

The background of the entire page is a photograph of a data center aisle. On the left, a long perspective view of the aisle is shown with blue overhead lights and blurred server racks in the distance. On the right, there is a close-up, vertical view of server racks filled with electronic components, with warm orange and yellow lights emanating from the units.

Data Centre Waste Heat Recovery Carbon Assessment Whitepaper

Cundall Data Centres R&D Workgroup

Executive summary

This report presents a carbon and resource analysis of Waste Heat Recovery (WHR) potential from data centres within the European Union, examining its viability as a decarbonization strategy across different cooling architectures and geographical locations.

As the EU data centre market's energy demand is projected to reach 98.5 TWh by 2030, driven by AI and cloud computing, regulatory frameworks like the recast Energy Efficiency Directive (EED) are mandating WHR implementation. This analysis moves beyond traditional, facility-centric metrics like Power Usage Effectiveness (PUE) and applies a carbon balance methodology, accounting for three factors: the upfront embodied carbon of WHR infrastructure, the change in the data centre's operational carbon and the societal benefits of displaced carbon from offsetting conventional heating. Three data centre archetypes are analysed across three distinct European climates and energy grids: Denmark, Ireland, and Poland.





Air-cooled data centre

The analysis of a 30MW air-cooled facility (baseline PUE 1.127) with direct evaporative cooling reveals that WHR can solve the industry's classic PUE-WUE trade-off.

In this case, waste heat recovery implementation is achieved by installing a WHR coil in the exhaust air path, that introduces additional pressure drop (associated with additional fan power required to overcome this). However, the energy saved by deactivating the evaporative cooling pumps outweighs this, resulting in a net-positive PUE improvement up to 1.117 when assuming waste heat recovery system running all year round.

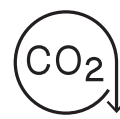
The primary benefit for this data centre architecture is the ~57.1% reduction in annual water consumption (WUE), achieved by switching off the evaporative media. This eliminates the associated "cooling water blowdown" and its chemical pollutants.



Water-cooled data centre (with air-cooled chillers)

The analysis of a 30MW water-cooled facility implementing a 10MW WHR system shows a consistent operational energy improvement, with PUE dropping from a baseline of ~1.24 to ~1.20. However, the value of this saving is proven to be entirely location-dependent.

Due to Poland's carbon-intensive grid (736 kg/MWh), the PUE improvement delivers an annual operational saving of 2,503 tonnes of CO₂. In Denmark, with its clean grid (243 kg/MWh), the exact same engineering improvement saves only 935 tonnes of CO₂. This demonstrates that WHR as an operational efficiency measure has over 2.5 times the carbon impact in high-carbon regions.



Holistic: carbon balance

The upfront embodied carbon investment for the WHR systems (147.5 tCO₂e for water-cooled, 198.5 tCO₂e for air-cooled) is modest. This investment is paid back rapidly by the societal displaced carbon savings, which range from 4,680 tCO₂e/year in Denmark (displacing a cleaner heating mix) to 14,222 tCO₂e/year in Poland (displacing coal-fired heating).

This report concludes that while WHR is a powerful decarbonisation tool, its success hinges on strategic integration. This requires a shift in perspective: viewing data centres not as energy consumers but as valuable thermal utilities. Success is predicated on co-location with reliable heat off-takers like district heating networks, supportive policy, and a design approach that prioritizes a holistic, whole-life carbon assessment over singular metrics.



Facebook, Luleå, Sweden © Lindman Photography

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Abstract

The rapid expansion of the data centre industry in the European Union presents a significant energy challenge, with consumption projected to increase by 28% by 2030.

As the data centre industry's energy consumption grows, driven by the expansion of cloud computing and artificial intelligence, its environmental impact is under increasing regulatory scrutiny within the European Union. Waste heat recovery (WHR) is emerging as a critical strategy to improve energy efficiency and contribute to circular economy principles.

This report investigates the potential of waste heat recovery (WHR) as a key decarbonisation strategy, mandated under the revised EU Energy Efficiency Directive.

This paper investigates the technical feasibility and whole-life carbon impact of implementing a 10MW WHR system within a 30MW data centre.

Two primary cooling architectures - direct air-side evaporative cooling and chilled water cooling - are modelled across three distinct European climates and energy grids: Denmark, Ireland and Poland.



Public Sector Data Centre © Designer Group

The methodology involves a comparative analysis of key performance metrics (PUE, CUE, WUE) under scenarios with no WHR and with WHR operating for 3, 6, and 12 months per year. Moving beyond the traditional metrics mentioned above, this analysis employs also a carbon balance methodology, evaluating the embodied carbon of WHR systems as well as the operational carbon impact on the data centre. The analysis extends beyond the data centre's operational boundary to quantify the embodied carbon of the required WHR infrastructure, and the potential carbon offset from displacing existing residential heating systems.

