HOLISTIC ENERGY MANAGEMENT AND THERMAL WASTE INTEGRATED SYSTEM FOR ENERGY OPTIMIZATION

HEATWISE

Efficiency metrics for the assessment of pilot sites

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Developing self-assessment tool with holistic algorithms

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Executive Summary

Data centres currently account for approximately 3% of Europe's total energy consumption and this share is expected to increase rapidly with the advancements in artificial intelligence (AI), internet of things, video streaming and social media. The increasing power demand from data centres in recent years has necessitated the systematic evaluation of energy efficiency based on the collected data. In this context, the European Commission has recently implemented a new European Union (EU)-wide rating scheme under the Energy Efficiency Directive (EED), which mandates data centre operators to periodically report Key Performance Indicators (KPIs) to a centralized European database. During the initial EED reporting period in 2024, approximately 36% of eligible data centres (around 770) submitted energy reports and 80% of the submitted values were judged reliable, which highlights the critical need for broader participation and improved data quality within the data centre sector. Accordingly, the HEATWISE aims to establish a KPI framework, building on a strong consensus regarding KPI definitions, that links thermal design and operation to energy efficiency and waste heat recovery practices in server rooms located in tertiary buildings.

This deliverable presents a comprehensive set of KPIs for evaluating the thermal and cooling efficiencies of pilot data centres, aligning with the recently adopted EED scheme. In this deliverable, each KPI has been discussed and analyzed in detail, and its applicability for specific pilot data centres has been thoroughly examined. The potential conflict between the recently updated Power Usage Effectiveness (PUE) calculation and waste heat recovery practices is thoroughly discussed. The thermal KPIs are implemented in the open-source Computational Fluid Dynamics (CFD) framework developed and validated in WP4 to simulate time and spatial variations of KPIs within the data centre environment. Simulation results revealed that the calculation of KPIs at the inlet of the servers enabled to investigate efficiency of a data centre locally, which helps to capture adverse thermal effects such as cold air by-pass and hot air recirculations in pilot data centres. This deliverable illustrates that the proposed KPI framework serves not only as a technical instrument for evaluating thermal and energy performance but also as a policy-aligned tool that enhances adherence to the EED. By integrating both Thermal KPIs and EED KPIs into a unified framework, the operational performance of the pilot data centre can be directly correlated with regulatory reporting obligations.

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List of abbreviations

Acronym	Meaning
DC	Data Centre
EED	Energy Efficiency Directive
CFD	Computational Fluid Dynamics
RCI	Rack Cooling Index
RTI	Return Temperature Index
RHI	Return Air Heat Index
SHI	Supply Air Heat Index
RI	Recirculation Index
LI	Leakage Index
CCI	Comprehensive Cooling Index
WHR	Waste Heat Recovery
WHUR	Waste Heat Utilization Restrictors
PUE-LC	Power Usage Effectiveness for Liquid Cooling
REF	Renewable Energy Factor
COP	Coefficient of Performance
CRAC	Computer Room Air Conditioning
CRAH	Computer Room Air Handle
PES	Primary Energy Savings
WUE	Water Usage Effectiveness
ERF	Energy Reuse Factor
HTE	Heat Transfer Efficiency
CDU	Cooling Distribution Unit

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PUE	Power Usage Effectiveness

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1. Introduction

Key Performance Indicators (KPIs) are essential tools for assessing, managing, and improving the performance of data centres. They provide measurable means to evaluate energy efficiency, cooling effectiveness, and compliance with regulatory and sustainability requirements. By tracking the right set of KPIs, operators can identify inefficiencies, optimise operations, and demonstrate accountability to both regulators and stakeholders.

Thermal KPIs such as the Return Temperature Index (RTI), Rack Heat Index (RHI), Rack Cooling Index (RCI), Recirculation Index (RI), and Leakage Index (LI) are widely used to assess airflow distribution, thermal compliance, and the overall effectiveness of cooling systems.[1] These indicators provide insight into whether cold air is delivered efficiently to IT equipment, whether recirculation or leakage occurs, and how well the thermal environment matches design expectations. Monitoring such metrics helps prevent hotspots, minimise unnecessary cooling energy use and safeguard the reliability of IT operations.

In parallel, EED-aligned KPIs, including Power Usage Effectiveness (PUE), Energy Reuse Factor (ERF), Renewable Energy Factor (REF), and Water Usage Effectiveness (WUE), link operational performance with broader policy and sustainability goals.[2] PUE, formalised in ISO/IEC 30134-2 (2016), remains the most widely applied efficiency metric, while ERF, REF, and WUE extend the framework to cover energy reuse, renewable integration, and water consumption. The EU Energy Efficiency Directive strengthens this approach by requiring reporting of PUE, ERF, average waste heat temperature, and volumes of heat reused. These indicators ensure compliance with EU sustainability regulations and highlight the contribution of data centres to decarbonisation, particularly through the reuse of waste heat in local energy systems.

Together, these KPIs offer a comprehensive framework for benchmarking data centre sustainability, enabling operators to optimize energy use, cooling efficiency, and resource consumption in line with the EU's energy and climate objectives.[3]

The importance of such a combined KPI framework becomes even clearer when considering the variability of the HEATWISE pilot sites, which operate in different climates and serve academic, research, HPC, and industrial purposes. A harmonised approach to KPI selection ensures comparability across these diverse environments, while also enabling the identification of best practices for energy efficiency and thermal management. Moreover, by including both technical and regulatory indicators, the project bridges the gap between operational optimisation inside the data centre and policy driven sustainability targets at European level.

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In addition, KPIs provide not only a practical way to monitor and improve operations but also a foundation for aligning data centre performance with the EU's broader climate and energy objectives. They capture both the micro-level dynamics of airflow, cooling, and IT stability, and the macro-level impact of energy reuse, water consumption, and decarbonisation. This dual perspective ensures that the outcomes of the project will be directly relevant for operators, regulators, and the wider community, offering guidance for future data centre design, reporting, and optimisation across Europe.

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2. KPIs for Data Centres

In this study, the KPIs have been categorized into two main groups: Thermal KPIs and EED KPIs. The Thermal KPIs focus on evaluating the data centre's cooling performance, airflow management, and thermal compliance, thereby providing insight into operational efficiency from a temperature and air distribution perspective. The EED KPIs, on the other hand, are aligned with the requirements of the EU Energy Efficiency Directive, enabling systematic monitoring of energy related metrics and facilitating compliance with regulatory frameworks. This classification ensures that the proposed Self-Assessment framework addresses both operational and regulatory performance objectives in a balanced manner. Further details on these categories are provided in Section 2.1 and Section 2.2.

2.1. Thermal KPIs

Thermal KPIs provide an operational lens on how effectively a data centre delivers the right air at the right temperature to IT equipment, complementing energy metrics by explaining why efficiency improves or degrades. Calculated from server, rack, aisle and room-level (e.g., inlet/outlet temperatures, airflow rates, pressure differentials) and/or CFD post-processing, they quantify airflow quality and heat-removal performance—identifying hotspots, bypass air, and recirculation paths that erode cooling effectiveness and resilience. Common indicators include Rack Cooling Index (RCI_{HI} and RCI_{LO}) for inlet temperature compliance, Return and Supply Heat Index (RHI and SHI) for heat pickup, Return Temperature Index (RTI) for return air utilization, and Leakage/Recirculation Indexes (LI and RI) for containment and mixing. Used consistently, Thermal KPIs enable rapid root cause analysis, guide capacity planning and control set points, validate retrofits and containment strategies, and ultimately underpin regulatory reporting by linking day to day thermal conditions to energy outcomes (PUE trends) and equipment reliability.

2.1.1. Rack Cooling Index (RCI)

The Rack Cooling Index (RCI) evaluates how effectively a data centre's cooling system maintains inlet temperatures within acceptable thresholds defined by ASHRAE TC 9.9 thermal guidelines. These guidelines specify a recommended inlet temperature range of 27°C to 32°C for IT equipment. RCI is divided into two components: RCI_{HI} and RCI_{LO}.[4]

These are defined below as:

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$$RCI_{HI} = \left[1 - \left(\frac{\sum_{i=1}^{n}(T_i - T_{R,HI})}{N \times (T_{A,HI} - T_{R,HI})}\right)\right] \times 100 \tag{1}$$

Where, T_i is the inlet temperature for the i^{th} rack, $T_{R,HI}$ is the ASHRAE maximum recommended temperature 27°C, $T_{A,HI}$ is the ASHRAE maximum allowable temperature 32°C and N is the total number of the servers.

$$RCI_{LO} = \left[1 - \left(\frac{\sum_{i=1}^{n}(T_{R,LO} - T_i)}{N \times (T_{R,LO} - T_{A,LO})}\right)\right] \times 100 \tag{2}$$

Where, $T_{A,LO}$ is the ASHRAE minimum allowable temperature 15°C, $T_{R,LO}$ is the ASHRAE minimum recommended temperature 18°C, N is the total number of the servers.

