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PILOT-SCALE LATENT HEAT STORAGE FOR WASTE HEAT RECOVERY FROM IMMERSION-COOLED DATA CENTERS WITHIN THE MODERATOR PROJECT

Summary

The rapid growth of data center electricity consumption results in large quantities of low-temperature waste heat that remain largely unused. The EU-funded Horizon MODERATOR project develops and demonstrates an integrated system combining immersion cooling and compact latent heat thermal energy storage (TES) for efficient waste heat recovery (WHR). This work presents the design and scaling strategy of a 240 kWh PCM-based storage system directly coupled to a 40 kW immersion-cooled data center. A salt-hydrate phase change material with a melting temperature of approximately 45 °C was selected to match the strict thermal boundary condition of a maximum 60 °C server outlet temperature. Single-cell and multi-cell experiments confirm stable phase-change behavior, reproducible energy capacity of 10–13 kWh per unit, and scalable hydraulic balancing. The full pilot installation will be commissioned starting June 2026, and operational data will be available for the full conference paper.

Keywords: waste heat recovery, latent heat storage, phase change material, immersion cooling, data centers, low-temperature heat, thermal energy storage

Field of application for the findings: Data center energy systems, low-temperature waste heat recovery, building and district heating integration

Addressed audience: Researchers and engineers in solar thermal systems, thermal energy storage, low-temperature heat recovery, and sustainable energy systems

1. Introduction

Global data center electricity consumption has reached approximately 460 TWh in 2022 and is expected to continue increasing significantly in the coming years [1]. Nearly all consumed electrical energy is ultimately converted into heat. While this represents a considerable secondary energy source, the relatively low temperature level of conventional air-cooled systems has historically limited efficient reuse.

Immersion cooling technology enables higher and more stable coolant outlet temperatures compared to air cooling, typically in the range of 45–60 °C, while improving thermal management and component reliability [2]. These elevated temperatures significantly improve the technical feasibility of direct heat reuse or thermal storage. However, effective storage of low-grade heat remains challenging due to limited temperature lift, hydraulic constraints, and the requirement for high volumetric energy density.

The MODERATOR project ("Immersion Cooling and Advanced Materials for Heat Recovery from Data Centers") addresses these challenges by developing and demonstrating an integrated waste heat recovery system combining immersion cooling and latent heat thermal energy storage. The present work focuses on the design and pilot implementation of the PCM-based storage subsystem

2. System Concept and Thermal Boundary Conditions

The waste heat recovery system couples a 40 kW immersion-cooled data center to a modular latent heat storage array via dedicated heat exchangers (Figure 1). A critical design constraint arises from the maximum permissible server outlet temperature of approximately 60 °C. This upper boundary directly determines the feasible melting temperature of the phase change material.

To ensure effective charging, a minimum temperature difference of approximately 5 K between the storage inlet temperature and the PCM melting temperature is required. Consequently, materials with melting temperatures near or above 58 °C would risk incomplete melting and limited charging performance under realistic operating conditions.

Latent heat storage was selected over sensible heat storage due to its higher energy density and quasi-isothermal heat transfer within the 40–70 °C range [3], [4]. In applications where temperature levels are constrained, the ability of phase change materials to absorb and release large amounts of heat within a narrow temperature band provides significant system-level advantages.

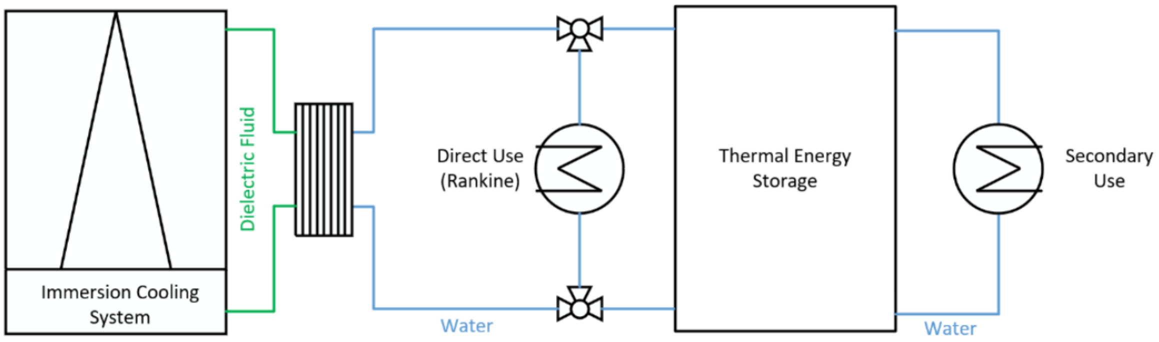

Figure 1: Schematic of the pilot plant with Immersion cooling system, direct use Rankine cycle, TES, and secondary use heat exchanger (from left to right).

3. Phase Change Material Selection and Storage Technology

Salt-hydrate-based phase change materials are particularly suitable for low-temperature thermal storage because of their high volumetric latent heat, non-flammability, and cost-effectiveness [5]. Nevertheless, typical challenges include supercooling, phase segregation, and corrosion effects [5], [6]. Within the MODERATOR project, extensive material screening and cycling tests were conducted to identify a stable formulation.

