" and 1") and having relatively large piping distances (>50 m) with several discrete heat losses between the heater and TES. Improvements are ongoing to reduce such losses. Figure 5 shows the measured internal concrete temperatures, from sensors cast 50 cm into every fourth element (in the series of 24 elements), attached to the HTF tubes. The recorded data shows that the TES elements provide stable and repetitive response over time.

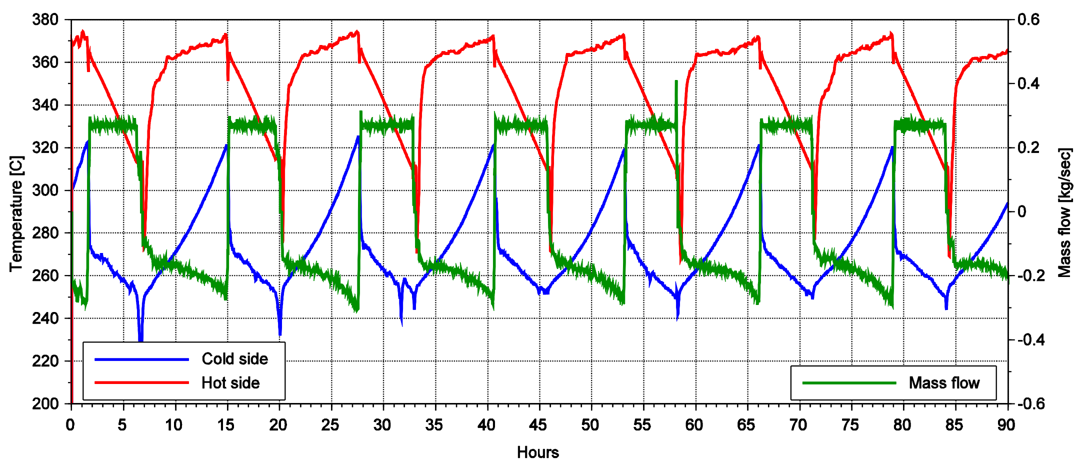


FIGURE 4. Measured HTF temperature and mass flow for one module over a period of four days.

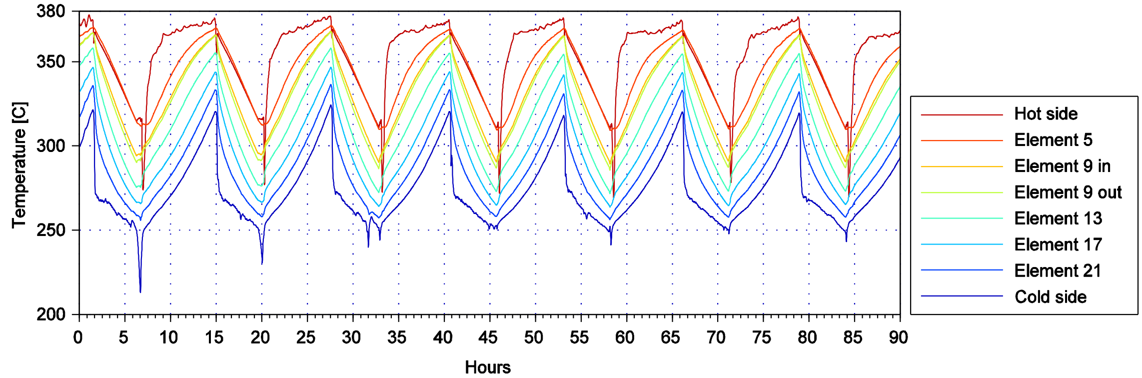


FIGURE 5. Measured internal concrete temperatures (sensors cast into the elements) and inlet/outlet temperatures for one module over a period of four days showing the repeatable performance of the storage.

The gross charged and net discharged energy and power is directly calculated based on measured mass flow ($\dot{m}$) and enthalpy difference (h) of HTF from inlet/outlet of the individual module during cycling. "Gross" in this respect refers to energy supplied to the TES, not accounting for the heat losses from the TES during charging, whereas "net" means the actual energy extracted from the TES by considering heat losses. In other words, during cycling where the TES goes from a given initial state (internal temperature distribution at $t = t_0$) through a complete charge/discharge cycle and ends up at the same state (at $t = t_1$), the difference between gross charge and net discharge over the complete cycle equals the total heat loss ($q_{cycle\text{-}loss}$). The relative cycled energy is therefore calculated from integrating power over time accounting for the measured total heat loss per cycle (eqns. 1, 2):