Table 2.1: RCI values with corresponding cooling performance.

RCI Value	Cooling Performance
100%	Ideal
≥96%	Good
91-95%	Acceptable
≤90%	Poor

2.1.2.Return Temperature Index (RTI)

The Return Temperature Index (RTI) is a metric used to assess the efficiency of an air management system in data centres. It is calculated based on the principles of heat transfer[4]. RTI is defined as:

$$RTI = [\frac{T_{return} - T_{supply}}{\Delta T_{equip}}] \times 100 \tag{3}$$

Where, T_{return} is the return air temperature of cooling unit, T_{supply} is the supply temperature of cooling unit and ΔT_{equip} is the temperature increase over the server.

In data centres, heat transfer occurs through two primary mechanisms:

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1. Within the server racks, where the cold air supplied by the cooling system is heated by the IT equipment.

2. Within the cooling system, where the heated air returning from the equipment is cooled down by the heat exchanger.

In both cases, maximizing the effectiveness of heat transfer enhances overall efficiency, which is the ideal operational condition.

Increasing the mass flow rate necessitates higher operating power from both rack and air handler fans, making this approach neither practical nor scalable. Consequently, airflow manipulation becomes the primary lever for optimizing thermal performance, highlighting the importance of including both rack and air handler flow rates in the definition of the Return Temperature Index (RTI). Notably, CRAC (Computer Room Air Conditioning) unit efficiency improves with higher return air temperatures.

Table 2.2: RTI values with corresponding cooling performance.

RTI Value	Airflow Status
100%	Ideal
> 100%	Net recirculation
< 100%	Net bypass

2.1.3.Return Heat Index (RHI) and Supply Heat Index (SHI)

The Return Heat Index (RHI) and Supply Heat Index (SHI) are dimensionless metrics used to evaluate the thermal performance of a data centre. These indexes are designed to analyze the convective airflow within an equipment room with a raised floor configuration.

A data centre's energy efficiency is affected not only by the type of cooling system employed but also by the configuration of the equipment room itself. This is because the layout significantly impacts the performance of mixing between hot and cold air streams, which in turn affects the overall thermal performance.

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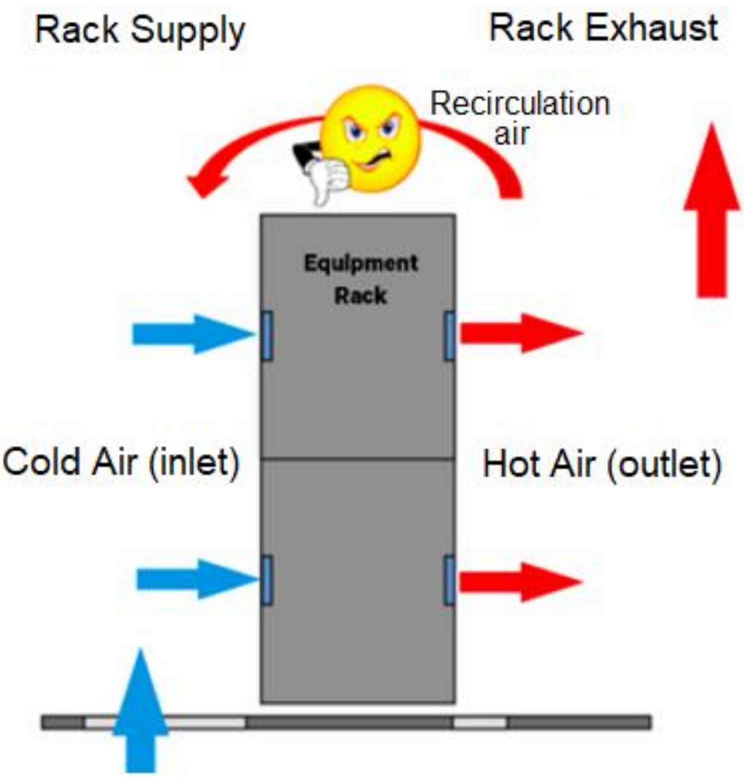

Figure 1.1: Wide Range of evaporating temperature[2].

The SHI and RHI metrics are defined below as:

$$SHI = \frac{\delta Q}{Q + \delta Q} \tag{4}$$

$$RHI = \frac{Q}{Q + \delta Q} \tag{5}$$

Where, Q is the total heat propagation of the racks and indicates the amount of cool air enthalpy increase before its entering to the rack. Total heat propagation of the racks is expressed as $Q = \sum_i \sum_j m^r_{i,j} C_p \big((T^r_{out})_{i,j} - (T^r_{in})_{i,j}\big)$. Where, $m^r_{i,j}$ is the entrance flow to the ith rack in the jth row. The simplified version of the SHI is $SHI = \frac{\sum_i \sum_j (T^{i,j}_{in} - T_{supply})}{\sum_i \sum_j (T^{i,j}_{out} - T_{supply})}$. In an optimal scenario, the sum of SHI and RHI approaches unity (SHI + RHI ≈ 1). As RHI increases, SHI correspondingly decreases, indicating improved alignment with ideal thermal management in data centre environments. A higher RHI signifies reduced mixing between the cold supply air and the hot exhaust air from the racks, with values exceeding 0.8 (or 80%) generally considered thermally efficient and acceptable in practice.

2.1.4.Recirculation Index (RI)

The inlet temperature of a server is expected to match the cooling system's supply temperature. However, due to recirculation effects, the temperature of the air increases as it travels from the cooling unit to the server inlets. To evaluate the impact of recirculation in an air-cooled data centre, the following recirculation index (RI) is proposed.

$$RI = [1 - \frac{(T_{rackInlet,mean} - T_{supply})}{T_{supply}}] \times 100 \qquad (6)$$

Where, $T_{rackInlet,mean}$ is the mean temperature of the rack inlet and T_{supply} is the supply temperature.

2.1.5.Leakage Index (LI)

Cold air leakage through a rack leads to a decrease in the outlet temperature of the associated server. To identify cold air leakage through the rack, which occurs due to gaps allowing cold air to flow into the hot region, the Leakage Index (LI) is proposed. The LI is a key metric that has been specifically developed by the DSTECH team to assess airflow inefficiencies in data centres. LI holds particular significance for Empa, where it will be thoroughly examined to assess its applicability and impact on data centre thermal management. The analysis conducted at Empa will provide valuable insights into how leakage affects cooling efficiency and overall performance, further validating the index's utility in real world scenarios.[6]

$$LI = [1 - \frac{(T_{rackOutlet,min} - T_{return})}{T_{rackOutlet,min}}] \times 100 \qquad (7)$$

Where, $T_{rackOutlet,min}$ is the minimum outlet temperature of the rack and T_{return} is the return temperature of the cooling unit.

2.1.6.Comprehensive Cooling Index (CCI)

To achieve a more holistic assessment of the system's performance, Norouzi-Khangah et al.[7]introduced the Comprehensive Cooling Index (CCI). This index not only incorporates elements from the previous indexes but also considers the average temperatures of both

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the cold and hot aisles between the racks, providing a more thorough evaluation of the cooling efficiency.[7] To determine the RCI value in the CCI equation, RCI_{HI} or RCI_{LO} is selected based on the inlet temperature. If the inlet temperature exceeds the maximum recommended temperature by ASHRAE, RCI_{HI} is used; otherwise, RCI_{LO} is applied.[6]

$$\begin{aligned} T_{in} \leq T_{R,HI} &\Rightarrow RCI = RCI_{LO} \\ T_{in} > T_{R,HI} &\Rightarrow RCI = RCI_{HI} \end{aligned} \tag{8}$$

$$CCI = min\left[(2 \times SHI) + \left(\frac{100 - RCI}{100}\right) + \left(\frac{100 - RTI}{100}\right) + \left(\frac{ATA - T_{out}}{ATA}\right)\right] \tag{9}$$

Where, T_{in} is the inlet temperature, $T_{R,HI}$ is the maximum recommended temperature and ATA is the average temperature of the aisle.

2.2. EED KPIs

The EU Energy Efficiency Directive (EED) is a key legislative framework designed to reduce energy consumption and greenhouse gas emissions across Europe. It establishes binding targets for Member States to deliver efficiency improvements. Core requirements include annual national savings, renovation of public buildings, mandatory energy audits for large companies, improved metering and billing practices, and measures to increase efficiency in heating, cooling, and digital infrastructure.