Results indicate that while WHR yields consistent improvements in data centre PUE, the net carbon benefit is profoundly influenced by the carbon intensity of the local electricity grid and the fuel mix of the displaced heat load. The study concludes that the success of WHR as a decarbonisation tool hinges on a complex interplay of engineering design, local climate, national energy policy, and urban heating infrastructure, highlighting that the greatest environmental value is realised when data centre heat displaces high-carbon fuels in regions with supportive regulatory frameworks and established district energy networks.

Introduction

The digital transformation of the global economy is inextricably linked to the proliferation of data centres. Within the European Union, the growth of this sector has been relentless, creating a significant and rapidly expanding energy demand profile.

In 2018, data centres across the EU consumed an estimated 76.8 TWh of electricity. Projections from the European Commission indicate that this demand is on a trajectory to increase by 28%, reaching 98.5 TWh by 2030, at which point it will account for 3.21% of the Union's total electricity demand.

Other industry forecasts suggest this growth could be even more pronounced, with some analyses projecting that European data centre power consumption could triple from its current level to 150 TWh by the end of the decade.

This escalating energy consumption is not a monolithic trend but is driven by the convergence of several powerful technological forces. The exponential increase in the use of Artificial Intelligence (AI) and machine learning workloads, which require high-density, power-intensive servers equipped with specialised accelerators like GPUs, is a primary catalyst. Concurrently, the expansion of the Internet of Things (IoT), the rise of edge computing architectures, and a general surge in digital products, streaming services, and cloud adoption contribute to this sustained growth.



This expansion places considerable strain on national electricity grids and positions the data centre industry as a critical stakeholder in the EU's broader energy and climate strategy.

A fundamental thermodynamic reality of data centre operation is that virtually all the electrical energy consumed by Information Technology Equipment (ITE) is converted into heat. This waste heat must be continuously and reliably removed by cooling systems to ensure the stable operation of the servers.

Historically viewed as a costly byproduct to be rejected into the atmosphere, this vast quantity of low-grade thermal energy is now being recognised as a valuable resource. The sheer scale of the industry's energy footprint - projected to be equivalent to 295 PJ/yr (approximately 82 TWh/yr) of recoverable heat - transforms this waste stream into a potential cornerstone of urban decarbonisation efforts. The implementation of waste heat recovery systems in data centres is justified both from the perspective of improving the energy efficiency of these facilities and aligning with national and European climate policy priorities.

The imperative for sustainable development in the data centre sector

The European Union has established an ambitious and increasingly stringent regulatory framework aimed at steering the data centre industry towards sustainability and its overarching goal of climate neutrality by 2050. This represents a fundamental shift from voluntary, industry-led initiatives to legally binding requirements, altering the risk and compliance landscape for data centre operators, investors, and developers across the continent.

The European Union's ambitious climate and energy targets, encapsulated in the 'Fit for 55' package, which aims for a 55% reduction in greenhouse gas emissions by 2030, have brought the data centre industry under intense regulatory scrutiny. The sector's significant energy consumption has made it a key focus area for policy intervention, moving sustainability from a voluntary corporate social responsibility initiative to a matter of legal and financial imperative.

Central to this new regulatory environment is the recast Energy Efficiency Directive (EED), Directive (EU) 2023/1791, which entered into force in October 2023. The revised directive establishes the 'energy efficiency first' principle as a legally binding tenet of EU energy policy, mandating its consideration in all major policy and investment decisions. Article 12 of the EED specifically targets the data

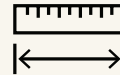
centre sector, introducing a pivotal requirement for all new and substantially refurbished data centres with a total rated energy input exceeding 1 MW. These facilities are now obligated to conduct a comprehensive cost-benefit analysis of utilising their waste heat to supply nearby district heating networks or other heat consumers. Where this is demonstrated to be technically and economically feasible, the implementation of waste heat recovery (WHR) becomes a de facto requirement.

This directive is complemented by the Commission Delegated Regulation (EU) 2024/1364, which establishes the first phase of a common Union-wide rating scheme for data centres. This regulation mandates that operators of data centres with an installed IT energy demand of at least 500 kW must annually report a suite of key performance indicators (KPIs) to a centralised European database.

The required metrics include:



Annual electricity and fuel consumption



Power Usage Effectiveness (PUE)

Developed in 2006 by The Green Grid, this metric defines the ratio of total energy consumed by the data centre to the energy supplied to the IT equipment racks. A PUE greater than 1 is standard, and the closer to 1, the better the energy efficiency*. According to Uptime Institute, the global average PUE dropped from 2.5 in 2007 to 1.55 in 2022. Modern cloud data centres aim for around 1.35 (air-cooled servers), while liquid-cooled servers can achieve PUE values as low as 1.15.



