

HOLISTIC ENERGY MANAGEMENT AND THERMAL WASTE INTEGRATED SYSTEM FOR ENERGY OPTIMIZATION



Lab testing results and improvement guidelines

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Executive Summary

This deliverable reports on the system-level testing of a hybrid cooling solution combining two-phase direct-to-chip liquid cooling with traditional air-based cooling.

The tests were originally planned to be done in ZutaCore facilities, nonetheless due to RISE's expertise and diverse suite of advanced sensors, the experiments were conducted at RISE labs in alignment with HEATWISE objectives, under controlled but realistic environmental and operational conditions. The main objective of this task was to assess the performance, reliability, and operational behavior of the integrated system, simulating actual usage scenarios, including troubleshooting, break-fix operations, and runtime performance under variable IT workloads.

The testing aimed not only to evaluate the system's thermal and energy efficiency but also to provide critical insights into the feasibility of hybrid cooling deployment in commercial data centers. The system was additionally evaluated for repeatability, reliability, and scalability, with a focus on optimizing energy efficiency. The setup and methodologies were shaped according to the requirements and deliverables defined in WP3 (deliverable D3.2) in which the potential waste heat was assessed based on historical data, and WP4 in which CFD simulations and experimental studies on data centre pilots were conducted to evaluate and optimize cooling efficiency (deliverables D4.1 and D4.2).

Key outcomes include **thermal performance**: when using Hybrid cooling the CPU temperatures reduced compared with the CPU temperatures when using air cooling only, eliminating thermal throttling, **energy efficiency**: CPU power savings was demonstrated across the test servers and reduced demand on air cooling. **Reliability**: Stable operation without critical errors; predictable thermal behavior under varying workloads and **optimization opportunities**: Improved heat recovery potential, , and integration of adaptive fan control.

These outcomes directly support the HEATWISE project's key performance indicators by demonstrating $\geq 20\%$ primary energy savings per server (PES), progress toward a Power Usage Effectiveness (PUE) of 1.05, and enhancement of the Energy Reuse Factor (ERF) toward 95%. Collectively, the findings validate hybrid cooling as a scalable, sustainable pathway for energy-efficient and heat-reusing data centers in line with HEATWISE objectives.

List of abbreviations

Acronym	Meaning
BEMS	Building energy management system
CFD	Computational Fluid Dynamics
CPU	Central Processing Unit
DC	Data Centre
DLC	Direct liquid cooling
HRU	Heat Rejection Unit
PUE	Power usage effectiveness
PES	primary energy savings

Introduction

The HEATWISE project aims to tackle the integration of waste heat and thermal energy management in tertiary buildings with significant IT loads. The objectives of the project are: to minimize waste heat, maximize energy efficiency, and generate additional value through intelligent energy reuse. These goals reflect a wider ambition to create a lasting impact on buildings' energy efficiency and thermal management optimization by bridging digital infrastructure demands with sustainability priorities.

As part of this broader effort, the present delivery report focuses on the system-level testing and validation of a hybrid cooling system combining two phase liquid cooling and air cooling. This specific contribution aligns with the HEATWISE project's ambitions by addressing how advanced cooling technologies can be practically deployed in real-world data center environments to reduce energy consumption and improve heat reuse potential.

From a scientific standpoint, system-level thermal testing under real-world workload scenarios is essential for validating the practicality and efficiency of such technologies. It allows researchers and industry stakeholders to evaluate key performance metrics, troubleshoot integration challenges, and develop optimization pathways. Hybrid solutions not only promise better energy performance but also open the door to innovative secondary uses of waste heat, as will be demonstrated in this project, further boosting their sustainability credentials.

This report presents HEATWISE contribution to this broader initiative through system-level testing of a hybrid cooling configuration. Conducted at the RISE lab, this work examines not only the thermal and power efficiency of the integrated solution but also its operational viability, repeatability, and capacity for optimization. The findings contribute to a more comprehensive understanding of how next-generation cooling solutions can be deployed at scale to support Europe's digital and climate goals.