Recent revisions place a stronger focus on data centers, obliging operators of larger facilities to measure and disclose their performance. The directive highlights the use of specific Key Performance Indicators (KPIs), such as Power Usage Effectiveness (PUE) for overall energy efficiency, Water Usage Effectiveness (WUE) for water use, the Energy Reuse Factor (ERF) for capturing and reusing waste heat, and the Renewable Energy Factor (REF) for integrating renewable sources. These indicators provide a standardized way to assess performance and demonstrate alignment with the EU's climate and sustainability objectives.

2.2.1.Waste Heat Utilization Restrictors (WHUR)

WHUR is a new KPI proposed in the literature as part of the Heatwise Project and currently in the development phase. The purpose of this KPI is to provide feedback on which portion of the waste heat supplied from the data centre restricts its use in the building. The restrictors are supply temperature, available heat energy and heat energy demand.

$$WHUR = f(T_{sup}, Q_{avail}, Q_{demand}) \tag{10}$$

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2.2.2.Power Usage Effectiveness (PUE) for Liquid Cooling

Power Usage Effectiveness for Liquid Cooling (PUE-LC) is an adapted version of the traditional Power Usage Effectiveness (PUE) metric, designed to assess how efficiently a data centre operates when using liquid based cooling systems such as direct-to-chip or immersion cooling. The standard PUE formula still applies:

$$PUE = \frac{E_{facility}}{E_{IT}} \quad (11)$$

Where $E_{facility}$ is the total energy consumed by the data centre facility, including cooling infrastructure, lighting, and power delivery, and E_{IT} is the energy used by IT equipment such as servers, storage, and networking devices.[8]

Liquid cooling can significantly reduce the energy required for air handling units, chillers, and fans. However, these reductions may not always be reflected in PUE due to a shift in power consumption from facility to IT load (e.g., removal of server fans).[9] In a study by Vertiv and NVIDIA, a hybrid liquid-air cooled data centre showed a modest PUE improvement from 1.38 to 1.35 when 75% of the IT load was liquid-cooled.[10]

More advanced liquid cooling technologies, such as two-phase immersion cooling, have been shown to reduce PUE values as low as 1.05 to 1.10 by eliminating the need for active air movement and reducing thermal resistance. These improvements make PUE-LC a useful but sometimes limited metric, since it may mask energy efficiency gains by including certain IT side savings in the denominator. As a result, many experts recommend using complementary metrics like Total Usage Effectiveness (TUE) for evaluating full system efficiency in liquid-cooled data centres.

Table 2.3: Cooling Efficiency Performance

PUE-LC Value	Cooling Efficiency Performance
≤ 1.10	Ideal (High-performance immersion/liquid cooling
1.11 – 1.20	Very Good (Direct-to-chip or hybrid systems)
1.21 – 1.40	Acceptable (Optimized air-liquid setups)
> 1.40	Poor (Mostly air-cooled or inefficient setups)

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2.2.3.Renewable Energy Factor (REF)

The Renewable Energy Factor (REF) indicates the portion of a data centre's total energy consumption that is sourced from renewables, including on site generation, owned renewable electricity, and verified renewable energy contracts.[9,10] The ISO/IEC 30134-3 and EN 50600-4-3 standards define it as:

$$REF = \frac{E_{ren}}{E_{total}} \qquad (12)$$

Where E_{ren} is the amount of renewable energy under the data centre's control (in kWh), and E_{total} represents its annual total energy use, including IT load and facility infrastructure (in kWh).[11] A higher REF denotes stronger renewable integration: values of 0.2–0.4 (20–40%) are common among data centres with partial green sourcing, while fully green sourced operations typically reach REF ≥ 0.5. Achieving REF ≥ 0.8 (80%) aligns with leading edge sustainability goals and regulatory incentives.[8]

Table 2.4: Renewable energy usage performance.

REF Value	Renewable Energy Usage Performance
≥ 0.80	Ideal – Net-zero or full 100 % renewable sourcing
0.50 – 0.79	Good – Strong commitment with diversified renewables
0.20 – 0.49	Acceptable - Partial renewables, notable progress
< 0.20	Poor - Minimal renewable usage, significant improvement needed

2.2.4.Coefficient of Performance (CoP)

Coefficient of Performance (CoP) is a key indicator of cooling system efficiency in data centres, defined as the ratio of useful thermal energy removed from the IT hall to the electrical energy input required by compressors, pumps, and fans. The standard formula is:

$$COP = \frac{Q_{cooling}}{E_{input}} \qquad (13)$$

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where $Q_{cooling}$ is the heat removed (kW) and E_{input} is the total electrical energy consumed (kW). Studies on two-phase immersion cooling, one of the most efficient liquid-cooling methods, demonstrate COP values reaching 19 to 26.7 under varying server loads. Another publication reports average annual COPs between 30 and 39 for Novec based immersion systems, highlighting a performance increase of up to 7 times compared to traditional air-cooled setups.[12,13]

Higher COP values indicate that less power is needed per unit of cooling, reflecting superior energy efficiency and cost savings in modern data centres.

Table 2.5: Cooling efficiency performance.

COP Value	Cooling Efficiency Performance
> 30	Ideal - High performance immersion/two-phase liquid cooling
10–30	Very Good - Direct liquid cooling or hybrid chilled water setups
4–9	Good - Standard chilled water systems
< 4	Acceptable to Poor - DX or basic air-cooled systems

2.2.5.Primary Energy Savings (PES)

Primary Energy Savings (PES) measures how much primary energy a data centres saves by using integrated systems such as Combined Heat and Power (CHP) or Combined Cooling, Heat and Power (CCHP) compared to conventional separate production of electricity and heat. The metric is expressed as:

$$PES = \left(1 - \frac{PE_{system}}{PE_{ref}}\right) \times 100\% \tag{14}$$

Where, PE_{system} is the primary energy input of the actual system (e.g., Combined Heat and Power system), $PE_{ref} = \frac{E_{el}}{\eta_{el,ref}} + \frac{Q_{th}}{\eta_{th,ref}}$ is the primary energy consumption of the reference (baseline) system with separate production, E_{el} is net electricity output of the system (kWh), Q_{th} is the useful thermal energy delivered (kWh), $\eta_{el,ref}$ is the reference efficiency for electricity generation (e.g., 0.4 for grid based supply) and $\eta_{th,ref}$ is the reference efficiency for thermal generation (e.g., 0.9 for gas boilers)

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International studies show that well integrated CCHP systems in data centres can deliver PES between 15% and 25%, while fully optimized facilities may reach 30%–40%.[14,15]

Table 2.6: Primary energy savings performance.

PES Value	Primary Energy Savings Performance
≥ 35%	Ideal – Advanced CHP/CCHP and onsite recovery systems
20 – 34%	Good - Effective integration and moderate reuse systems
10 – 19%	Acceptable - Basic CHP implementations
< 10%	Poor - Minimal primary energy efficiency

2.2.6.Water Usage Effectiveness (WUE)

Water Usage Effectiveness (WUE) evaluates the volume of water a data centres consumes per unit of IT energy usage, offering insight into water sustainability for cooling and humidification systems.[16] It is mathematically defined as:

$$WUE = \frac{V_{water}}{E_{IT}} \tag{15}$$

where V_{water} is the annual volume of water used (in Liters) and E_{IT} is the IT energy consumption (in kWh). According to industry reports, traditional data centres using evaporative or water-cooled systems often present WUE values between 1.5–2.5 L/kWh, whereas state of the art, hybrid-cooled facilities such as those operated by major cloud providers achieve ≤ 0.3 L/kWh, typically through closed loop systems or adiabatic cooling.[16,17]

Lower WUE values indicate superior water efficiency performance. Specifically, WUE ≤ 0.3 L/kWh reflects best in class systems that minimize fresh water dependency, while values above 1.5 L/kWh suggest high water reliance and potential stress on local water resources.[16]

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Table 2.7: Water usage effectiveness performance.