The share of renewable energy used



Water Usage Effectiveness (WUE)

A metric created by The Green Grid in 2011 to measure the amount of water a data centre uses for cooling and other operations. It is calculated by dividing the annual site water usage (in liters) by the IT equipment energy usage (in kWh). A lower WUE indicates greater water efficiency.



Energy Reuse Factor (ERF)

Defined in the European standard EN 50600-4-6 and adopted in legislation such as Germany's Energy Efficiency Act (EnEfG), this metric expresses the proportion of recovered waste heat relative to the total energy consumption of the data centre.



MSFT CPH07 © Microsoft

The amount of waste heat recovered and whether it is exported to third parties.* However, this metric has a known limitation that is relevant when comparing cooling technologies. The denominator (IT load) includes all power supplied to the rack, which comprises not only the electronic components but also “parasitic” loads within the IT equipment, such as built-in cooling fans and internal power distribution losses. In high-powered air-cooled racks, these fans can consume 15-20% of the total rack power, even though they are technically part of the cooling infrastructure. To address this, more granular metrics have been proposed by the Green Grid. ITUE (IT-power usage effectiveness) is a PUE-like metric for the IT equipment itself, measuring the ratio of total IT power (supplied to the rack) to the actual compute power (used by electronic

components). A more comprehensive, holistic metric is TUE (Total-power usage effectiveness), which provides a complete energy picture from the utility to the silicon by combining the two metrics: $TUE = PUE \times ITUE$.

This reporting obligation creates an unprecedented level of transparency, allowing regulators, investors, and the public to benchmark the sustainability performance of facilities across the Union.

This two-pronged regulatory approach fundamentally alters the strategic calculus for data centre operators. The feasibility assessments mandated by the EED force WHR onto the design agenda, while the public reporting of the ERF creates a powerful incentive to implement it. Furthermore, these regulations are being echoed at the

national level. Germany's Act to Enhance Energy Efficiency (Energieeffizienzgesetz, EnEFG), for instance, goes a step further by setting mandatory reuse targets, requiring data centres commissioning from July 2026 to reuse 10% of their waste heat, a figure that rises to 20% from 2028. This legislative framework signals a clear and irreversible policy direction: data centres are no longer viewed merely as energy consumers but are being recast as potential thermal utilities, with an obligation to integrate their operations into the wider energy ecosystem. This integration is also becoming a prerequisite for accessing green finance under frameworks such as the EU Taxonomy, which requires demonstrable sustainability, including efficient heat reuse, for an activity to be classified as environmentally sustainable.

These regulations build upon the foundations laid by voluntary initiatives like the Climate Neutral Data Centre Pact (CNDP). The Pact saw over 100 operators and trade associations commit to ambitious targets, including achieving a PUE of 1.3 in cool climates by 2025 for new builds, practicing water conservation, and procuring 100% carbon-free energy by 2030. While instrumental in fostering industry awareness and collaboration, the self-regulatory nature of the CNDP is now being superseded by the formal, enforceable mandates of the EED and national laws. This evolution from suggestion to requirement means that WHR is no longer merely an operational efficiency measure; it is becoming a critical tool for ensuring regulatory compliance, securing planning approvals, and future-proofing data centre assets against evolving environmental standards.

General overview of data centres

The dynamic digitalisation of the economy and daily life is driving the growth of cloud services, artificial intelligence, and machine learning. The backbone of this transformation is the data centre. Data centres are the foundational infrastructure of the modern information age, physical facilities that house the servers, storage systems, and networking equipment essential for processing, managing, and disseminating the vast quantities of data that underpin the global digital economy.

The market has evolved from simple, privately-owned server rooms to a diverse ecosystem of complex facilities designed to meet specific business and technological needs. This ecosystem can be broadly categorized into several distinct types, depending on business models and data types: enterprise, colocation, hyperscale, edge, modular etc. Regardless of type, the core mission of any data centre is to ensure the uninterrupted operation of its IT equipment.

This requires a specialised and resilient infrastructure built on several key components:



Compute and storage

The heart of the data centre consists of servers, that provide processing power and memory, and storage systems that hold the data.



Power infrastructure

To ensure continuous operation, data centres employ multiple layers of power redundancy. This includes uninterruptible power supplies (UPS) to protect against brief outages and power sags, backup generators for longer disruptions, and Power Distribution Units (PDUs) to manage and distribute electricity to the server racks.



Networking

A complex web of switches, routers, firewalls, and cabling provides the connectivity between servers, storage, and the outside world, forming the data centre's communication backbone.