Contributions of Former Work Packages

According to the delivery report D3.2, which analyzes historical data, in the different pilot sites, among others, when temperature requirements are significantly lower, waste heat energy should be supplied directly to the main building system. For instance, as illustrated in Table 1, at the Aalborg pilot site, if the potential at the different supply temperatures is utilized fully, the building could cover 38% of the total heating energy use with a supply temperature of 40°C. The corresponding potentials at other supply temperatures are also reported in Table 1.

Table 1 AAU Potential specific energy [kWh/m²] demand possible to cover at different supply temperatures if the waste heat is provided directly at the system level.

Supply temperature	Heating	Ventilation	Domestic hot water	Miscellaneous	Total savings potential
30°C	1.4	5.3 – 5.7	0	<0.1	15%
40°C	1.8	15.3 – 18.1	0	<0.1	38%
50°C	3.3	18.7 – 19.2	0.8	<0.1	51%
60°C	11.2	19.3	1.8	<0.1	72%
70°C	14.0	19.3	1.8	0.1	79%

Considering the analysis mentioned above, table 2 below, demonstrates potential energy use at different temperatures levels at EMPA pilot site for the High Temperature grid supply (to which the cooling system will be connected).

Table 2 EMPA Energy use at the different temperature levels for the HTE- High Temperature grid supply. The values have unit of kWh/m².

Supply temperature	2022	2023	2024
X ≤ 25°C	0.00	0.00	0.00
25°C < X ≤ 30°C	0.03	1.50	0.90
30°C < X ≤ 35°C	0.02	0.00	0.00
35°C < X ≤ 40°C	0.02	0.02	0.03
40°C < X ≤ 45°C	0.01	0.02	0.04
45°C < X ≤ 50°C	0.01	0.02	0.11
50°C < X ≤ 55°C	0.03	0.06	0.11
55°C < X ≤ 60°C	0.10	0.22	0.39
60°C < X ≤ 65°C	0.44	0.37	0.95
65°C < X ≤ 70°C	0.00	0.00	0.00
70°C < X ≤ 75°C	0.00	0.00	0.00
75°C < X ≤ 80°C	0.00	0.00	0.00

$80^{\circ}\text{C} < X$	0.00	0.00	0.00
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Within the framework of WP4, Computational Fluid Dynamics (CFD) studies were conducted to evaluate and optimize the thermal and cooling performance of pilot data centres. Different cooling configurations were considered across sites, including air cooling (AAU, PSNC) and direct-to-chip two-phase cooling (EMPA, RISE). Comprehensive monitoring of inlet/outlet rack temperatures, IT loads, power consumption, and ambient conditions provided the basis for realistic model validation.

Key objectives were to establish baseline performance, identify hotspots, and assess inefficiencies such as bypass flows, cold air leakage, and uneven airflow. Thermal KPIs (RTI, RHI, RCI, RI, LI) and energy-related indicators like PUE and COP were used to quantify improvements.

CFD simulations revealed the benefits of retrofitting strategies, including cold/hot aisle containment, optimized perforated tile placement, and airflow management. Results confirmed that containment measures and optimized cooling setpoints were the most effective interventions.

The project investigated two-phase modeling, with particular attention to film boiling phenomena that define the operational limits of cooling systems. Advanced two-phase CFD models were validated against benchmark problems, demonstrating improvements in heat transfer efficiency (up to 57% increase in Nusselt number) and critical heat flux (>60% rise) using micro-baffle designs. These findings highlight the potential of direct-to-chip cooling for high-density IT workloads.

Experimental validation from WP5 and WP6 confirmed the reliability of the CFD predictions. Hybrid-cooled servers showed reduced cooling power demand and improved thermal resistance compared to air-cooled cases. The combined numerical and experimental results formed the basis of an improvement guide, offering a roadmap that integrates single-phase retrofitting with state-of-the-art two-phase cooling. This methodology provides a transferable framework for sustainable data centre thermal management, aligning with the Energy Efficiency Directive and supporting HEATWISE's broader sustainability goals

Across all pilot sites, KPI improvements were most strongly associated with containment measures and optimized cooling setpoints, confirming the importance of holistic airflow management.

Experimental Framework

The objective was to simulate the actual usage and impact of the system. System usage and implications included operational activities, troubleshooting, defect resolution and break-fix scenarios, as well as performance testing (e.g. improved run-time results) across varying workloads with repeatable outcomes.

