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Advancing Sustainability in Data Centers: Evaluation of Hybrid Air/Liquid Cooling Schemes for IT payload using Sea Water

Imran Latif, Muhammad Mubashar Ashraf, Umaima Haider, Gemma Reeves, Alexandrina Untaroiu, Fábio Coelho, Denis Browne

***Abstract*—The growth in cloud computing, big data, AI and -performance computing (HPC) necessitate the deployment of additional data centers (DC's) with high energy demands. The unprecedented increase in the Thermal Design Power (TDP) of the computing chips will require innovative cooling techniques. Furthermore, DC's are increasingly limited in their ability to add powerful GPU servers by power capacity constraints. As cooling energy use accounts for up to 40% of DC energy consumption, creative cooling solutions are urgently needed to allow deployment of additional servers, enhance sustainability and increase energy efficiency of DC's. The information in this study is provided from Start Campus' Sines facility supported by Alfa Laval for the heat exchanger and CO_2 emission calculations.The study evaluates the performance and sustainability impact of various data center cooling strategies including an air-only deployment and a subsequent hybrid air/water cooling solution all utilizing sea water as the cooling source. We evaluate scenarios from 3MW to 15+1MW of IT load in 3MW increments which correspond to the size of heat exchangers used in the Start Campus' modular system design. This study also evaluates the CO_2 emissions compared to a conventional chiller system for all the presented scenarios. Results indicate that the effective use of the sea water cooled system combined with liquid cooled systems improve the efficiency of the DC, plays a role in decreasing the CO_2 emissions and supports in achieving sustainability goals.**

***Index Terms*—Cloud Computing, Data center Sustainability, Energy Efficiency, Hybrid Cooling Technologies, Liquid Cooled Technologies**

I. INTRODUCTION

A. Background

ALL cloud computing services, which have become integral to modern digital infrastructure, reside in data centers. These facilities are the backbone of the digital economy, hosting the computing power and data storage essential for cloud services, big data analytics, artificial intelligence (AI), high-performance computing (HPC) and other advanced technologies. However, as the demand for cloud computing continues to surge, the energy consumption of data centers has escalated to levels that pose significant environmental challenges.

According to the International Energy Agency (IEA) [1], global data center energy consumption was estimated at 460 TWh in 2022, with projections suggesting that it could exceed 1,000 TWh by 2026. Moreover, the recent data indicates that data centers are responsible for approximately 1% of global energy-related greenhouse gas (GHG) emissions, and this proportion is expected to rise. Notably, within these facilities, energy consumption is predominantly driven by IT hardware (40%) and cooling systems (40%) [2].

A recent JLL report [3] predicts ”by 2027, average rack density is set to reach 50kW per rack, surpassing the current average of 36kW”. This is only the start of increasing rack densities as artificial intelligence, new designs of GPU, CPU and machine learning needs drive the need for radical change. The pace of change we are seeing in design innovation brings with it a new era of development and a need for a change in cooling approach. Hence, the data center industry is at a turning point in its evolution with demand predicted to increase exponentially and environmental factors becoming critical to efficient design. The challenge is how to design and implement new strategies in line with this increase in both demand and environmental requirements.

Addressing this challenge necessitates the development and implementation of sustainable design strategies that can both accommodate the anticipated exponential growth in data demand and mitigate the environmental impact of data center operations. This requires a paradigm shift in the design, construction, and operation of data centers, with an emphasis on energy efficiency, improving heat dissipation management, and the adoption of innovative cooling technologies.

Data center cooling market is rapidly expanding, with its global value estimated at $10.5 billion in 2022 and projected to reach $19.7 billion by 2027, reflecting a Compound Annual Growth Rate (CAGR) of 13.2% [4]. This growth is driven by the increasing demand for efficient thermal management as data centers expand to meet rising digital service needs. Air cooling is deemed as the mainstay for cooling data centers, however, there are various underutilized free-cooling sources such as sea water, river water, lake water, aquifers and boreholes which could bring a wealth of benefits to the data

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center industry. These cooling sources if correctly maintained are neither depleted or damaged by being used for cooling in these types of systems and since water is much more thermally efficient than air provide operation efficiencies on sites where they may be used. Recent GPU servers, especially those used to run power-hungry tasks like large language models (LLMs), consume far more energy than traditional CPU servers. These GPUs require considerable power to handle the massive computational load of training and inference for AI models, resulting in significant amounts of heat generation due to their high power densities. Thus, emerging technologies like direct-to-chip (DTC) and immersion cooling are gaining traction, potentially reducing energy use by at least 30% compared to traditional methods, thereby playing a critical role in reducing operational costs and environmental impact [5].

To further achieve sustainability in data centers with a focus on cooling efficiency, various standards, regulations, and policies have been developed globally. In Europe, the EU Green Deal [6] and the Corporate Sustainability Reporting Directive (CSRD) [7] are pivotal in setting ambitious targets for reducing energy consumption and carbon emissions in data centers. The EU Green Deal aims to make Europe the first climate-neutral continent by 2050, pushing data centers to adopt more sustainable practices. Meanwhile, the CSRD mandates that large companies, including those operating data centers, disclose their environmental and sustainability impacts, encouraging transparency and accountability. Other initiatives such as the EU's Code of Conduct for Data Centre Energy Efficiency [8] provide guidelines for reducing energy consumption and carbon emissions. In the United States, the Energy Star program for data centers offers certification for facilities that meet energy efficiency benchmarks. Additionally, organizations like the Green Grid and the International Organization for Standardization (ISO) have established metrics and certifications, such as Power Usage Effectiveness (PUE) [9] and ISO 50001 for energy management [10], to encourage the adoption of best practices in energy efficiency and sustainability.

B. Case Study Site - Start Campus

The SINES DC facility, developed by the Start Campus [11] in Sines, Portugal is a 1.2GW data center campus designed to be built incrementally across six buildings by 2030. It is set to be Europe's largest and most sustainable data ecosystem with market-leading global connectivity. SINES DC provides maximum flexibility for its customers with powered shell, turn-key and build-to-suit solutions. The company's advanced offer is AI-ready and addresses the future needs of the industry by integrating liquid cooling technologies into its flexible and scalable design. With a total combined investment value of €8.5bn, the project is set to use 100% renewable energy and targets an industry-leading Power Usage Effectiveness (PUE) of 1.1 by harnessing the cooling power of the sea.

The first building which this paper is based upon, SIN01, is set to deliver an initial 15MW of IT capacity by the end of 2024 and will be expanded to 26MW through the use of liquid cooling technologies and in direct response to customers' demand. Subsequent buildings SIN02 through SIN06, will support up to 240MW of IT capacity each and will be constructed sequentially to achieve 1.2GW of IT capacity by 2030.

Fig. 1. Start Campus Data Center Site.

Fig. 1 shows an aerial shot of the SIN01 facility, highlighting the sea water intake and return.