WUE (L/kWh)	Water Usage Effectiveness Performance
≤ 0.30	Ideal – Ultra-efficient hybrid/closed-loop systems
0.31–1.00	Good - Efficient evaporative or indirect system
1.01–1.50	Acceptable - Common conventional setups
> 1.50	Poor - Water intensive cooling approaches

2.2.7.Energy Reuse Factor (ERF)

The Energy Reuse Factor (ERF) measures the share of a data centre's total energy consumption that is exported for productive external use such as district heating, facility heating, or other thermal processes. It is defined mathematically as:

$$ERF = \frac{E_{reuse}}{E_{total}} \tag{16}$$

Where, E_{reuse} is the annual energy amount (e.g., kWh of heat) actually reused outside the data centre boundary, E_{total} is the facility's total annual energy consumption, inclusive of IT, cooling, lighting, and power infrastructure loads.[18]

A practical example: if a data centre consumes 10,000 MWh and reuses 2,000 MWh as district heating, the ERF equals 0.20 (20%). Real world scenarios in Nordic regions report ERF ≈ 0.05–0.15 for free air-cooled sites, while fully integrated heat networks in modular facilities can achieve ERF ≈ 0.20–0.35.[18,19]

Table 2.8: Energy reuse factor performance.

ERF Value	Energy Reuse Factor Performance
≥ 0.30	Ideal – Dedicated heat reuse with district integration
0.10–0.29	Good - Campus level or building energy reuse
0.05–0.09	Acceptable - Limited reuse in cooler climates
< 0.05	Poor - No meaningful energy reuse

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2.2.8.Heat Transfer Efficiency (HTE)

Heat Transfer Efficiency (HTE) quantifies the performance of heat exchangers or thermal transfer loops within a data centre by comparing actual heat transfer to the maximum possible thermal exchange under given temperature gradients. The metric is defined as:

$$HTE = \frac{Q_{actual}}{Q_{max}} = \frac{\dot{m}.\,c_p.\,(T_{out} - T_{in})}{\dot{m}.\,c_p.\,\left(T_{max,in} - T_{min,in}\right)} \quad (17)$$

Where, $\dot{m}$ is fluid mass flow, $c_p$is fluid specific heat (kJ/kg·°C), $T_{out} - T_{in}$ is actual temperature drop across the exchanger and $T_{max,in} - T_{min,in}$ is the maximum theoretical temperature drop given inlet conditions.[20]

Experimental studies of data center heat exchangers such as split natural cooling systems report HTE values between 0.75 and 0.88, with optimal designs featuring micro-heat-pipe arrays achieving around 0.85.[20] Another study focusing on liquid-to-air row-through exchangers found outlet air temperatures closely tracking inlet coolant temperatures, indicative of transfer efficiencies around 0.80–0.90 depending on airflow and coolant flow balances.[21]

Table 2.9: Heat transfer efficiency.

HTE Value	Heat Transfer Efficiency
≥ 0.85	Ideal – Micro heat pipe or advanced cold plate designs
0.75–0.84	Good - Well designed CDU or cold plate system
0.50–0.69	Acceptable - Standard shell type exchangers
< 0.50	Poor - Fouled or undersized units

2.2.9.CDU Heat Exchanger Effectiveness

CDU Heat Exchanger Effectiveness evaluates the thermal performance of the cool distribution unit's (CDU) heat exchanger within a data centre, determining how effectively it transfers heat from the facility's coolant loop to the secondary cooling circuit. It is defined as:

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$$\epsilon_{HX} = \frac{T_{out,secondary} - T_{in,primary}}{T_{in,secondary} - T_{in,primary}} \tag{18}$$

where $T_{out,secondary}$ and $T_{in,secondary}$ are secondary loop outlet and inlet temperatures, and $T_{in,primary}$ is the primary coolant inlet temperature.[22,23] High effectiveness ($\epsilon > 0.7$) indicates efficient heat transfer with minimal temperature differential, while lower values suggest the need for larger heat exchangers or higher flow rates.

Data centre CDUs typically demonstrate heat exchanger effectiveness in the range of 0.65–0.85, with values above 0.80 considered excellent in systems equipped with plate and frame or gasketed plate designs.

Table 2.10: CDU Heat exchanger effectiveness performance.

Value	CDU Heat Exchanger Effectiveness
≥ 0.80	Ideal – High efficiency plate and frame design
0.70–0.79	Good - Typical high performance CDUs
0.60–0.69	Acceptable - Standard shell and tube or plates types
< 0.60	Poor - Inefficient, may require redesign

2.2.10. CDU Capacity Utilization

CDU Capacity Utilization evaluates how much of a coolant distribution unit's rated thermal capacity is actively used within a data centre. It provides insight into equipment sizing, operational efficiency, and redundancy planning. The utilization is calculated as:

$$Utilization = \frac{Q_{actual\ load}}{Q_{CDU\ rated}} x100\% \tag{19}$$

where $Q_{actual\ load}$ is the real time or average heat load serviced by the CDU (in kW), and Q$Q_{CDU\ rated}$ is its nominal design capacity (in kW), as specified by the vendor. *While not* explicitly published as a formula in vendor documents, this expression follows standard thermal utilization principles used in engineering design and is directly implied in manufacturer case examples and sizing guidelines.[24]

Recent examples from vendors like CoolIT and LiquidStack indicate that maintaining CDU operation between 60% and 80% utilization balances thermal efficiency with operational

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headroom.[24,25] Undersized or underutilized systems (< 40%) result in inefficient capital deployment, while overutilization (> 80%) can stress thermal margins during peak loads.

Table 2.11: CDU capacity utilization performance.

Utilization %	CDU Capacity Utilization Performance
≥ 0.80	Overutilization can stress thermal margins during peak loads.
0.60–0.79	Good - Well balanced capacity and efficiency
0.40–0.59	Acceptable - Some overcapacity, manageable
< 0.40	Poor - Over provisioned, inefficient resource use

2.2.11. Coolant Flow Rate Efficiency

An effective coolant flow rate is fundamental for efficient heat removal in liquid-cooled data centre. Optimizing chilled water flow rate is a critical factor in enhancing the thermal performance and energy efficiency of data centre cooling systems. In this context, several thermohydraulic relationships govern system behaviour, particularly with respect to inlet water temperature, pump power, and Power Usage Effectiveness (PUE).[25]

The cooling capacity provided by Computer Room Air Handler (CRAH) units can be expressed as:

$$C = \dot{m} \times c_p \times (T_{return} - T_{supply}) \tag{20}$$

where $\dot{m}$ is the chilled water mass flow rate, c_p is the specific heat of water, and $(T_{return} - T_{supply})$ represents the temperature difference across the coils.[26]

The inlet water temperature to the rack is influenced by both ambient temperature and pump flow rate. As the flow rate from the dry cooler to the buffer heat exchanger Q_{inr} increases, the temperature of water entering the racks also increases due to reduced residence time in the buffer. Conversely, when the flow rate from the buffer heat exchanger to the racks Q_{ins} increases, the inlet temperature tends to decrease owing to improved heat exchange and quicker circulation.

The power consumption of the pumps can be determined based on the pressure drop and the flow rate, given by:

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$$P_{ps} = \frac{\Delta\mathrm{P} \cdot\ Q_{ins}}{\epsilon} \tag{21}$$

where P_{ps} is the power of the pump, $\Delta\mathrm{P}$ is the pressure drop across the rack, Q_{ins} is the flow rate from the buffer heat exchanger to the racks, and ϵ is the pump efficiency. While Eq. (21) is based on a linear relationship between flow, pressure drop, and pump power, in practice, the actual power may deviate from linearity due to variations in pump efficiency with flow rate and system dynamics. Nevertheless, this formulation provides a reliable engineering estimate for typical data center operating conditions, as ΔP and Q remain relatively small and within a narrow range, making the linear approximation practical and acceptable.

As Q_{ins} increases, the pump power consumption increases due to greater circulation demand between racks and the buffer tank. Additionally, the flow rate through the rack varies based on the number of active servers. A higher number of servers leads to more localized heating and a demand for higher coolant throughput, which dynamically increases the power required by the pumps. Therefore, pump sizing and control must be aligned with real time thermal loads in the IT space.

Flow rate has a direct impact on both cooling effectiveness and energy performance. If the flow rate is too low, it can cause cold and hot air to mix within the data centre, reducing the effectiveness of free cooling and elevating rack inlet temperatures. On the other hand, if the flow rate is excessively high, although thermal control may improve, the energy consumed by the pumps increases disproportionately, reducing the overall system efficiency.

Thus, there exists an optimal flow rate region where cooling capacity is maximized while pump energy consumption is minimized. Maintaining operation within this zone ensures thermal stability without excessive energy penalty.

2.2.12. Temperature Differential of Heat Rejection Unit

$$T_{HRU} = T_{out} - T_{in} \tag{22}$$

Where, T_{in} is the inlet temperature of the heat rejection unit and T_{out} is the outlet temperature of the heat rejection unit.