The complete system was tested and optimized to achieve maximum energy efficiency.

Methodology

The methodology employed for testing the hybrid cooling systems within the HEATWISE Project was centred on a data-driven approach that aimed to evaluate the efficacy, efficiency, and overall performance of both air and liquid cooling mechanisms under a range of IT load conditions. The testing process incorporated comprehensive monitoring and analysis to capture detailed thermal and power consumption data, enabling accurate comparisons between different cooling strategies. To ensure robust and representative results, the experiments utilized Open Compute Project (OCP) servers, various ODM servers, and Thermal Test Vehicles (TTVs). This combination of hardware provided a broad perspective on system behaviour and performance across diverse configurations, supporting a thorough assessment of the hybrid cooling systems' operational effectiveness and scalability.

The data acquisition system uses open-source tools Prometheus, Zabbix, VictoriaMetrics, and Grafana, each serving a key role in the data pipeline. Prometheus and Zabbix automate data extraction, transformation, and validation, VictoriaMetrics provides high-performance, long-term storage for large time-series datasets and Grafana delivers real-time, dynamic dashboards for analysis and monitoring.

This integrated platform collects and processes data at 1-minute intervals or less from multiple sources, ensuring scalable, reliable, and easily visualized metrics across data centers, IT infrastructure, and building systems.

The tests duration was about 110 hours for air cooling setting and about 60 hours for hybrid cooling setting.

Test Environment:

Considering RISE's extensive expertise and the availability of well-equipped facilities featuring advanced measurement systems with a wide variety of sensors, the experiments were conducted at the RISE premises. The setup included nine Open Compute Project (OCP) servers, each equipped with two Intel Xeon E5-2678 v3 processors, collectively representing a typical data center configuration. These servers were retrofitted with ZutaCore's HyperCool® Heat Rejection Unit (HRU), which enabled two-phase liquid cooling using Opteon™ SF33 as the working fluid. The testbed

incorporated a server wind tunnel to simulate varied inlet air temperatures and IT workloads under controlled airflow and pressure conditions (see Figures 1.a and 1.b).

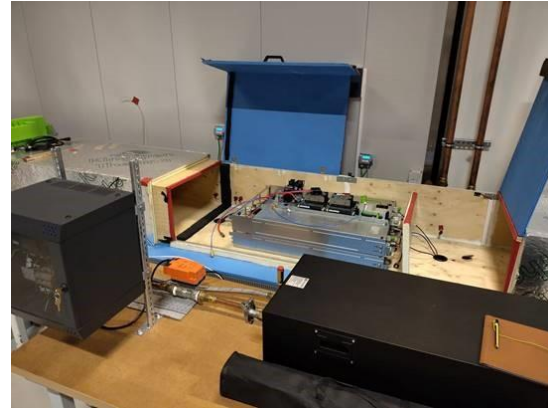
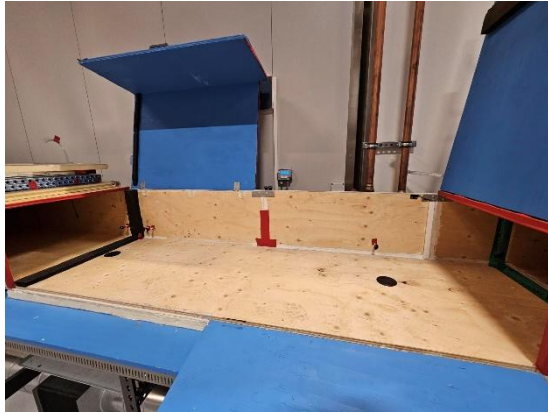


Figure 1.a Empty wind tunnel and Figure 1.b Wind tunnel with servers

The hybrid system utilized Opteon™ SF33 as the dielectric working fluid, circulating through cold plates mounted directly on CPUs. Vaporized fluid was condensed in the HRU and rejected to a facility-side dry cooler in a closed-loop configuration. Data acquisition was managed using an open-source toolchain (Prometheus, Zabbix, Grafana, VictoriaMetrics) for real-time monitoring. Following in Figure 3, is a schematic view of the closed-loop experimental setup for the two-phase liquid cooling system.