The selection of IT equipment, including CPU and GPU configurations, is determined by the customers leasing space within the SINES DC. Start Campus maintains a chip-agnostic approach, and can support a diverse range of hardware, including but not limited to NVIDIA, AMD, and Intel chips. The infrastructure is highly flexible, capable of accommodating various IT setups and cooling technologies in response to customer requirements.

SIN01 is designed to operate at up to 15MW of IT load using Computer Room Air Handler (CRAH), Coolant Distribution Unit (CDU) and rear door systems in an air-cooled hall. A rear door heat exchanger solution, optimized for current rack densities of nearly 50kW per rack, has been deployed. For the remaining portions of the building, Start Campus plans to implement a similar cooling strategy to accommodate the projected increase in rack densities.

The next stage of development for this site was the introduction of a Liquid Cooled Lab ("LCL") currently sized to be able at full deployment, to provide 1MW of IT load, allowing for the test of new cooling technologies such as DTC and Immersion. In this subsequent deployments, they intends to densify its existing footprint, to support high-performance racks exceeding 100kW per rack. These racks will likely be cooled using direct-to-chip (DTC) technology, ensuring efficient thermal management even at elevated power densities.

This paper will investigate the opportunities provided by the possibility of operating at higher temperatures in liquid cooled systems through the use of sea water being used not just once in the air-cooled halls but again in the LCL providing the cooling for two very different systems from one water source whilst still maintaining the Water Usage Effectiveness (WUE) of 0.

Liquid cooling deployments are still being developed in the market but with a surge towards embracing these new technologies owners are often faced with challenges of a re-

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quirement for hybrid designs and maintaining plant efficiency. Within this paper we will investigate Start Campus' already efficient free cooling system and introduce an approach to take the system a step further in its sustainability journey. We will also show how the reuse of one water source for both applications is possible and the environmental benefits compared to installing a traditional chiller-based system. The benefits for the cooling do not stop there, they may even lead to great benefits in terms of tangible heat for recovery into other onwards systems.

A key factor in the design process is the temperature at which any liquid cooled (immersion or direct-to-chip [DTC]) space is permitted to run. There is currently much research going into the optimum temperatures at which to run servers in these systems and as this research continues there will be much clearer guidelines on what is and isn't possible for daily operation and therefore also what quality of heat may be recovered. Any recovered energy no matter the grade is a benefit as this energy was not needed to be produced.

C. Summary and Paper Layout

Cloud computing, which relies on data centers equipped with extensive IT hardware—including servers, storage, and networking equipment—to handle the immense volume of IT workloads and store zettabytes of data, faces significant challenges in managing the heat generated by these operations. Typically, the majority of energy consumption in data centers is driven by servers, followed by storage and then networking equipment. Efficient cooling mechanisms are not just critical but essential for maintaining the smooth operation of digital services; without proper cooling, IT hardware performance can degrade, leading to potential service interruptions and reduced reliability. As the demand for cloud-based and other digital services grows, implementing advanced cooling solutions becomes imperative to manage energy consumption, ensure operational stability, and sustain the long-term viability of data centers, making cloud computing a more robust and responsible option for the future.

This study explores and evaluates novel design strategies that align with the growing demand and the imperative for environmental sustainability in the data center industry by examining current practices, technological advancements (such as Liquid Cooling), and future trends (such as AI-driven and IoT applications). We make the following contributions to the development of an advanced sustainable data center infrastructure cooling consumption challenges: (i) We provide a real-world case study of a sustainable data center with advanced cooling strategy. This case study is the first large-scale data center using fully non-potable water (sea water in particular) for cooling. (ii) We propose a novel dual reuse of one cooling medium, in particular, recovering the fluid from air-based cooling and re-using it for liquid cooling within the same colocation data center facility. (iii) Our sea water flow optimization allows data center operators to efficiently expand the computing power within the existing facility with reduced capital and operational expenses.

The paper is organized as follows. Section II reviews existing literature on data center heat reuse and innovative cooling from both academic and industry perspectives, followed by our contribution to the existing body of knowledge. Section III provides an overview of the benchmarking methodology and the technical analysis model employed. Section IV describes the deployed and proposed case study deployment, followed by a discussion of the results in Section V, which demonstrates the potential impacts of this work. Finally, conclusions and future research directions are presented in Section VI.

II. LITERATURE REVIEW

The efficient utilization of data center rejected heat has become a growing area of research, as data centers consume significant amounts of energy and generate substantial heat that is often just rejected with no consideration for onward use. In this section, we will thoroughly review the existing literature on data center heat reuse and innovative cooling approaches from both academic research (Section A) and industry (Section B) spheres. This will be followed by our contribution to the existing knowledge, with the aim of achieving optimal sustainability in data centers.

A. Data Center Heat Reuse and Innovative Cooling – Scientific Research Perspectives

The rapid expansion of data centers, driven by the increasing demand for digital services, has led to significant energy consumption and associated environmental impacts. As the number of data centers is increasing, so does the heat they generate, which is often viewed as a byproduct requiring disposal. However, the advent of advanced cooling technologies and the pressing need for sustainable practices have raised the interest in repurposing this waste heat as a valuable resource. The current state of research and industry innovation presents a multifaceted approach to addressing the dual challenges of energy efficiency and environmental sustainability in data center operations.

Academic research has extensively explored hybrid cooling systems (HCS) that integrate conventional cooling methods with advanced technologies such as spray cooling and absorption chillers. These systems have demonstrated considerable potential in reducing energy consumption, enhancing exergy efficiency, and delivering cost savings [12]. Furthermore, heat recovery systems, including the use of heat pumps and organic Rankine cycles (ORC), have shown promise in capturing and repurposing waste heat, thereby significantly lowering CO_2 emissions [13]. Liquid cooling and immersion cooling techniques, particularly those utilizing hot water, have emerged as effective methods for improving waste heat recovery, with studies reporting up to 80% efficiency in heat recovery [14]. However, no studies have specifically investigated the use of fully non-potable water—such as seawater—for cooling a large-scale (GW) data center while maintaining a Water Usage Effectiveness (WUE) of 0.

Multiple studies have explored the waste heat reutilization of the data centers. Ljungqvist et al. [15] provide a realistic assessment of heat reuse opportunities from direct free air-cooled data centers in the subarctic climate of Luleå, Sweden. The study determines that higher exhaust temperatures (30, 40,

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and 50°C) increase both the ideal heat reuse temperature (13, 17, and 18°C, respectively) and the energy reuse factor (ERF) (0.50, 0.59, and 0.66, respectively). Adjusting heat reuse temperatures to align with monthly averages further improves ERF by 11–31%. Additionally, raising exhaust temperatures enhances cooling efficiency, improving the PUE from 1.045 to 1.012 and stabilizing exhaust flow. The study by IBM [16] explores a cooling system for data centers that reuses high-temperature water (up to 60°C) from liquid cooling devices directly for neighborhood heating. By eliminating chillers, this method significantly reduces electrical power consumption and captures 85% of the heat generated by CPUs and other components. This system can operate year-round in any climate without pre-cooled heat carriers. The analysis indicates that integrating this technology with district heating systems could meet 9.7% of Europe's thermal demand, offering a viable path to zero-emission data centers and substantial cost savings amid rising energy prices. Zimmermann et al. [17] studied the energy and exergy efficiencies of Aquasar, the first hot water supercomputer prototype. The results showed that a heat recovery efficiency of 80% and an exergetic efficiency of 34% were achieved with a water temperature of 60°C. Antal et al. [18] use Computational Fluid Dynamics (CFD) simulations to explore scenarios affecting server room temperatures. They developed a neural network model that processes this simulation data to accurately forecast temperatures, achieving an error rate below 1% (less than 1°C). This approach addresses the computational challenges of real-time predictions effectively.