$$Power_{th} = \dot{m}_{HTF}(h_{HTF-in} - h_{HTF-out}) \quad (1)$$

$$Energy_{th} = \int_{t_0}^{t_1} Power_{th} dt - q_{cycle-loss} \quad (2)$$

The TES is charged aiming at reaching a highest possible inlet temperature while maximizing power by adjusting the HTF flow. Since the inlet temperature is stable at around 370 °C, the charge power is also relatively stable. However, during charging the ΔT over the TES decreases, hence the mass-flow is adjusted accordingly. The TES is discharged with an inlet temperature controlled considering the TES outlet temperature reflecting the behavior of a steam generator in a typical CSP plant. Each module is charged/discharged to meet the designed 250 kWh_{th} capacity. Figure 6 shows the measured net relative energy and power over four days of continuous operation, with approximately 7h:30m charging and 6h:00m discharging time.

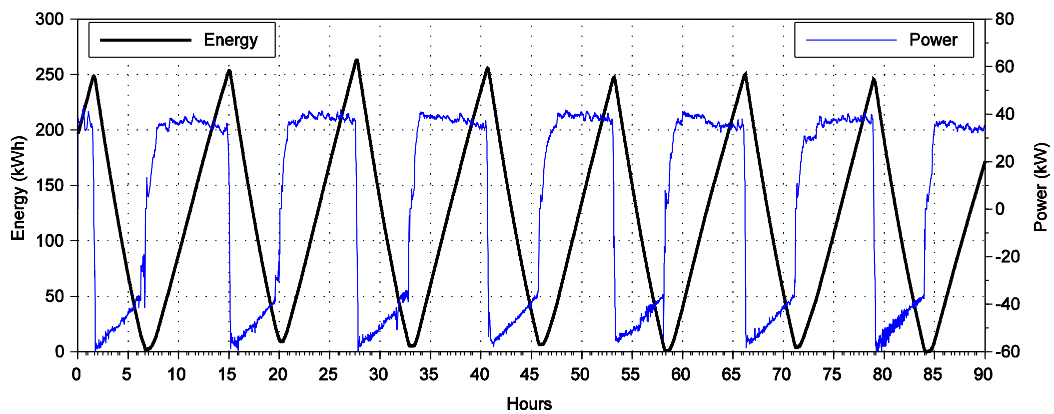


FIGURE 6. Calculated relative storage energy (black) and related power (blue) based on measured HTF mass flow and inlet/outlet temperatures for one 250 kWh_{th} module over a period of four days.

PILOT STORAGE SYSTEM PERFORMANCE AND VALIDATION

Validation of system performance is done through direct comparison between measured sensor values and numerically simulated performance. An advanced Matlab-Simulink model with a fluid structure interaction model based on the finite element method has been developed for accurately predicting the TES system performance. By simulating and comparing the TES inlet/outlet temperature profiles after commissioning to later results proves the stability and robustness of the TES. Figure 7 shows one charge/discharge cycle after the system was commissioned during early phase, and Figure 8 shows results from cycling after more than 1000 hours of operation. The difference in simulated versus measured performance after operation for 1000 hours is nearly indistinguishable. Even more importantly, the TES as whole shows absolutely no sign of degradation. The difference between measured and simulated cold side temperatures during charge in Fig. 7 is due to differences between real and modelled initial temperature conditions of the TES. However, the match is near perfect at the end of charge period and during discharge, thus the model represents the true TES energy and temperature state when the discharge begins.

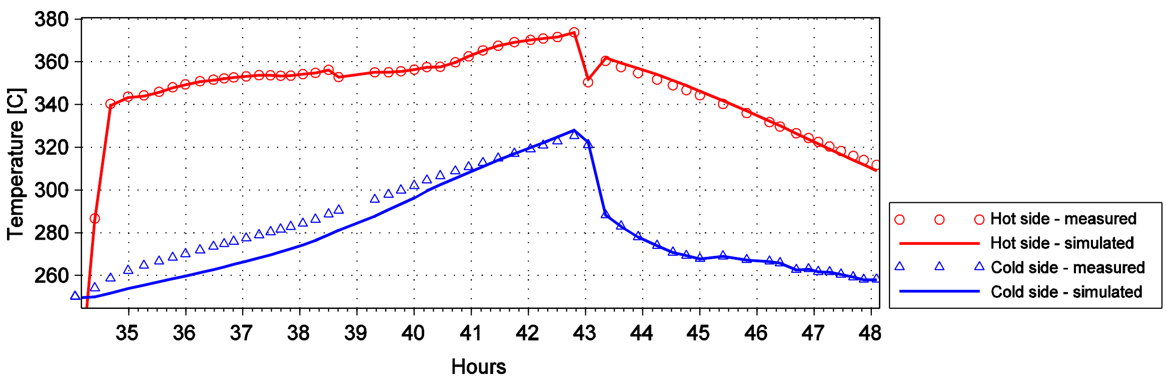


FIGURE 7. Simulated and recorded HTF inlet/outlet temperatures for one 250 kWh_{th} cycle after commissioning.