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2.2.13. Heat Rejection Efficiency

In data centres, where nearly all electrical energy consumed by IT equipment is ultimately converted into heat, the ability to effectively reject that heat to the external environment is fundamental to operational efficiency, equipment longevity, and sustainability. This process known as heat rejection encompasses all systems and mechanisms that transfer internal thermal loads to the ambient air or water outside the facility. The effectiveness of this process is captured by the concept of heat rejection efficiency, which defines how well the cooling system dissipates thermal energy with minimal resource input.

At its core, heat rejection efficiency is a thermodynamic ratio that quantifies how much of the absorbed heat within the data centre is successfully removed:

$$\eta_{HR} = \frac{Q_{rejected}}{Q_{absorbed}} \tag{23}$$

Where, $Q_{absorbed}$ is the heat generated by servers and infrastructure, and $Q_{rejected}$ is the portion expelled by cooling systems such as dry coolers, cooling towers, or liquid-to-air heat exchangers. An ideal system would achieve $\eta_{HR} \sim 1$ but real-world conditions such as airflow resistance, poor heat transfer surfaces, or elevated ambient temperatures lower this efficiency.[26]

Table 2.12: Heat rejection efficiency performance.

Range	Heat Rejection Efficiency Performance
$\eta_{HR} \geq 0.9$	Excellent: Nearly all absorbed heat is effectively rejected; highly efficient system.
$0.8 \leq \eta_{HR} < 0.9$	Good: Minor inefficiencies due to ambient conditions or system losses.
$0.6 \leq \eta_{HR} < 0.8$	Moderate: Significant inefficiencies; optimization needed in cooling tower/dry cooler performance.
$\eta_{HR} < 0.6$	Poor: Inefficient heat rejection, likely leading to higher operating costs and thermal risks.

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2.2.14. Electricity Demand for Cooling Needs

Cooling systems in data centres are responsible for a substantial share of electricity use, often ranging between 20% and 50% of total energy consumption, depending on climate, cooling architecture, and IT load. This electricity supports components such as chillers, CRAC/CRAH units, pumps, fans, and control systems that remove heat generated by servers[28].

The total energy required for cooling can be expressed as:

$$E_{cooling} = \int_0^t (P_{chillers} + P_{fans} + P_{pumps} + P_{aux})\, dt \tag{24}$$

where each term represents the instantaneous power draw of core cooling subsystems over time. Although the formulation is expressed in terms of power integrated over time in practice, cumulative energy consumption is often used, since it requires less stringent temporal resolution.

Climate is a dominant factor: in hot or humid regions, mechanical chillers and high fan speeds increase electricity use, while cold climates allow the use of free cooling (economizers), significantly reducing compressor operation.

Cooling electricity demand is also impacted by:

$$V = \frac{P_{IT}}{\rho C_p \Delta T} \tag{25}$$

Where, V is the volumetric flow rate (m^3/s), P_{IT} is the IT power load (W), ρ is the air density, C_p is the specific heat capacity and ΔT is the temperature rise across the servers (°C). A higher ΔT reduces the required flow and thus fan power consumption. Liquid cooling systems, which enhance heat transfer and reduce fan and chiller load by maintaining higher coolant temperatures and allowing energy reuse.

Hot/cold aisle containment and elevated supply temperatures, which improve ΔT and minimize mixing losses[29].

Further optimizations include:

- Dynamic airflow control via variable speed fans
- AI based setpoint management responding to real time thermal loads
- Economizer operation during suitable outdoor conditions

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As workloads scale and rack densities rise, addressing cooling electricity demand is essential for cost control, sustainability, and carbon reduction. Reducing this demand improves PUE, lowers operational expenditure, and helps data centre align with global energy efficiency and climate goals[30].

2.3. Discussion on the PUE and Waste Heat Recovery

A central debate in EU data centre policy revolves around how PUE interacts with Waste Heat Recovery (WHR). PUE has long been the dominant efficiency metric, defined as the ratio between the total energy consumed by the data centre and the energy used directly by IT equipment. It is widely used in contracts, benchmarking, and regulation as a measure of operational efficiency.

However, the Energy Efficiency Directive (EED) and its delegated acts now require data centres to report not only PUE but also Energy Reuse Factor (ERF), average waste heat temperature, and volumes of waste heat reused. The intent is to encourage sector coupling, recognising that waste heat exported to district heating networks displaces fossil-based energy and contributes to decarbonisation.

The conflict arises because some draft ISO/IEC 30134-2 updates propose including the energy consumed for upgrading/exporting heat into the PUE boundary. This creates contradictory interpretations: EU policy promotes waste heat reuse as a sustainability goal. On the other hand, if heat pumps or exchangers used for boosting waste heat are counted within PUE, operators risk artificially worsening their efficiency scores when they invest in WHR.

This tension risks creating a perverse incentive: operators may avoid connecting to district heating networks to protect their PUE targets, even if community emissions would fall through heat reuse.

A balanced approach is needed that takes into account both the EU rules and the concerns of the data centre industry. The EU wants all electricity used to export heat to be included in the PUE calculation, so that nothing is hidden and the numbers are fully transparent. But the industry argues that this makes PUE look worse than it really is, and could discourage companies from investing in waste heat recovery, even though this is good for the environment. The best solution is to keep PUE as the main efficiency measure, but always report it together with the Energy Reuse Factor (ERF) and other waste heat indicators. In this way, PUE continues to show how efficient the data centre is in its own operations, while ERF clearly shows the benefits of reusing heat for the community. This dual reporting gives a fairer picture, avoids wrong incentives, and helps both policy makers and operators to see efficiency and sustainability side by side.

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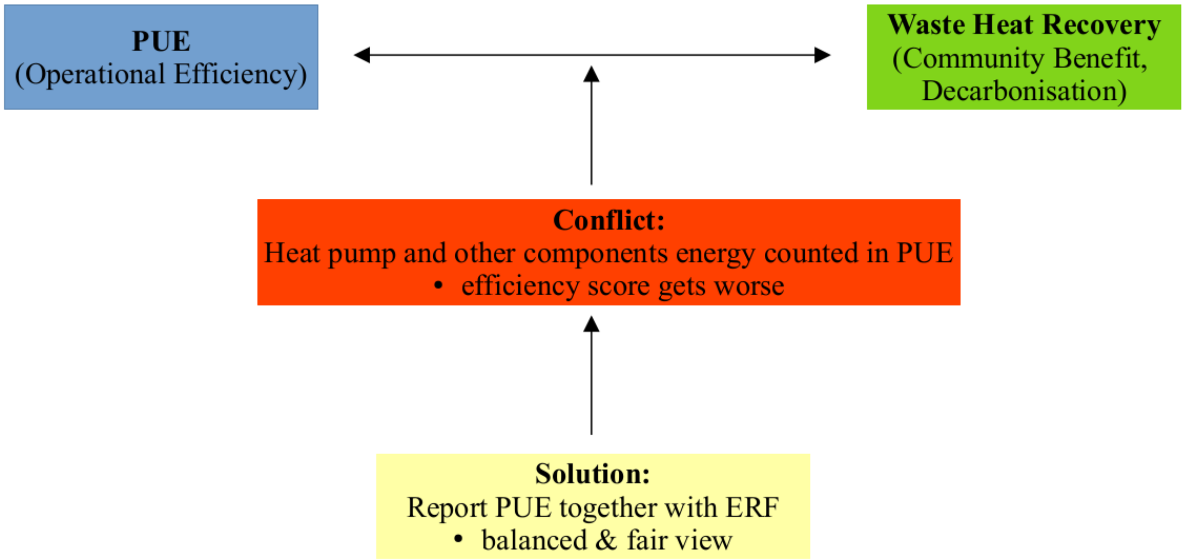


Figure 2.1: Conflict between PUE and waste heat recovery.