In addition to these technological advancements, computational modeling has played a crucial role in optimizing data center operations. The use of neural networks and Computational Fluid Dynamics (CFD) simulations has enabled precise predictions of server room temperatures and facilitated the development of optimized cooling strategies, achieving high accuracy and efficiency in real-time applications [18], [19]. Beyond traditional cooling methods, alternative applications of waste heat have been explored, ranging from residential heating and greenhouse warming in sub-arctic regions to low-temperature desalination, demonstrating the versatility of data center waste heat reuse [20].

Despite significant advancements, the dual reuse of a cooling medium—initially utilized for air-cooled IT hardware and subsequently recovered for liquid cooling within the same colocation facility—remains unexamined in current research. This innovative approach offers promising potential for enhancing cooling efficiency and optimizing resource utilization in data centers.

Along with the technical analysis multiple studies have explored the economic benefit aspect of the data center's waste heat reutilization. These studies have shown promising results such as Li et al. [14] have found that the integration of the thermal energy storage into district heating could reduce the peak load by 31% and cut the annual energy cost by 5%. Eduard et al. [21] did a case study on heat recovery from a data center to heat an indoor swimming pool. The stimulation result revealed that the data center operator reduced its operational expenses and generated additional incomes by selling the excess heat, achieving a net present value after 15 years of €330,000. Eduard et al. [22] also did some research on the feasibility and economic analysis of heat recovery systems. Various other studies can be looked at to highlight the economic impact of the utilization of recovered heat from the data centers [23]–[28]. Building on this, optimizing seawater flow through expanded liquid cooling deployments could further enhance data center capacity, enabling colocation facility operators to scale computational resources within existing infrastructure while reducing capital and operational costs. However, this area remains largely unexamined in existing research, highlighting a valuable opportunity for further investigation into its operational impacts (with economic analysis beyond the scope of this paper).

B. Data Center Heat Reuse and Innovative Cooling - Industry Status Quo

According to Open Compute Project (OCP) heat reuse data [29], over 70 data centers worldwide (with an additional 12+ under construction) capture excess heat generated by their operations and repurpose it for industrial or commercial uses, thereby reducing overall energy consumption and carbon emissions. Various hyperscalers and colocation providers have undertaken initiatives to optimize the reuse of heat released by data centers. For instance, Equinix's innovative Heat Export program recovers residual heat from its data centers and repurposes it to heat buildings in surrounding communities, grow fruits and vegetables, and warm the Aquatic Centre for the Paris 2024 Olympics [30]. Similarly, waste heat from a Google data center in Finland will be used to warm homes and businesses, with 97% of the recovered heat being carbon-free [31].

In another example, Digital Realty's Cloud House data center in London employs a river dock cooling system, which is 20 times more energy-efficient than traditional cooling methods, significantly reducing the carbon footprint of their operations [32]. This system adopts a circular approach by returning the same amount of water to the River Thames as is withdrawn. Additionally, in Italy, Aruba, in collaboration with Alfa Laval, utilizes groundwater as the primary cooling energy source, ensuring high efficiency and minimal environmental impact [33].

Several other big tech companies' data centers worldwide have also implemented innovative cooling methods using non-potable water. For example, Google's data center in Belgium uses industrial canal water, treated on-site to remove impurities, for cooling [34]. Further to cool Google's data centers more efficiently, DeepMind and Google conducted live experiments at two real-world facilities in partnership with Trane Technologies, using their reinforcement learning system, which led to energy savings of 9% and 13% at the two sites [35]. Facebook combines direct air cooling with evaporative cooling using non-potable water sourced from a nearby municipal wastewater treatment plant [36]. Apple's data center in Reno uses a mix of direct evaporative cooling and chiller systems, relying on non-potable water from nearby municipal wastewater sources [37].

In light of these developments in sustainability, no industry-level studies have specifically investigated the combined use

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of fully non-potable seawater for cooling, optimized seawater flow for enhanced liquid cooling, and the dual reuse of a cooling medium across both air-cooled and liquid-cooled IT hardware deployment within a single data center facility.

C. Contribution to existing knowledge

The studies discussed in the previous sections, including the comprehensive review in [38] and the detailed analysis of data center compute cooling strategies in [39], highlight a notable gap in the current literature. To the best of our knowledge, no prior research on achieving data center sustainability has addressed the following aspects:

- The use of fully non-potable water (specifically sea water, in our case) for cooling a large-scale data center with an IT capacity of up to 1.2GW.
- Increased computing deployment capacity (MW) due to sea water flow optimization as a result of increased liquid cooling deployments. This will allow the colocation data center owners/operators to efficiently expand the computing footprint within the existing facility with reduced capital and operational expenses.
- The dual reuse of a cooling medium: first, for air cooled IT hardware and recovering the fluid from this loop and re-using it for liquid cooling of IT hardware within the same colocation data center facility.
- The simultaneous real time implementation of the aforementioned strategies in a colocation data center.

III. METHODOLOGY

This section highlights the methodology used to analyze the heat transfer within the hybrid air/liquid cooling distribution at varying IT load deployments and the data center energy savings focused on sustainable practices. The cooling system in this study is designed to operate efficiently across all seasonal conditions. Modelling was performed to ensure that operational loads meet the required IT hardware temperature set points under both summer and winter temperature extremes. The maximum modelled seawater flow rate accommodates seasonal load variations without compromising the system's overall efficiency. The analysis is carried out in three steps, i) The plate heat exchangers (which are a key component in the free-cooling system) analysis is carried out using Alfa Laval's heat exchanger software, ii) The obtained results from the power consumption are then compiled to obtain the Data Center Key Performance Indicators (KPI's) mainly Power Usage Effectiveness (PUE), iii) Lastly the carbon emissions are calculated for the hybrid air/liquid cooling systems and compared with a more traditional chiller system.

This section introduces the calculation tools used from Alfa Laval's [40] software suite. Alfa Laval is the global leader in heat transfer technology and is renowned for providing bespoke energy efficient engineering solutions. The heat transfer, carbon emission and energy savings calculations are carried out through Alfa Laval's proprietary software suite. ALICE (Alfa Laval's Intelligent Configurator Engine) which complies with Air Conditioning, Heating, and Refrigeration Institute (AHRI) certifications standards and is utilized for the heat exchanger calculations and the EHP (Energy Hunter Program), which is used to calculate potential energy savings compared to other technologies by using efficient plate heat exchangers. This tool specializes in providing calculations for potential energy savings, monetary benefits, and reduction in carbon emissions and water consumption. The layout of the software is shown in the Fig. 2 for reference.