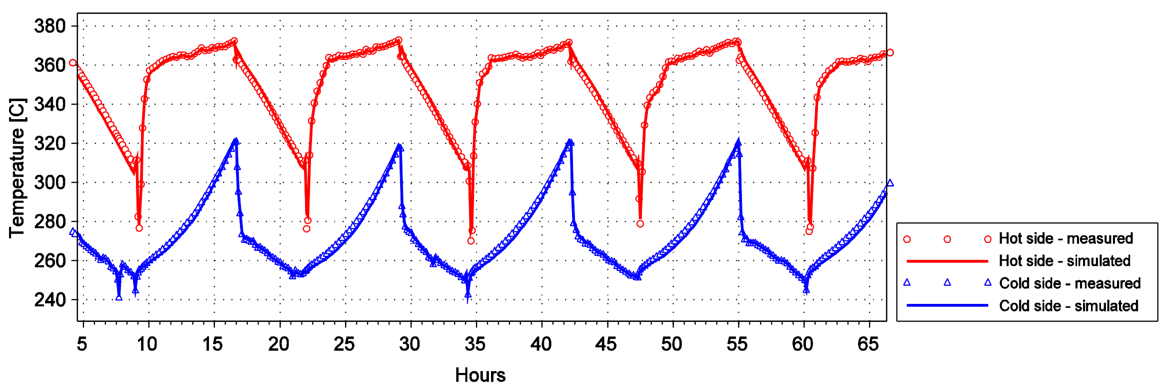


FIGURE 8. Simulated and recorded HTF inlet/outlet temperatures for 250 kWh_{th} cycles after > 1000 operating hours.

PERFORMANCE OF LARGE-SCALE STORAGE SYSTEM

As reported in the previous section, EnergyNest's simulation tool calculates performance of the TES with high degree of accuracy. This tool has also, among other cases, been used to simulate performance of a specific large-scale TES in a commercial application. The case study considers a 1300 MWh_{th} TES in a 50 MW_{el} (net) parabolic trough CSP plant with thermal oil HTF. A reference two-tank indirect molten salt TES is used for performance comparison and benchmarking of the EnergyNest technology. The simulation model used to calculate gross power block output during TES discharge is based on an empirical model of a 30 MW_{el} SEGS VI power block, scaled to 50 MW_{el} as reported in [6]. The model calculates gross power output based on HTF mass flow and inlet temperature to the steam generator; hence it considers the effect of decreasing HTF temperature on steam cycle efficiency. The performance comparison is based on gross power block output during TES discharge adjusted for TES parasitic losses in both charge, discharge and standby modes. Table 1 displays calculated parasitic losses for an EnergyNest and molten salt TES for the case of nominal charge/discharge. The design conditions for nominal energy input of 1300 MWh_{th} considers a charge of 8h:45m, a discharge of 11h:15m and a stand-by period of 4h:00m for both TES systems.

TABLE 1. TES systems parasitic losses and power block output with design conditions of 1300 MWh_{th} discharge.

Parameter	Unit	EnergyNest	Molten salt
Gross power block output	MWh_{el}	480.4	492.7
HTF pumps; charge (additional HTF for TES)	MWh_{el}	-17.2	-16.8
HTF pumps; discharge	MWh_{el}	-17.3	-16.1
Salt pumps & auxiliaries; charge	MWh_{el}		-8.4
Salt pumps & auxiliaries; discharge	MWh_{el}		-8.8
Salt auxiliaries; stand-by (4 hours)	MWh_{el}		-1.8
Gross power block output – TES parasitic losses	MWh_{el}	445.9	440.8

Performance has been simulated over four days with variable solar energy; one day with nominal energy and three part-load days. HTF outlet temperature from the solar field is assumed to be 391 °C at all times, whereas the HTF discharge temperature from molten salt is assumed to be 379 °C. Figure 9 shows the HTF inlet/outlet temperature for EnergyNest TES and Table 2 presents a comparison of the gross and net output for both TES systems. The parasitic losses during nominal conditions (Table 1) of charge and discharge are converted to specific losses in MWh_{el}/MWh_{th} and stand-by losses are converted to specific losses in MW_{el}. These specific losses are then used to calculate overall parasitic losses for the three part-load days based on energy charged/discharged and number of stand-by hours. The total electricity output is 1.6 % higher from EnergyNest TES than from molten salt TES due to significantly reduced parasitic losses, mainly due to the avoidance of electricity consumed by the salt pumps and stand-by heat tracing.