2.4. Calculation of the KPIs from CFD Simulations

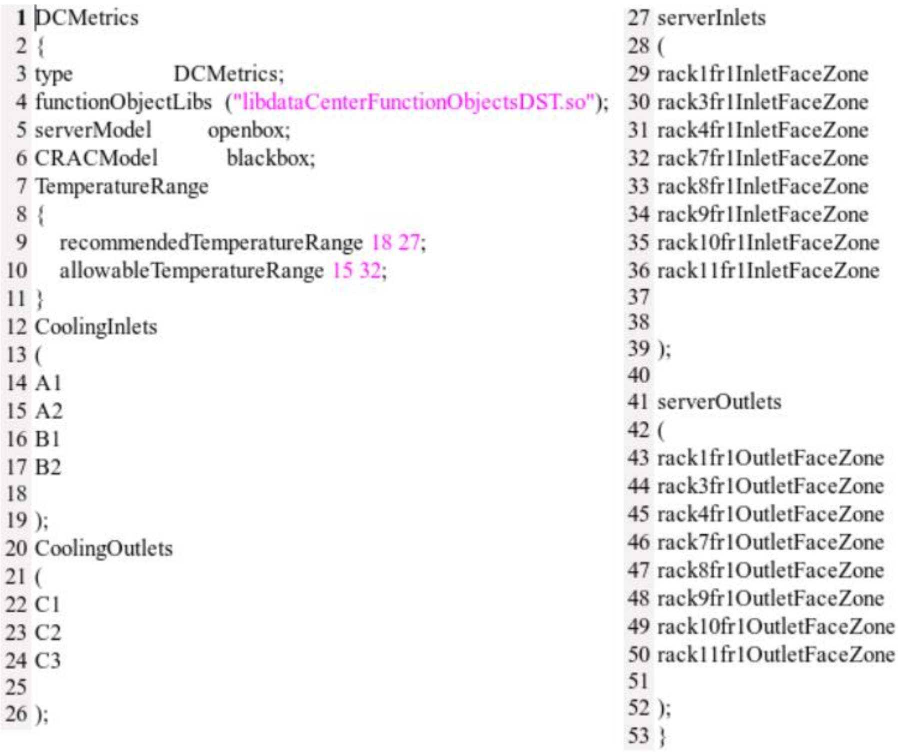
By default, OpenFOAM does not report data centre efficiency metrics in its standard solver output, but its extensible functionObject framework makes on the fly KPI computation straightforward.

Thermal KPIs can be computed within the dataCenterDST © by leveraging the DCMetrics function object. The metrics defined in Section 2.1 based on each server's or cooling unit's inlet and outlet temperatures are evaluated during the solution process. To implement this, you simply define a faceZone for each inlet and outlet surface in DCMetrics; the function object then determines the average temperature in each zone at every time step and automatically calculates the corresponding KPIs for real time presentation to the user.

During each time step, the solver will:

- Read the area averaged mean temperature (and mass flow, if needed) in each faceZone
- Apply KPI formulas
- Write the results automatically to the postProcessing folders.

Because it runs inside the solution loop, there's no separate post processing step, KPIs are computed and output in situ, at the exact time resolution of the CFD simulation. This approach leverages OpenFOAM's open-source architecture to deliver real time performance monitoring with minimal overhead.



```
DCMetrics
{
type             DCMetrics;
functionObjectLibs  ("libdataCenterFunctionObjectsDST.so");
serverModel      openbox;
CRACModel        blackbox;
TemperatureRange
{
    recommendedTemperatureRange 18 27;
    allowableTemperatureRange 15 32;
}
CoolingInlets
(
A1
A2
B1
B2

);
CoolingOutlets
(
C1
C2
C3

);
serverInlets
(
rack1fr1InletFaceZone
rack3fr1InletFaceZone
rack4fr1InletFaceZone
rack7fr1InletFaceZone
rack8fr1InletFaceZone
rack9fr1InletFaceZone
rack10fr1InletFaceZone
rack11fr1InletFaceZone


);

serverOutlets
(
rack1fr1OutletFaceZone
rack3fr1OutletFaceZone
rack4fr1OutletFaceZone
rack7fr1OutletFaceZone
rack8fr1OutletFaceZone
rack9fr1OutletFaceZone
rack10fr1OutletFaceZone
rack11fr1OutletFaceZone

);
}
```

Figure 2.2: DCMetrics function object.

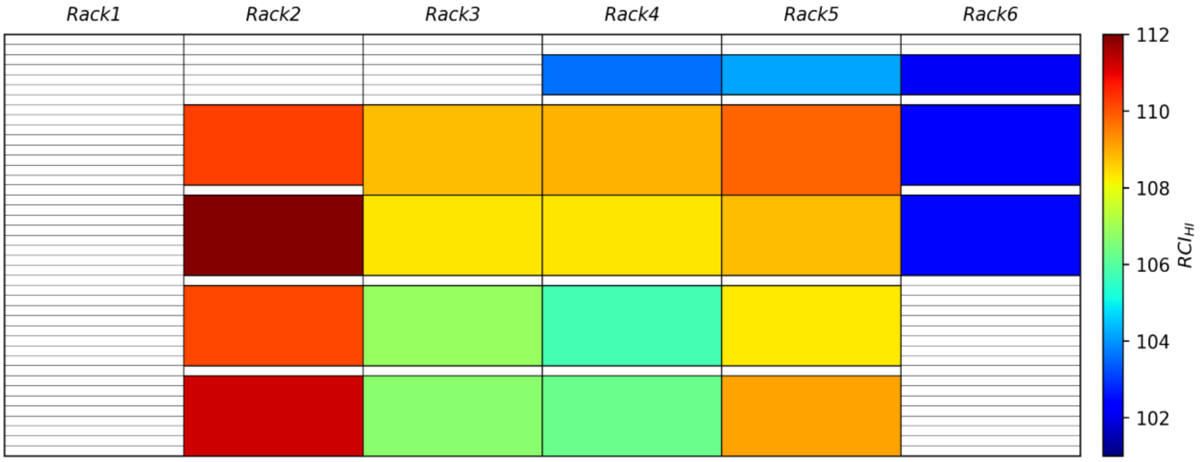


Figure 2.3: RCI_{HI} metric for active servers of AAU Data Centre.

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3. Pilot Data Centres

The HEATWISE pilot data centres cover a diverse set of climates and operational profiles, offering a unique opportunity to evaluate cooling and energy management strategies across different environments. Aalborg University (AAU) in Denmark represents a university data centre with moderate IT loads, where sustainability and efficient thermal management are essential for academic computing. EMPA in Switzerland provides a research focused testbed with advanced monitoring and innovative cooling systems, making it a reference site for energy efficient building integration. The Poznan Supercomputing and Networking Center (PSNC) in Poland adds the high performance computing perspective, where intensive workloads require robust and efficient cooling infrastructures to ensure both performance and reliability. Research Institutes of Sweden (RISE) introduces the industrial dimension, piloting the HEATWISE hybrid cooling concept in a heterogeneous IT environment. This pilot will not only test hybrid liquid–air cooling solutions but also demonstrate the potential of waste heat recovery for industrial integration.

Together, pilot sites form a complementary portfolio spanning academic, research, HPC, and industrial contexts enabling comprehensive evaluation of thermal and EED KPIs and waste heat recovery strategies. This diversity provides that the project's outcomes reflect realistic conditions and provide transferable insights for sustainable data centre operations across Europe.

3.1. Cooling System Characteristics

Air-cooled data centres rely on CRACs and CRAHs to deliver conditioned air to IT inlets and remove exhaust air. Good airflow management is essential: hot/cold aisle layout and full containment reduce bypass air and recirculation, enabling higher supply setpoints and lower fan and compressor energy. The EU Code of Conduct (EU CoC) explicitly lists contained hot or cold aisles as an "expected" practice for new build or retrofit projects.[31,32]

Server inlet environmental envelopes are governed by ASHRAE Thermal Guidelines. The recommended server inlet temperature range is 18–27°C (applicable across classes A1–A4 in the 4th edition reference card), with wider "allowable" ranges by class. Operating within the recommended range is consistent with high reliability while enabling significant economizer hours in many climates.[33,34]

Climate strongly affects achievable efficiency. Locations with lower ambient dry bulb and/or wet bulb temperatures provide more hours of air or water side economization ("free cooling"). The EU CoC highlights siting guidance (cooler/less humid climates,

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facilitation of free cooling) and the use of Typical Meteorological Year (TMY) data to evaluate non-refrigerated operation.[31,35]

Liquid cooling (direct-to-chip cold plates or immersion) moves heat with far higher capacity than air, replacing much of the fan energy with lower-power pumping and allowing warmer coolant temperatures. This supports compressor-free operation (e.g., dry coolers) and enables practical heat reuse. Industrial guidance from the Open Compute Project (OCP) and ASHRAE details component requirements, flow rates, materials compatibility and water quality for safe operation.[36,38]

Warm-water liquid cooling (e.g., “W4” supply temperatures up to ~45 °C in OCP nomenclature) increases the potential for year-round free cooling across a wide range of climates, and high-profile demonstrations (e.g., NREL HPC) show operation without mechanical refrigeration while also enabling campus heat reuse.[36,39,40]

Hybrid configurations combine liquid cooling for high-density racks with air cooling for residual loads. This approach is common during transitions, capturing much of the energy benefit of liquid cooling while leveraging existing air systems. Studies and guidance underline that the primary gain comes from replacing fan power with lower pump power and from raising heat rejection temperatures to unlock free cooling and heat reuse.[37,41]

The pilot data centres included in this study employ different cooling strategies depending on their function, infrastructure, and operational requirements.