The bar graph shown in Fig. 3 is the average sea water temperature measured over the last seven-year period in the Sines, Portugal area. The two temperature values 15°C and 20.9°C utilized in this analysis relate to the values shown in this graph [41].

The methodology is explained through the block diagram shown in the Fig. 4.

Now we introduce the governing equations used for the analysis. Equations 1 and 2 shows the energy balance where T represents the temperature, and the subscripts h and c signify the hot and cold side accordingly. Throughout the calculations Celsius unit is used to represent the temperatures. The U is the overall heat transfer coefficient, m is the mass flow rate and c_p is the heat capacity at the constant pressure.

$$\frac{dT_h}{dx} = -\frac{UA(T_h - T_c)}{\dot{m}_h c_{p_h}} \tag{1}$$

$$\frac{dT_c}{dx} = \frac{UA(T_h - T_c)}{\dot{m}_c c_{p_c}} \tag{2}$$

The heat transfer rate is shown in Equation 3. ΔT_{LM} shown in Equation 4 is the logarithmic mean temperature difference.

$$Q = A \cdot U \cdot \Delta T_{LM} \tag{3}$$

$$\Delta T_{LM} = \frac{\Delta T_A - \Delta T_B}{\ln\left(\frac{\Delta T_A}{\Delta T_B}\right)} = \frac{(T_{h,\text{in}} - T_{c,\text{out}}) - (T_{h,\text{out}} - T_{c,\text{in}})}{\ln\left(\frac{T_{h,\text{in}} - T_{c,\text{out}}}{T_{h,\text{out}} - T_{c,\text{in}}}\right)} \tag{4}$$

The general forms of the Continuity and Momentum momentum equation (Navier stokes) for the incompressible fluids are shown in Equations 5 and 6, respectively, where $\vec{v}$ represents the velocity vector, ρ is the density, p is pressure and $\underset{\rightarrow}{F}$ represents the forces in the system.

$$\nabla \cdot \vec{v} = 0 \tag{5}$$

$$\rho\left(\frac{\partial \vec{v}}{\partial t} + \vec{v} \cdot \nabla \vec{v}\right) = -\nabla p + \mu \nabla^2 \vec{v} + \underset{\rightarrow}{F} \tag{6}$$

The above Equations 1 - 6 have been used in tabulation of the results using Alfa Laval's ALICE software.

The data center KPI's Power Usage Effectiveness (PUE) per ISO/IEC 30134-2:2018 standard [9], is shown in Equation 7, where E_T is the total energy, E_{IT} is the IT energy, E_{mis} is the miscellaneous energy which includes all the miscellaneous resources. except the IT. PUE represents the efficiency of the data center center and a lower PUE indicates the higher efficiency of the data center.

$$\text{PUE} = \frac{E_T}{E_{IT}} = \frac{E_{\text{mis}} + E_{IT}}{E_{IT}},\ [1 \leq \text{PUE} \leq \infty] \tag{7}$$

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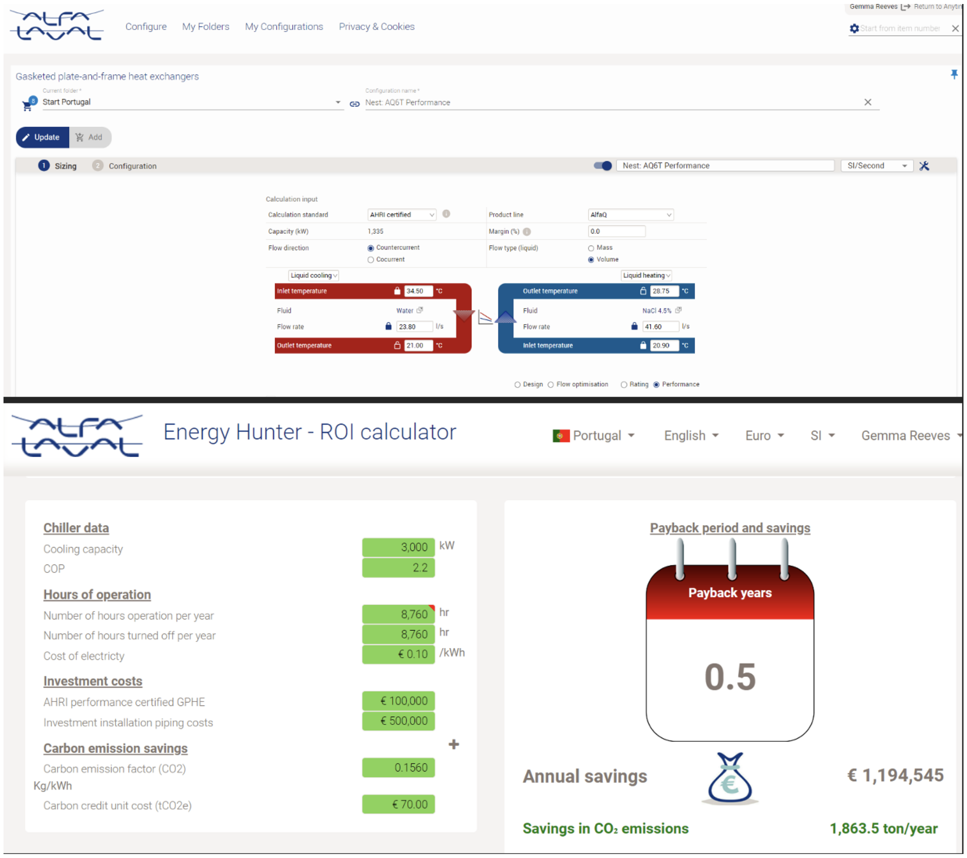

Gasketed plate-and-frame heat exchangers

Current folder*: Start Portugal
Configuration name*: Nest: AQ6T Performance

Nest: AQ6T Performance

Calculation input

Calculation standard	AHRI certified	Product line	AlfaQ
Capacity (kW)	1,335	Margin (%)	0.0
Flow direction	● Countercurrent ○ Cocurrent	Flow type (liquid)	○ Mass ● Volume

Liquid cooling

Inlet temperature	34.50	°C
Fluid	Water	
Flow rate	23.80	l/s
Outlet temperature	21.00	°C

Liquid heating

Outlet temperature	28.75	°C
Fluid	NaCl 4.5%	
Flow rate	41.60	l/s
Inlet temperature	20.90	°C

○ Design ○ Flow optimisation ○ Rating ● Performance

Chiller data		
Cooling capacity	3,000	kW
COP	2.2	
Hours of operation		
Number of hours operation per year	8,760	hr
Number of hours turned off per year	8,760	hr
Cost of electricty	€ 0.10	/kWh
Investment costs		
AHRI performance certified GPHE	€ 100,000	
Investment installation piping costs	€ 500,000	
Carbon emission savings		
Carbon emission factor (CO2) Kg/kWh	0.1560	
Carbon credit unit cost (tCO2e)	€ 70.00	

Payback period and savings

Payback years

0.5

Annual savings	€ 1,194,545
Savings in CO₂ emissions	1,863.5 ton/year

Fig. 2. Alfa Laval's Software Suite Dashboard [40].