A salt-hydrate PCM with a melting temperature of approximately 45 °C (PCM45) was selected for the pilot installation. This melting temperature ensures complete melting under a maximum inlet temperature of 60 °C while maintaining sufficient temperature lift for integration into secondary heating systems. Laboratory and prototype testing confirmed a latent heat exceeding 200 kJ kg^{-1}, stable cycling behavior beyond 1000 charge–discharge cycles, and corrosion rates below critical thresholds.

The storage architecture is based on directly filled modular units ("Compact Cells"), developed within this project, rather than encapsulated packed-bed configurations. Each Compact Cell provides 10–13 kWh of usable thermal capacity within the 30–60 °C operating range. The units are designed for a maximum operating pressure of 6 bar and maximum temperature of 75 °C, enabling compatibility with hydronic heating systems. The direct-fill approach reduces thermal resistance and increases effective energy density compared to macro-encapsulation concepts.

4. Experimental Validation and Scaling

Single-cell experiments were conducted to characterize charging and discharging behavior under dynamic operating conditions. Charging tests at 2.5–10 kW show well-defined temperature plateaus during melting, confirming quasi-isothermal latent heat absorption. Discharging experiments at 20–40 kW demonstrate stable crystallization behavior and reproducible energy delivery between 10 and 13 kWh per unit. The measured energy output is consistent with theoretical predictions based on the PCM mass and enthalpy data.

To evaluate hydraulic scalability, a six-cell parallel configuration was operated under field conditions. Temperature measurements within each cell showed nearly identical charging and discharging curves, indicating successful hydraulic balancing and uniform flow distribution. No evidence of preferential flow paths or incomplete crystallization was observed. These results confirm that the modular design can be scaled while maintaining predictable thermal behavior.

5. Pilot Design and Commissioning

The full MODERATOR pilot consists of a 4×5 array comprising four cells in series and five parallel branches, resulting in a total of 20 storage units (Figure 2). The nominal storage capacity is approximately 240 kWh. The series configuration increases the achievable temperature lift, while the parallel arrangement limits pressure drop and ensures balanced flow distribution.

Based on validated scaling from single- and multi-cell experiments, the total usable storage capacity is expected to range between 200 and 260 kWh, depending on operating conditions. Charging power is expected to lie between 12 and 50 kW under current hydraulic constraints, while discharging power may reach 100–200 kW depending on flow conditions and heat exchanger performance.

All storage components will be delivered to the pilot site in spring 2026. Commissioning of the integrated immersion cooling and waste heat recovery system is planned for June 2026. Consequently, system-level operational data including charging efficiency, discharge performance, and integration behavior will be available for inclusion in the full conference paper.

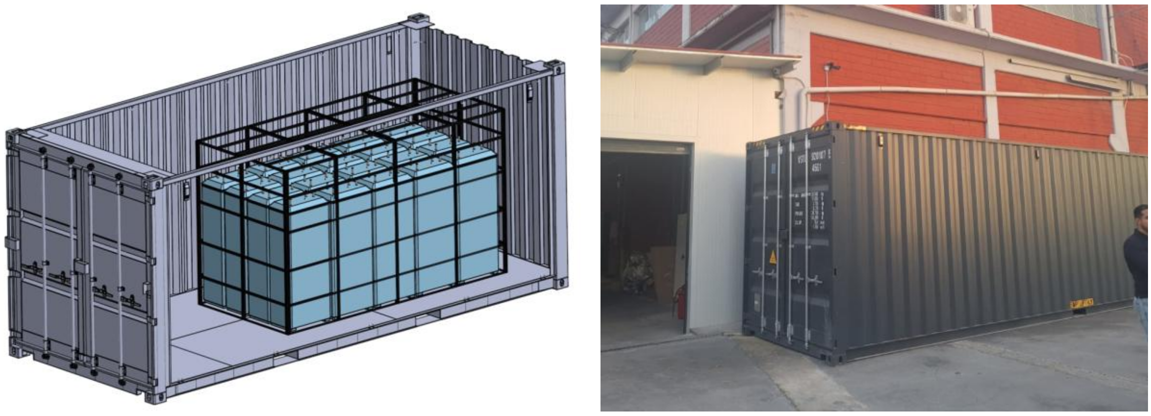

Figure 2: Left: Moderator 4x5 cell array storage pilot. Right: Pilot container at proposed location.

6. Conclusions

This work presents the design and pilot implementation of a 240 kWh latent heat storage system for waste heat recovery from immersion-cooled data centers. The selection of a 45 °C melting salt-hydrate PCM enables reliable operation under a strict 60 °C thermal boundary condition. Experimental validation demonstrates stable phase-change behavior, reproducible energy capacity, and scalable hydraulic balancing. The upcoming pilot operation will provide the first integrated demonstration of immersion cooling combined with modular latent heat storage at this scale. The results are expected to contribute to the advancement of low-temperature heat recovery and sector coupling strategies in building and district heating systems.

7. References

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