The Empa facility primarily relies on air cooling. Cooling is delivered through computer room air conditioning (CRAC) units, which supply cold air to the racks while drawing warm air back for heat rejection. The system follows a conventional room level air distribution strategy. Empa has also integrated advanced monitoring tools to evaluate thermal behaviour and energy efficiency.

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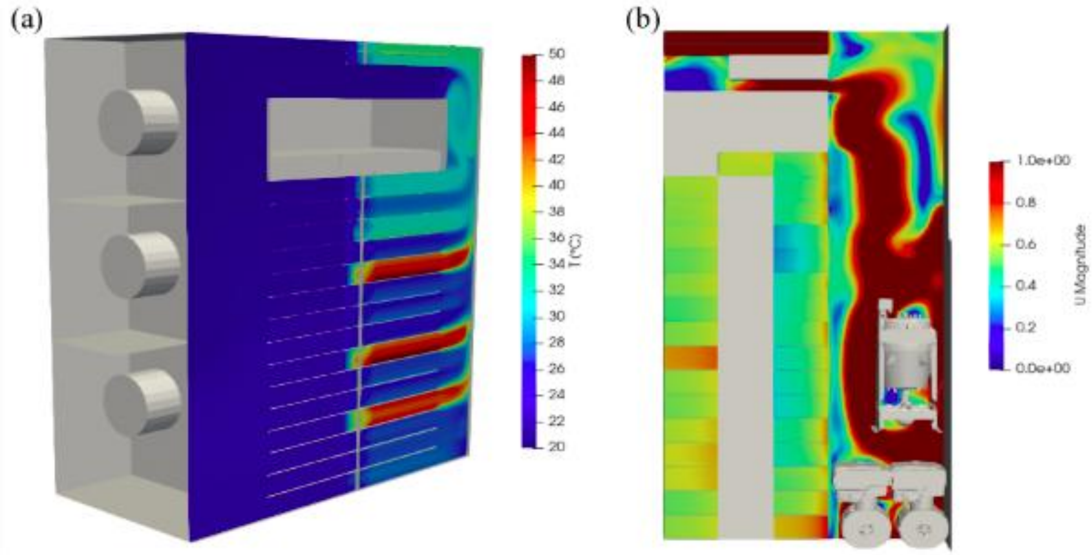

Figure 3.1: Simulated (a) temperature and (b) velocity distributions at EMPA Data Centre

The PSNC high performance computing centre is illustrated in Fig. 3.2. PSNC operates with air cooling supported by two HVAC units and a room ventilation system. The cooling units deliver conditioned air directly into the room to maintain suitable inlet temperatures for the servers. The system is designed for continuous operation under heavy computational loads, characteristic of HPC environments.

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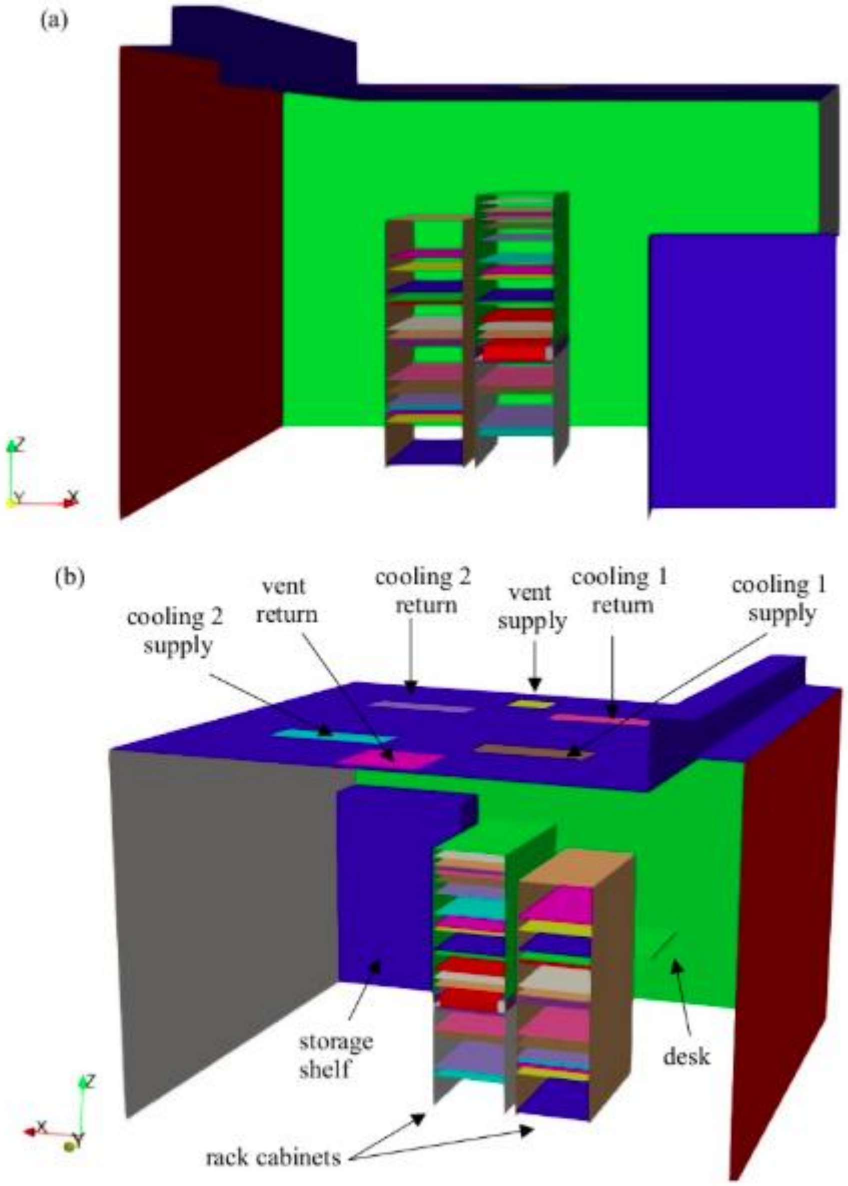

Figure 3.2: Three-dimensional views of the PSNC Data Centre: a) Front and b) back views.

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The Aalborg University data centre uses air cooling via fan coil units. Conditioned air is supplied from fan coils positioned in the room, which regulate temperature and humidity. The configuration is tailored to academic computing needs, where sustainability and moderate IT loads are primary concerns.

Figure 3.3: Images of the experimental studies conducted by AAU team.

RISE hosts the Thermal Testing Devices (TTVs), which will provide the majority of the IT heat load. Since the TTVs only emulate microprocessors, the measurable parameters are limited to their power consumption and temperature.

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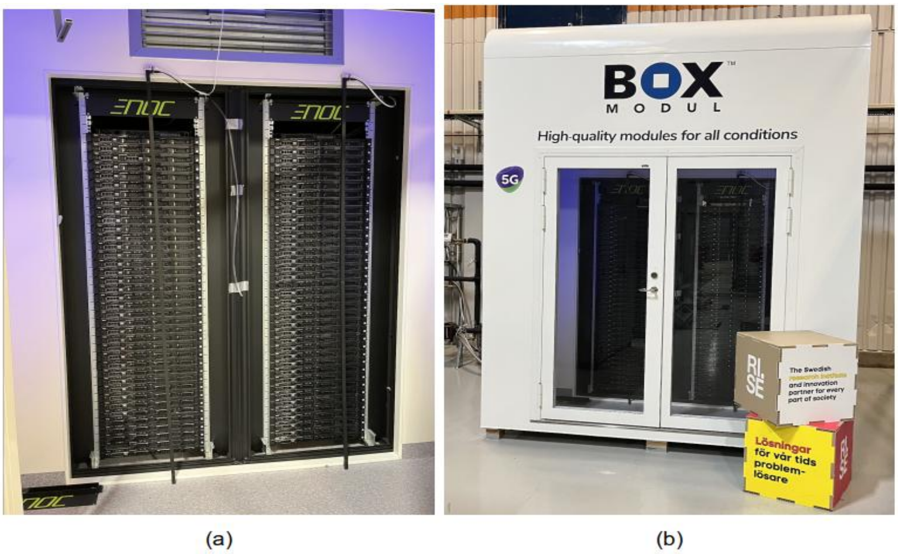
(a)
(b)

Figure 3.4: Three-dimensional views of the RISE Experimental Facility: a) inside and b) outside views.