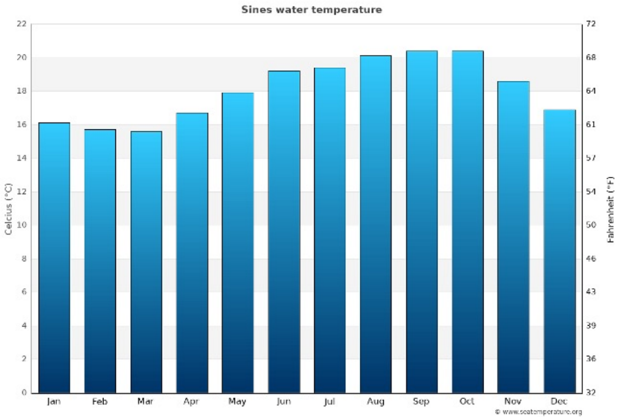

Fig. 3. Ocean Surface Water Temperature Histogram [41].

A. Technical Analysis Model

Fig. 5 represents a system where inputs undergo specific processes that transform them into outputs. This reflects a systematic approach to operations, where raw data or materials are processed through defined steps or algorithms, resulting in a final product or solution. In this case the output parameters are shown in the last section of the block diagram. The technical analysis for the KPI's evaluation is shown in Fig. 5.

The assumptions made in order to provide a constant baseline in the calculations are as follows:

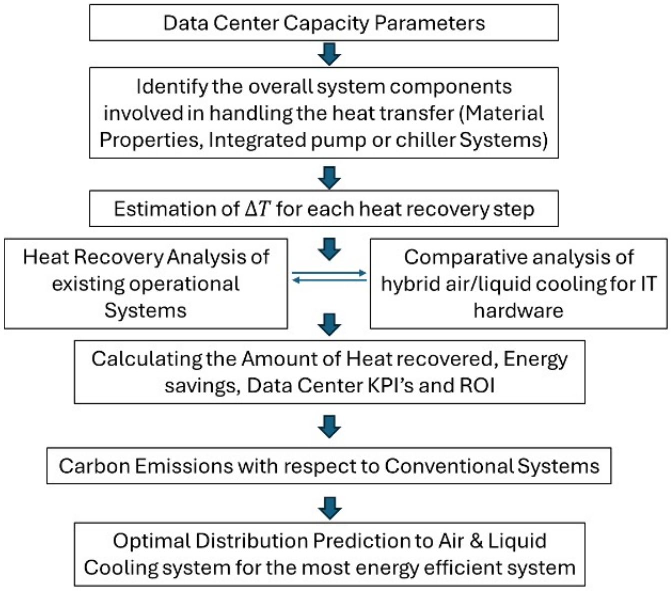

Fig. 4. Research Methodology.

- **Stable Energy Prices:** Energy prices were provided by the site and were assumed to remain stable over the analysis period, allowing for consistent calculations.
- **Consistent Operational Conditions:** Data center operational conditions (load, temperature and environmental

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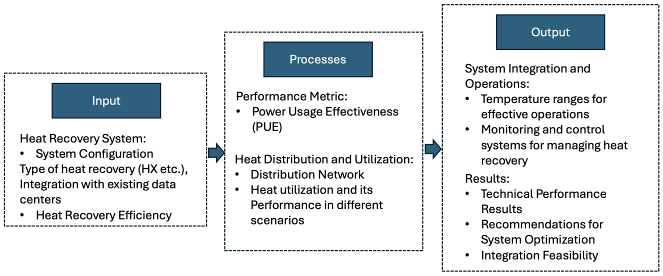

Fig. 5. Technical Analysis Model.

conditions) based on site data were assumed to remain consistent, providing a stable basis for technical analysis.

- **Water Availability and Regulatory issues:** The sea water extraction scenario that has been outlined would be governed by an abstraction licence with the local regulator (the Environment Agency in this case) which sets limits on the volume, flow, quality, temperature.

The limitations identified during the analysis are reported as follows:

- **Primary Data Limitations:** The accuracy of primary data may be limited by the availability and willingness of industry participants to share detailed information.
- **Secondary Data Limitations:** Secondary data sources may contain outdated or region-specific information that may not be universally applicable.
- **Modeling Limitations:** The analytical models may not capture all real-world complexities and variations in data center operations and heat reuse systems.
- **Market Fluctuations:** Economic analysis may be affected by unpredictable market fluctuations, regulatory changes, and technological disruptions.
- **Simulation Limitations:** Technical analysis using simulations may not fully represent the performance of heat reuse systems under all possible scenarios.

IV. DEPLOYED AND PROPOSED CASE STUDY DEPLOYMENT RESULTS

In this research study six case studies were analyzed. Among the six case studies, three have already been deployed (1, 2 and 3) and the other three (4/5A/5B) are theoretical possible future deployment configurations. The case studies are the base to analyze the KPI's, effectiveness and the scalability of the various modular block designs. The study observes the hybrid air/liquid cooling setups along with the potential of sea water for cooling applications. The already deployed system provides very valuable information into the operational efficiency and practical implementation of the designs. The planned case studies show the potential for future mixed deployments/balanced systems (air/liquid) consisting of a 9MW Air system with a 6MW liquid cooling component and a 3MW Air system with a 12MW liquid cooling component. The modeled systems aim to further explore the potential for the enhanced performance and scalability in more complex configurations. The modeled cases are shown in the Table I below.

TABLE I
CASE STUDY SCENARIOS

Data Center Case Studies (Start Campus)	
Deployed	
1	3 MW Air Modular Block Design [HEX A]
2	3 MW Air 400 kW liquid
3	5x3 MW Air 1 MW liquid
Proposed	
4	3x3 MW Air 6 MW liquid
5 A	3 MW Air 12 MW liquid [20.9 °C]
5 B	3 MW Air 12 MW liquid [15 °C]

The cooling flow diagram shown in the Fig. 6, outlines the configuration for hybrid air/liquid cooling IT halls, the system is designed to utilize the sea water for liquid cooling. This diagram serves as a detailed representation of the data center's cooling infrastructure, integrating both air and liquid cooling mechanisms to optimize temperature management. In the diagram, each segment is uniquely labeled to specify the conditions at various points within the system for different case studies.

These labels provide a method to follow the operational parameters and cooling strategies employed at each stage. The state names are given for the flow reference. In Fig. 6 s4 is equal to s4a and s4b but a heat recovery system could be deployed at this point to harness the extra available heat based on the available data from our analysis. Similarly, s9a shows where a similar heat recovery system configuration could be placed.

The incoming temperatures from the sea are set to 15°C and 20.9°C based on the sea seasonal temperature data provided by the site. An example of heat reuse applications is listed in Fig. 6, but these are just a sample of possible applications based on the available temperature ranges which will be further explored in a subsequent paper.