Future work related to performance evaluation will include: 1) Effect of varying HTF inlet temperatures on solar field efficiency 2) the use of a more accurate model of a 50 MW_{el} power block representing modern CSP plants, 3) days with above nominal energy available for TES, 4) heat losses from the TES systems, and 5) parasitic losses calculated for part load operation.

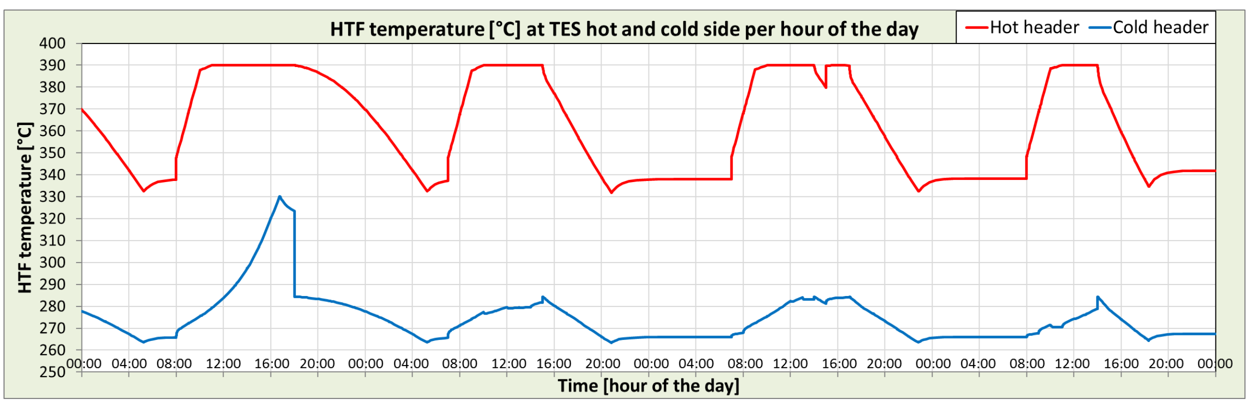


FIGURE 9. Simulated HTF temperature profile for EnergyNest 1300 MWh_{th} TES for four days with variable solar conditions.

TABLE 2. Performance comparison of EnergyNest vs. molten salt

Day	Charge/ discharge [MWh_{th}]	Stand-by hours [h]	EnergyNest		Molten salt	
			Gross el. [MWh_{el}]	Gross el. – TES parasitic [MWh_{el}]	Gross el. [MWh_{el}]	Gross el. – TES parasitic [MWh_{el}]
1	1300	4	480.4	445.9	492.7	440.8
2	629	10	230.8	214.1	238.4	209.7
3	757	8	279.7	259.6	286.9	254.1
4	465	14	166.6	154.3	176.2	152.0
TOTAL	3151			1073.9		1056.6

SUMMARY

The demonstrated and measured performance of the 2 x 500 kWh_{th} thermal energy storage pilot plant matches the predictions from numerical simulations; the testing proves the practical and operational feasibility of the EnergyNest concrete-based TES. Measured HTF temperature and mass flow after more than 1000 hours of cycling operation shows stable and repetitive performance. The difference between simulated performance versus measured sensor data is nearly indistinguishable which proves that the solid-state storage medium performance is constant with no sign of degradation.

Moreover, simulations of large scale systems indicate that overall CSP plant performance can be improved by using EnergyNest type TES rather than conventional two-tank, indirect, molten salt TES. The EnergyNest technology allows for simple, low cost, modular and fully scalable TES systems using solid-state storage medium. It is ideally suited for CSP plants and many other energy storage applications. The excellent thermal and mechanical properties of the special solid-state storage medium significantly improve performance over prior concrete-based TES systems and provides a competitive alternative over molten salt. The technology supports numerous other applications within industry such as waste heat recovery and conventional thermal power plants. The benefits of the technology solution include simplicity in installation and operation, low investment and operating cost, modularity and scalability from small to very large plants, and possibility for significant local content as the main components (steel and concrete) are global commodities.

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