Table 3.1: Pilot data centre's cooling methods.

Pilot Data Centre	Cooling Method	Key Characteristics
Empa (Switzerland)	Direct-to-chip liquid cooling (hybrid cooling)	Air-cooled and direct-to-chip liquid cooled servers, enhanced monitoring systems
PSNC (Poland)	Air cooling	Two HVAC units and one ventilation system; tailored for HPC workloads.
AAU (Denmark)	Air cooling	Two Fan coil units distributing cold air within the room; academic and research focus.
RISE (Sweden)	Direct-to-chip liquid cooling (hybrid cooling)	Direct-to-chip liquid cooled TTVs

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3.2. KPI Selection Framework for Pilots

The HEATWISE project defines Key Performance Indicators (KPIs) to create a clear and consistent framework for evaluating data centre efficiency from both an operational and regulatory perspective. Instead of focusing only on one metric like Power Usage Effectiveness (PUE), the approach combines thermal indicators (such as RCI, RTI, RHI, LI, RI) with EED-aligned indicators (such as ERF, REF, WUE, CoP). This combined approach makes it possible to track not only airflow quality, cooling efficiency, and thermal performance, but also compliance with the EU Energy Efficiency Directive (EED) and wider sustainability goals. In this way, KPI selection supports fair benchmarking, ensures regulatory compliance, and shows the added value of energy reuse and decarbonisation.

The choice of KPIs is based on four main criteria. Measurability means that the indicators can be calculated directly from sensors, monitoring tools, or simulation results. Data accessibility requires that the necessary information can be collected reliably from existing IT and cooling systems, using common formats and standard logging intervals. Regulatory alignment ensures that the selected KPIs match the indicators required by the EED, such as PUE, ERF, and WUE. Finally, operational relevance means that the KPIs provide practical insights to improve cooling strategies, detect inefficiencies, and guide energy optimisation measures. By following these principles, the project ensures that the KPI framework is both technically sound and practically useful, helping the pilot sites demonstrate efficiency, compliance, and sustainability within a shared EU context.

3.3. KPI Applicability per Pilot

For pilot sites operating with conventional air cooling, the evaluation framework will focus on the calculation of PUE and COP in addition to the standard thermal KPIs, thereby capturing both energy efficiency and cooling performance. In contrast, for pilots deploying direct-to-chip liquid-cooled servers, the assessment will combine thermal KPIs with the set of EED KPIs. This ensures that not only the thermal management of the IT environment is quantified, but also that the reporting aligns with the European Energy Efficiency Directive, providing a complete picture of sustainability and compliance.

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Table 3.2: Operational and Regulatory KPIs in Pilots.

Pilot Data Centre	Cooling Method	Eligible KPIs
Empa (Switzerland)	Direct-to-chip liquid cooling	Thermal and EED KPIs (sections 2.1 and 2.2)
PSNC (Poland)	Air cooling	Thermal KPIs (section 2.1)
AAU (Denmark)	Air cooling	Thermal KPIs (section 2.1)
RISE (Sweden)	Direct-to-chip liquid cooling	EED KPIs (section 2.2)

To enable KPI calculations across the pilot data centre, both IT system data (e.g., server performance, power consumption, utilization and inlet temperature, outlet temperature and CPU temperature) and cooling unit data (e.g., supply temperature, flow rates, and energy use) will be continuously transferred into the centralized Data Management System being developed under WP6. This common platform ensures that all relevant operational parameters are collected, harmonized, and stored in a standardized way, making them directly accessible for further analysis.

Once the data is available, the Self-Assessment Tool will automatically process it to compute the defined KPIs. These indicators will cover thermal performance, energy efficiency, and other parameters aligned with the project's objectives.

Finally, the Self-Assessment Tool will generate a structured report that complies with the requirements of the EED. The report will not only provide KPI results but also organize them in a transparent, auditable format suitable for regulatory submission and benchmarking.

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3.4. Data Integration and Standardization

3.4.1 Common data model and KPIs

To compare pilot sites fairly, all sites should adopt standardized KPI definitions from the ISO/IEC 30134 series (and the equivalent EN 50600-4-x series where applicable). In particular:

- PUE (Power Usage Effectiveness) for infrastructure efficiency, with measurement categories and reporting conventions, as defined by ISO/IEC 30134-2 and The Green Grid's consolidated methodology.[42,43]
- WUE (Water Usage Effectiveness) for water impacts, defined in ISO/IEC 30134-9; report sources of water consistently.[44,45]
- REF (Renewable Energy Factor) and other KPIs referenced by the EU CoC for environmental reporting.[32]

Using these harmonized definitions ensures that calculations, measurement boundaries (including partial PUE where full boundaries are not measurable), and public claims are consistent and auditable.[43]

3.4.2 Time resolution and collection intervals

Minimum and preferred logging intervals are laid out in the EU CoC Best Practices (Monitoring section):

- At entry level, periodic manual readings are allowed (e.g., at peak load), but automated methods are preferred.
- Automated daily readings are recommended for energy and environmental parameters.
- Automated hourly readings provide effective assessment of load dependent performance and are recommended where feasible.[32]

For KPI computations, use energy integrals over a defined time base (e.g., hourly or daily kWh), not just instantaneous power snapshots; this is consistent with The Green Grid methodology, which emphasizes energy based sampling and clear reporting of averaging intervals and boundaries.[43]

When comparing sites across climates or evaluating design options (e.g., economizers), use climate inputs such as TMY weather files for modelling and compliance assessments

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(e.g., ASHRAE 90.4 references TMY3 hourly bins for mechanical energy calculations). Document the selected meteorological dataset and year.[35]

3.4.3 Instrumentation scope and data completeness

At minimum, instrument total facility energy and IT energy (for PUE), plus room level temperature and humidity; increase granularity with distribution board and cabinet metering, and collect CRAC/CRAH supply/return conditions. These points are explicitly required or encouraged for Code of Conduct reporting and performance management.[32]

Handling missing and inconsistent data

- Flag gaps and estimates: If meters fail or boundaries are incomplete, mark imputed periods clearly and apply PUE or other partial boundary metrics rather than silently extrapolating.[43]
- Prefer aggregation over interpolation: For KPI reporting, aggregate energy over available intervals; avoid interpolating long gaps that could bias annualized KPIs. Align with ISO/IEC 30134 reporting conventions and EU CoC reporting guidance.[32,42]
- Context metadata: Store the KPI category (measurement class), boundaries, averaging interval, and any site specific exclusions (e.g., office loads). This information is required for transparent comparison across pilots by ISO/IEC 30134-2 and The Green Grid guidance.[42,43]

3.4.4 Suggested project conventions (for consistency across pilots)

These conventions are not mandated by the standards but help practical integration:

- Use a common timestamp standard (ISO 8601 with timezone offset) and store both local time and UTC for cross-site analysis.
- Adopt hourly logging as the default granularity for energy and environmental data, with optional 1-min data retained at the site level for diagnostics. Clearly document the aggregation method for each logged point (e.g., mean, sum, first, last, or difference). This is particularly important for instantaneous values such as power, where local spikes can otherwise lead to misleading results.
- Maintain a data quality status per point (valid/estimated/missing) and a simple gap register for auditability.

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4. Conclusion

This deliverable has established a harmonised framework for assessing the efficiency of data centres within the HEATWISE project by integrating both Thermal KPIs and EED-aligned indicators into a consistent methodology. The work has shown that combining operational thermal performance metrics with regulatory energy and sustainability KPIs enables a comprehensive evaluation that captures not only cooling effectiveness and airflow management but also compliance with the EU Energy Efficiency Directive and related sustainability targets. By linking KPI derivation directly to CFD simulations through the OpenFOAM functionObject framework, the methodology ensures that performance assessment can be conducted in a transparent, standardised, and automated manner across all pilot sites.

The comparative analysis of pilot sites demonstrates that different cooling strategies such as air-cooled, liquid-cooled and hybrid systems present distinct opportunities and constraints in terms of energy efficiency, thermal performance, and heat-reuse potential. The harmonised KPI selection and data-integration conventions developed here provide a robust basis for consistent evaluation of these pilots, ensuring comparability despite differences in infrastructure, climate conditions, and operational practices. This is particularly important in light of upcoming regulatory revisions, where waste-heat recovery and renewable integration will play an increasingly significant role in determining compliance and long-term sustainability.

The methodology developed in this deliverable is central to the project's validation activities. It lays the foundation for the next phases where real pilot data will be used to refine efficiency strategies, assess the benefits of advanced cooling solutions, further develop the Self-Assessment Tool and test how effectively the framework can be applied across different environments.

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