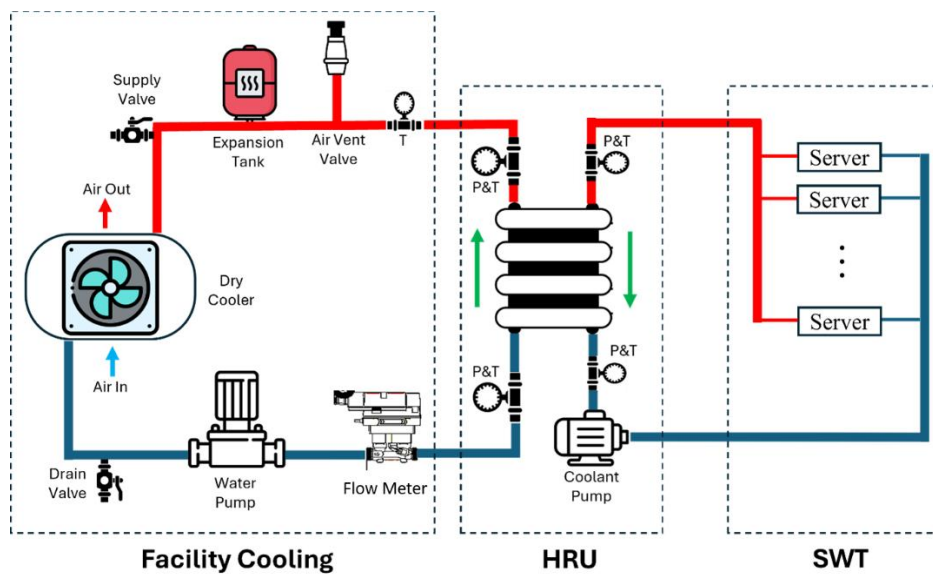


Figure 2 Schematic view of the closed-loop experimental setup

Test Conditions:

- Server inlet temperatures ranged from 25°C to 45°C.
- CPU workloads varied from idle to full load (0% to 100%).
- Fixed fan speeds were used; airflow and vapor pressure were modulated.
- Data acquisition and analysis leveraged Prometheus, Zabbix, Grafana, and Victoria Metrics.

Test Objectives:

- Validate system integration and performance under realistic data center scenarios.
- Assess troubleshooting, operational behavior, and break-fix scenarios.
- Analyze the effect of hybrid cooling on performance repeatability and reliability.
- Optimize the system for energy efficiency aligned with WP3 (thermal management optimization) and WP4 (system integration and validation).

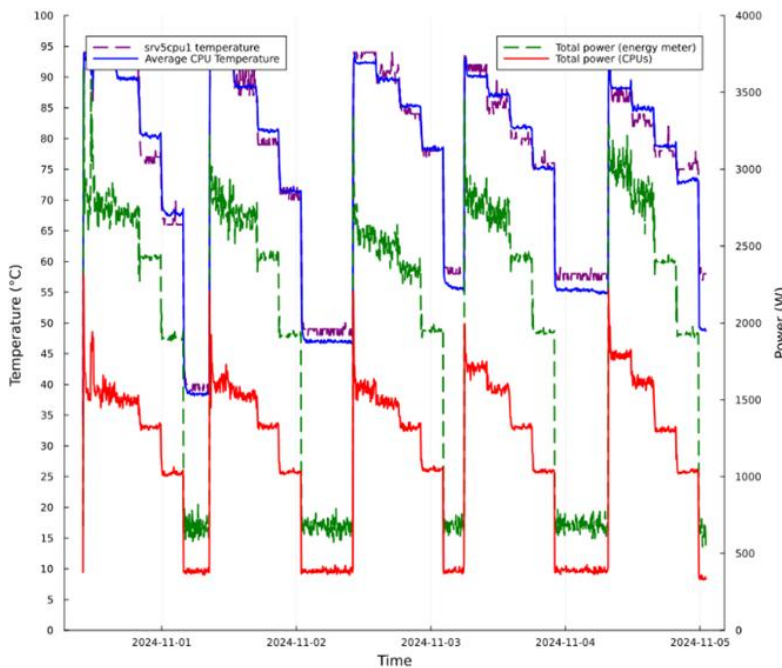
Results and Analysis

Thermal and Performance Efficiency

A notable reduction in CPU temperatures was observed during hybrid cooling operation. Under full load at 25°C inlet air temperature, average CPU temperatures (all retrofitted servers) dropped by approximately 40%. The two-phase system effectively leveraged the latent heat of vaporization, resulting in consistent and efficient thermal regulation across varying load conditions. Importantly, thermal throttling, which was present in several air-cooled cases, was nearly eliminated in hybrid scenarios, demonstrating improved system stability.