Fig. 6 is a simplified representation of the overall system layout, as well as showing the existing (HEX-A) infrastructure it outlines the possible heat reuse locations (Heat Recovery System A and B). The lines are used to represent the path of the fluid flows in the primary and secondary sides of the system. The sea water is represented by the orange lines and the blue lines are used to indicate the fluid in the air and liquid cooling lab. Each line shows the direction of flow and is labeled with the state which will be referenced through the study. The case study positions that are considered are also shown in the diagram by the purple dashed boxes. An example of this is case 1 which shows the HEX-A deployment with an air cooling system. Cases 2 to 5B use the outlet temperatures from HEX-A as an input for the thermal analysis of HEX-B and the onward liquid cooling lab system. The possible heat recovery positions are also shown in Fig. 6 (Heat Recovery System A and B) along with some possible applications at that location.

Fig. 6 also demonstrates that the temperature obtained from HEX-A would be in the lower range and thus can be deployed to a limited number of applications including greenhouse heating systems at its current level. In order to make best use of the sea water available and to increase

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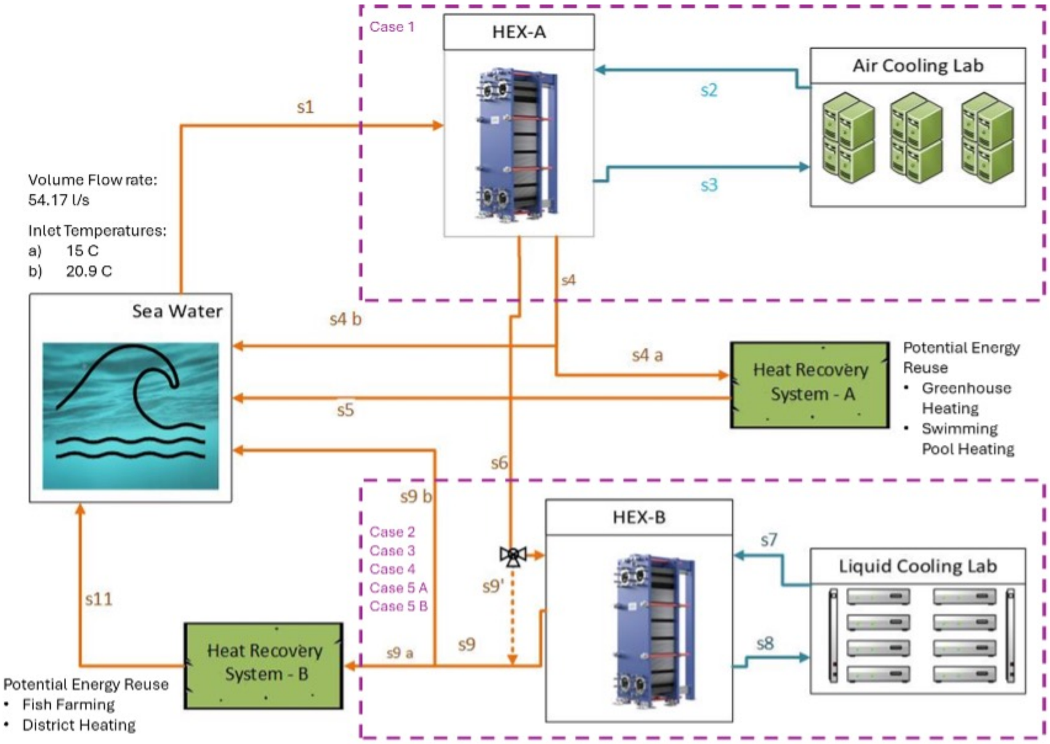

Fig. 6. Cooling Flow Diagram.

the temperature for slightly higher temperature applications, it may then be passed through the liquid cooling systems to absorb more heat and consequently enabling it to be utilized for a broader range of applications which require slightly elevated temperature ranges including fish farming or district heating. Fig. 6. provides an overview of the data related to the heat exchanger performances. It illustrates the volumetric flow rates in the heat exchanger designs analyzed in this study. The color scheme referenced in the legend distinguishes between the hot (data hall) and cold side (sea water) of the heat exchanger, providing a clear visual representation of each section.

Fig. 7 also shows the heat exchanger performance based on the already installed units. The graphs show both deployed and proposed case studies, offering a detailed comparison of their performance metrics. Since the study is intended to put more focus on the liquid cooling systems, the volumetric flow rates for each case heat exchanger performance are displayed only as a reference. These flow values could be adjusted to suit the deployed liquid cooled technologies in the white space as required.

Data center heat management must be considered. Heat is created in the data center white space which must be dispersed and heat energy is very useful in many applications. The heat reuse options, if the heat is recovered, range from normal household use to industrial scale applications depending upon the temperature requirement. The heat generated in data centers is termed as low temperature waste heat but still it can be applied to various applications depending upon the onward temperature needed. Energy reuse from data centers has an opportunity to play a role for both practical energy solutions and environmental sustainability.

This paper assesses the potential of sea water for data center cooling systems and the sea water mass flow rate plays an important role in this type of system. In order to support this the bar graphs in Fig. 7. depicts each operating case and its associated flow rate to enable a better appreciation for the factors being considered. For example the bar graph for the 3MW Air [HEX-A] shows the volume flow rate values considered for that specific case for both sides of the heat exchanger. Additionally in the same graph the change in the volume flow rate required to meet the 3MW load depending upon the incoming sea water temperature of 20.9°C and 15°C is also shown. Since sea water is an integral part of the system this needs to be closely monitored due to constraints on the available sea water flow rate. The importance of this key parameter demonstrated in order to support the data calculated in Fig. 9 of the resultant mixed sea water outlet temperatures.

The low temperature waste heat from data centers can include several applications one of the most straightforward of which is newer generations of district heating (utilizing recovered heat to warm buildings or supply hot water). The recovered heat can also be used for industrial processes that may require low temperature heat, or it could be utilized to preheat systems for higher temperature applications. This can contribute to not only increasing energy efficiency but also a reduction in data center carbon footprint. The preheating applications utilizing the recovered heat of data centers has multiple applications in supplementing heating sources which often rely on fossil fuels. This process not only contributes to

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Fig. 7. Sea Water Volumetric Flow for Deployed and Proposed Case Studies.

energy conservation but also aids in reducing greenhouse gas emissions, thus supporting efforts to mitigate climate change. Overall, the integration of waste heat recovery into data center operations represents a practical and environmentally responsible approach to managing and utilizing energy resources. Table II below highlights the applications of heat reuse based on the available Temperature ranges [42].

The opportunity within this paper looks at an alternative to heat recovery wherein the heat or in this case cool from the sea water system is used to initially cool the air cooled halls and then is reused again to cool the liquid cooled halls which are able to run at slightly elevated temperatures.

This brings a new meaning to heat recovery wherein the recovered energy is further utilized within the data center infrastructure rather than needing to be taken to another application for onward use.