The following two graphs in figure 4 present the CPU temperatures measured under air cooling and hybrid cooling. The CPU temperatures decrease significantly when switching from air cooling to hybrid cooling across all CPU load conditions. The link to the complete dataset used for this analysis will be published on the project website <https://heatwise.eu/>.

Temperatures and total power over time (air cooling)



Temperatures and total power over time (hybrid cooling)

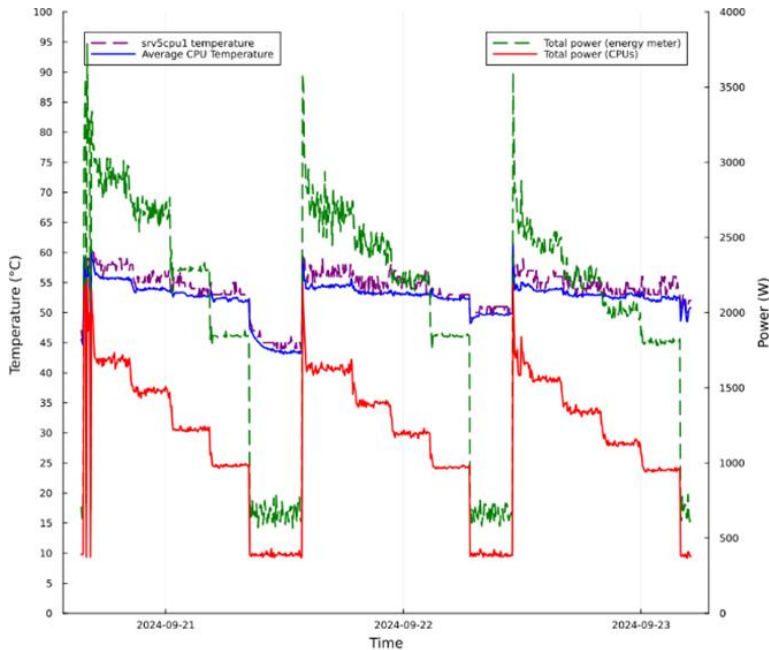


Figure 3 CPU temperature and power consumption for air cooling and hybrid cooling

Energy Efficiency and Power Dynamics

A consistent reduction in cumulative CPU power consumption was measured across the server array during hybrid operation. The CPUs draw less electrical power once cooled more effectively by the two-phase liquid system. This originates from the temperature-dependent reduction in leakage current and efficiency gains achieved under hybrid cooling.

This efficiency gain was accompanied by a marked reduction in air cooling demand, particularly at higher ambient temperatures. By offloading heat directly at the chip level, the hybrid configuration enabled efficient operation even at inlet temperatures above ASHRAE guidelines, without compromising performance. The system maintained comparable total power usage despite the fixed fan speeds, suggesting further savings potential under dynamic airflow control.

Operational Observations and Troubleshooting Readiness

The hybrid system exhibited robust operational integrity across all test conditions. No critical errors or breakdowns were recorded, and the liquid cooling loop remained stable throughout. Notably, some signs of memory throttling were detected during high-load operations under fixed fan conditions, attributed to suboptimal airflow over memory modules. This observation underscores the need for system-level airflow optimization as part of future design considerations.

Operationally, the system's responsiveness to different load profiles was consistent and repeatable, indicating predictable thermal behavior. This supports the reliability of the

integrated system in live environments, where workload variability and dynamic performance requirements are typical.

Repeatability and Reliability Under Varying Loads

Testing across multiple cycles confirmed that the hybrid system maintained a consistent thermal and energy performance profile. In repeated load tests, CPU temperature and power readings remained within tight tolerances, supporting the repeatability of the thermal control mechanisms. This finding is particularly relevant for production environments, where predictable behavior across different operational states is essential.