V. RESULTS AND DISCUSSION

The analysis of different case studies described in previous sections is summarized in the Table III. It highlights the Pump power required for the liquid cooling activity and Power Usage Effectiveness (PUE) which is an important key performance indicator (KPI) to estimate the performance of the data center. The underlying table discusses the aforementioned case studies from air cooled systems to the hybrid air/liquid cooling systems. The study focuses on a single water source, in this case sea water, however this approach to cooling does not have to be limited to sea water. The focus of this study is to address the system efficiency that may be achieved from a free cooling source. These free cooling sources could include; Sea water, river water, canal water, aquifer water, lake water, borehole water etc. When considering use of any free cooling source local regulations, permits and resultant dispersal of the outgoing fluid needs to be reviewed when considering site suitability for this type of cooling approach.

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TABLE II
HEAT REUSE TEMPERATURE RANGES [42]

Temperature	Applications
10-20°C	Cooling Applications, Aquaculture, chilled water for air conditioning
10-20°C	Cooling Applications, Aquaculture, chilled water for air conditioning
20-30°C	Radiant Floor Heating, Greenhouse Heating, Cooling for electronics, Fish Farming
30-40°C	Domestic hot water heating, Low Temperature space heating, Spa or hot tub heating, Algae farming, Process heat - snow melting loop
40-50°C	Swimming pool heating, hydronic heating systems
50-60°C	Low Temperature Thermal Desalination, Industrial processes, District heating (Low Temperatures)
60-70°C	Household Applications (Laundry, dish washing etc.), Enhanced Greenhouse Heating, Building Heating
70-80°C	Sterilization and sanitation, Absorption chillers, Process Heating applications
80-90°C	Industrial procedures, District Heating (High temperature Applications)
90-100°C	High temperature absorption chillers
100-110°C	Water Desalination, Steam generation, Industrial uses or even cooking processes

The information displayed shows the impact on energy efficiency and required pump power for each specific case. It should be noted in all scenarios that the amount of water extracted from and returned to the sea remains constant (water neutral).

The 3MW air-cooled modular block design shows the PUE value of 1.23 with no pump power since no liquid cooling is discussed at that point. In contrast it can be observed that case 4, case 5 A and case 5 B has a relatively efficient PUE value of 1.12 with the pump powers of 0.0019MW, 0.0041MW and 0.0034MW respectively. The most effective scenario came from the full deployment design of the 15MW IT cooling load. Taking into consideration the increased power of the liquid cooling which adds more pump power, the fans capacity required for the air cooling is reduced and replaced by the pump power to maintain the effective PUE value of the entire system, Case 3 reflects this efficient value of PUE at 1.11. This PUE value is based on the Start Campus' data center design at the peak IT capacity deployment.

Case 4, case 5A and case 5B show slightly higher PUE values. In these cases although the pump power may have been increased due to the additional liquid cooling load, with the CPU temperature being lowered the fan power at the server level is reduced. Reports from industry state this can be at peak about 20% of the total server power. It can be seen that case 3 also contains 1MW of liquid cooling integration into the system the pump power required to deliver this 1MW is relatively low (0.0019MW) and therefore provides little contribution to the system thus maintaining the same PUE value of 1.11 as of the air-cooled system.

Table III underscores the trade-offs between cooling efficiency and pump energy consumption across different configurations, illustrating that while more advanced cooling methods can enhance energy efficiency, they may also increase pump power requirements.

Fig. 8 illustrates the comparative savings in CO_2 emissions associated with different cooling scenarios compared to a conventional chiller cooled system. Additionally, the values of the maximum available flow to mixed flow temperatures (liters per second, l/s) are shown in the bar graph against two key metrics: total site CO_2 emissions savings and chiller-specific CO_2 savings (assuming a Chiller COP of 2.2- provided by Start Campus). The blue bar in Fig. 8. represents the total site wide CO_2 savings comparing the use of a chiller to the sea water cooled system in the hybrid air/liquid cooling scenarios with varying capacities. The orange bar is representative of the Liquid Cooled Lab (LCL) being deployed as a separate site with a separate cooling demand. In the case of the 3MW No LCL scenario, with a total sea water flow of 54.17 l/s, no additional CO_2 savings are realized (orange bar). This becomes our baseline case with a CO_2 emission saving of 9,556.4 tons per year for the sea-cooled system compared to a traditional chiller based system. In comparison, if we were to consider the introduction of the 400 kW LCL system as may be seen in the 3MW Air + 400kW LCL scenario this maintains the same sea water flow rate and results in an increased CO_2 saving totaling 10,830.6 tons per year. This 10,830.6 tons may be further broken down into if additional chiller capacity needed to be deployed to meet the 400kW LCL demand the additional chiller deployment would result in an increased CO_2 consumption of 1,274.2 tons per year.

The 15MW Air + 1MW LCL scenario, features a significantly higher total sea water flow of 270.85 l/s in line with the required heat rejection and demonstrates substantial CO_2 savings of 50,967.3 tons per year compared to if the system were to be exclusively chiller cooled. This configuration, assuming the LCL as a separate entity, yields a chiller-specific saving of 3,185.5 tons per year. This is further enhanced in the possible expansion of the liquid load to 9MW Air + 6MW case, which, despite maintaining the same total sea water flow rate, achieves identical total CO_2 savings but with remarkable chiller-specific savings of 19,112.7 tons per year, illustrating the increased efficiency of the larger liquid cooling system. This highlights the benefits of this new previously unexplored possibility of having a hybrid system installed using the sea water to first cool the air systems then to subsequently cool the LCL. This revolutionary approach requires no increase in sea water extraction effectively, using the sea water twice. Finally, the 3MW Air + 12MW LCL scenarios, with flow rates of 182 l/s and 162 l/s respectively, both achieve the same total CO_2 savings of 47,781.8 tons per year.

The savings related to a comparison with a chiller are elevated in these cases totalling 28,669.1 tons of CO_2 saved per year demonstrating that the integration of large scale liquid cooling systems is influential on the attainable CO_2 emission reduction through efficient cooling. This forms the basis of the following bar graph, which presents the difference in CO_2 emissions between different cooling configurations whilst

TABLE III
PUE FOR CASE STUDIES

	Case Studies	**PUE**	**Pump Power [MW]**
1	3 MW Air Modular Block Design [HEX A]	1.23	
2	3 MW Air 400 kW liquid	1.23	0.00077
3	5x3 MW Air 1 MW liquid	1.11	0.0019
4	3x3 MW Air 6 MW liquid	1.12	0.0055
5 A	3 MW Air 12 MW liquid [20.9 °C]	1.12	0.0041
5 B	3 MW Air 12 MW liquid [15 °C]	1.12	0.0034

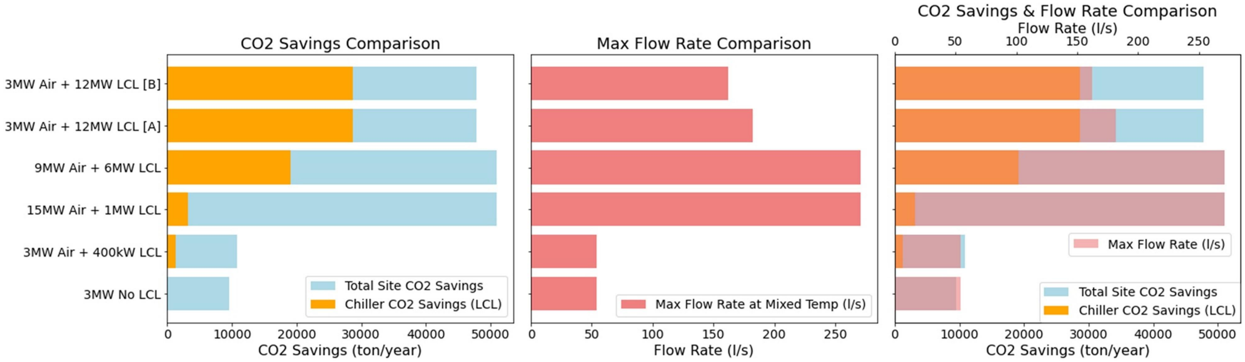

Fig. 8. CO_2 Savings and Max Flow Rate for Deployed and Proposed Case Studies.

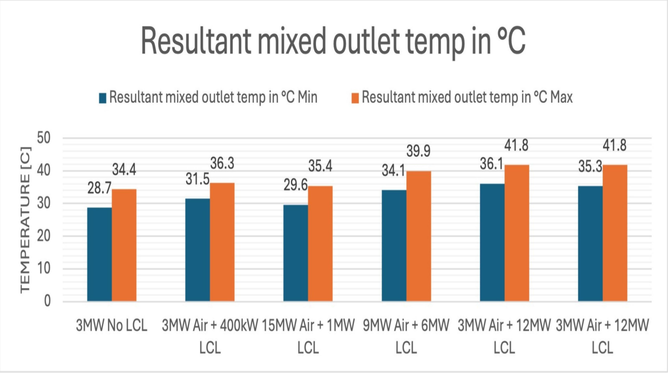

Fig. 9. Resultant Mixed Sea Water Outlet Temperature.

highlighting that higher liquid cooling capacities translate to higher total and chiller-specific CO_2 savings, opening up the possibility of optimizing cooling solutions for even better environmental returns.

The results shown in this study provides critical information for various scenarios of a hybrid air/liquid cooling system in a data center particularly in terms of temperature management, cooling efficiency, and CO_2 emissions reduction. The obtained results indicate the mixed outlet temperature values increasing with the incremental increase of IT loads in the liquid cooling deployments. For instance, the 12MW full occupation scenario shows the temperature value of 41.8°C. The results also suggest that the liquid cooling strategies can effectively control the higher thermal loads consequently contributing to the overall efficiency of the data centers. The higher availability of the flow rates at mixed temperature also implies that liquid cooling is better suited for high-density environments where large thermal loads must be dissipated efficiently. The lower flow rates in some of the full occupation scenarios suggest that the system design including the pump and piping configurations play an important role to maximize the benefits of liquid cooling without compromising the performance of the system.

In terms of the environmental impact, the results show the significant reduction in the CO_2 emissions with the incorporation of liquid cooling into the already efficient free-cooled system. The reduction in the emissions is significant for the cases involving more liquid cooling loads where emission savings exceed more than 50,000 tons annually compared to the traditional chiller-based cooling systems. The obtained results demonstrate the impact of liquid cooling not only for improving the cooling efficiency of the data centers but also to contribute meaningfully to the sustainable energy goals. The results also show a broader impact of the hybrid air/liquid cooling strategies aiming to balance the high performance of the data centers with the sustainable energy goals.

The data reviewed within this study indicates that whilst the water-cooled system demonstrates superior performance, it does require a higher initial investment and slightly more complex infrastructure. If the system is well designed then maintenance of the water-cooled system can be kept to a minimum in line with traditional cooling strategies. However, when looking at these costs the total cost of ownership and environmental impact as well as the initial capital investment should be fully assessed.

The results of this study suggest that data centers should move towards adopting water-cooled systems where possible to optimize heat reuse and improve overall sustainability. The findings also underscore the importance of continuous monitoring and data analysis to maximize the benefits of heat recovery systems for achieving sustainable data center operation.

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VI. CONCLUSION AND FUTURE WORK

The study analyzed the impact of multiple air/liquid configurations in the data center halls. The impact is examined based on the energy efficiency, CO_2 emissions savings, and operational performance. The liquid cooling systems highlighted in this study utilizes the sea water for the cooling of IT hardware. The various scenarios discussed in this study range from air-only data hall cooling systems to various combinations of air and liquid cooling capacities.

It can be observed from the results section that the mixed outlet temperatures varied significantly, and the highest temperature observed in the full occupation case of 12MW liquid cooling. This indicates that liquid cooling, while effective in managing higher loads, requires careful management to maintain optimal temperatures particularly if the system is retrofitted into an existing design. If a fully liquid cooled system is planned to be deployed from design/build stage, then consideration for the type of cooling in the data halls needs to be made to ensure that the required temperatures are maintained through good design. Simultaneously the flow rate which is dependent on the liquid cooling capacities needs to be balanced depending on the cooling load required. Liquid cooled systems also have the capacity to handle higher thermal loads more efficiently contributing to the overall cooling efficiency of the system.

The other aspect of this research study includes the savings in CO_2 emissions across all the discussed case studies compared to using a standard chiller for the entire sea cooled site. The most significant savings were observed in the 15MW Air + 1MW LCL and 9MW Air + 6MW LCL configurations. These full occupation scenarios show the substantial 50,000 tons of CO_2 savings annually. The CO_2 emissions have also shown a direct link to the cooling load capacity such as when isolating the savings in CO_2 emissions linked to the LCL the most significant savings are shown by the scenarios with highest cooling capacity. Notably the 12MW liquid cooling full occupation scenario achieved the CO_2 savings of nearly 29,000 tons annually which indicates the effectiveness of large-scale liquid cooling both in the gray and white space to reduce chiller related emissions.

In conclusion, the study underscores the importance of free liquid cooling systems in optimizing data center performance. While air cooling remains effective for lower loads, the integration of liquid cooling is essential for managing higher loads and achieving substantial CO_2 emissions savings. The results also highlight the need for cooling infrastructure designs that balance temperature management, flow rate, and emissions savings to meet the specific requirements of the data center environment being addressed.

There are several promising future directions for the potential research and key points intended to be discussed in the continued research.

1) Water-cooled systems have a higher potential for heat recovery, leading to greater environmental benefits. Future research will be focused on the possibilities of using the results from this study to investigate options for heat reuse from sea water cooled systems.
2) The current research lays the foundation and it may pave the way for the researchers to dive deep into techno-economic and ecological aspects of sea water cooling deployment.
3) Detailed analysis of the possible on site and off site heat reuse options for both small and large scale applications including district heating, waste to energy, fish farming, agriculture and Low Temperature Thermal Desalination.

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