System Optimization Considerations

The data revealed that the amount of heat captured by the HRU increased as inlet air temperatures rose, suggesting a favorable opportunity for integrating waste heat recovery systems. Furthermore, auxiliary components such as the Platform Controller Hub (PCH) and memory modules also benefited from the liquid cooling environment, which could translate to longer component lifespans.

Additional improvements may be achieved by optimizing the thermal interface materials. Future iterations should also explore active fan modulation and adaptive cooling logic to unlock additional energy savings.

Conclusions and Proposed Enhancements

The system-level evaluation at RISE facility has confirmed the efficacy of the hybrid cooling solution in addressing critical challenges of energy efficiency, thermal regulation, and operational robustness in data centers. By combining direct to chip liquid cooling with existing ai-based systems, the integrated approach provides a viable and scalable route toward greener digital infrastructure.

The hybrid approach demonstrated improved performance in both thermal and energy dimensions, with the added benefits of operational consistency and readiness for real-world deployment. Its capability to maintain high efficiency at elevated temperatures positions it well for use in future data centers seeking to optimize energy use while reducing environmental impact.

These findings contribute directly to the HEATWISE project's objectives and align with the HEATWISE project's KPIs by simultaneously lowering CPU temperatures, cutting cumulative CPU power consumption across nine servers, and reducing reliance on airside cooling at higher inlet air temperatures (25–45 °C).

These improvements directly support the Primary Energy Saving goal of $\geq 20\%$ per server through more efficient processor operation, contribute to achieving a Power Usage Effectiveness (PUE) ≤ 1.05 by minimizing fan and CRAH overhead, and enhance the Energy Reuse Factor (ERF) toward the 95% target by shifting a greater proportion of waste heat into the liquid loop at usable temperature levels. Together, these results validate hybrid cooling as a practical and scalable pathway for energy-efficient, heat-reusing data centers in line with HEATWISE's mission and underline the potential of hybrid cooling as a key enabler in the transition toward climate-neutral, high-performance computing environments in Europe.

The results demonstrate strong potential for utilizing waste heat in heating applications. Although demand at the pilot sites is seasonal, dropping off during the summer months, the recovered heat, reaching temperatures of up to 65°C, can still be supplied directly. This makes it suitable for partial integration into a high-temperature network, such as providing hot water for residents' showers.

Several areas for improvement have been identified to further enhance the performance and energy efficiency of the hybrid cooling system:

1. **Dynamic Airflow Optimization:** The current tests were conducted with fixed fan speeds, which limited the system's adaptability to variable loads. Implementing dynamic fan control algorithms would allow real-time adjustment of airflow, potentially reducing unnecessary energy consumption and improving memory module cooling, which was occasionally subject to throttling.

2. **System Integration Enhancements:** Improvements can be explored in areas such as optimizing mounting pressure, contact uniformity, or flow distribution in manifolds, to support better thermal performance.
3. **Enhanced Monitoring and Diagnostics:** Integrating smarter sensors and more granular data acquisition could improve the visibility into component-level performance and enable predictive maintenance strategies.
4. **Modular Deployment Assessment:** A follow-up investigation should evaluate how this hybrid system can be deployed modularly across different data center environments, including constraints in retrofit scenarios and impact on existing infrastructure.

These improvement avenues align closely with HEATWISE goals and will form the foundation for system adaptation at pilot sites. Implementation will be guided by:

- Calibration of hybrid cooling parameters using CFD simulation outputs.
- Adjustment of control schemes for fan speeds and coolant flows based on site-specific operational baselines.
- Infrastructure compatibility checks and modular deployment strategies customized per site.
- Early integration of KPI tracking for energy consumption, thermal performance, and system responsiveness to be used in WP5 monitoring activities.

It is recommended that the pilot sites carry out targeted evaluations to further validate system robustness and performance under diverse conditions, including:

- **Energy density effects** to assess how varying energy densities influence cooling efficiency
- **IT load behavior** – test both constant and dynamic loads, including bursty patterns such as AI workloads with surges
- **Emergency scenarios** – simulate failure modes and stress conditions to verify system resilience
- **Weather implications** – evaluate performance under different ambient conditions
- **Control responsiveness** – measure latency, dynamism, and inertia of the system under varying operational states

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