Cooling infrastructure

A fundamental thermodynamic reality of data centre operation is that virtually all the electrical energy consumed is converted into heat. This heat must be continuously and reliably removed by cooling systems to prevent equipment failure. Maintaining precisely controlled environmental conditions (temperature and humidity) in accordance with ASHRAE guidelines is a critical aspect of infrastructure design and operation. The energy consumed by these cooling systems constitutes a major operational cost, can account for 15% to 50% of total operational expenses.



The reliability of this infrastructure is often classified using a “Tier” system, which categorised the level of redundancy and fault tolerance.

A Tier 1 facility offers basic capacity with little to no redundancy, resulting in up to 28.8 hours of potential annual downtime.

In contrast, a Tier 4 facility is fully fault-tolerant with redundancy for every component, guaranteeing 99.995% availability, which translates to less than 26.3 minutes of downtime per year.

Achieving these high levels of availability requires immense investment in redundant power and cooling paths (e.g., N+1 or 2N redundancy), which in turn drives up energy consumption.

Multi-storey hyper-scale data centre, South-East Asia

Sustainable development of data centres

The data centre industry is actively implementing sustainability strategies, focusing on reducing energy consumption - particularly in cooling systems - and tracking the carbon footprint throughout the entire investment lifecycle. Most large facilities secure 100% of their energy demand from renewable or low-emission sources through long-term Power Purchase Agreements (PPAs), significantly supporting the energy transition.

Due to increasing demand for new investments, colocation data centre operators and technology companies are considering Small Modular Reactors (SMRs) as low-emission and stable power sources. This approach can reduce carbon footprints, improve cost predictability, and enhance energy security.

For many years, Power Usage Effectiveness (PUE) has been the data centre industry's dominant metric for energy efficiency. Defined as the ratio of total facility energy consumption to the energy delivered to the IT equipment, it provides a simple measure of the "overhead" required to power and cool the facility. While PUE has been instrumental in driving improvements in electrical and mechanical system design, its limitations are becoming increasingly apparent in the context of advanced cooling technologies and holistic sustainability strategies like waste heat recovery.



TN2, London, United Kingdom



The core deficiency of PUE is its potential to mask significant overall energy savings, particularly in the transition from air to liquid cooling. As liquid cooling technologies reduce the need for high-power server fans, energy efficiency is gained both within the server (the denominator of the PUE equation) and in the facility's air handling infrastructure (part of the numerator). If the percentage reduction in both is similar, the PUE ratio can remain largely unchanged, despite a substantial drop in the facility's total energy consumption.

A theoretical case study highlighted this discrepancy, showing a 10.2% reduction in total energy use after a partial liquid cooling conversion, while the PUE improved by less than 4%.

This report posits that a similar, and perhaps even more pronounced, inadequacy of PUE exists when evaluating the benefits of waste heat recovery. The implementation of a WHR system often introduces new parasitic loads, such as pumps for the heat recovery loop or increased fan power to overcome the static pressure of a new heat recovery coil. These additional loads can increase the non-IT energy consumption, potentially leading to a neutral or even slightly negative impact on the data centre's PUE.

However, this narrow, facility-centric view completely ignores the primary benefit of WHR: the vast quantity of displaced carbon emissions in the wider community.

When data centre waste heat is used to warm homes and businesses, it directly displaces the need for conventional heating sources, which are often fossil-fuel-based. The societal carbon saving from avoiding the combustion of natural gas in thousands of individual boilers can vastly outweigh the marginal increase in the data centre's own operational carbon footprint. This creates a scenario where a project that is "PUE-neutral" could be profoundly "carbon-negative" from a holistic, societal perspective.

Therefore, this report proposes a holistic carbon balance methodology, which provides a comprehensive accounting of the environmental costs and benefits of implementing WHR. Its key components are described in the Net Zero Carbon Design chapter.

By calculating the balance for different data centre archetypes across diverse European climates and energy grids, this analysis aims to provide a data-driven answer to the question of when and where waste heat recovery is a genuinely effective decarbonisation strategy.

Waste heat recovery from data centres

Waste Heat Recovery (WHR) is the process of capturing the residual heat from one source and repurposing it for beneficial use, such as supplying district heating networks. This approach aligns with the principles of a circular economy, turning an energy liability into a community asset.

The implementation of heat recovery systems in data centres is a rational and justified approach, both from the perspective of modern energy ecosystem efficiency and national climate policy. It also supports decarbonisation initiatives within the district heating sector.

From a thermodynamic perspective, data centres offer excellent conditions for efficient heat recovery. In systems based on Computer Room Air Handling (CRAH) units, the return temperature of the cooling fluid can reach 32°C. With increasing server rack power density and the use of advanced GPU processors, direct liquid cooling is becoming more common, with return fluid temperatures reaching up to 50°C. These parameters make waste heat from data centres a viable low-grade heat source for heat pumps, comparable to geothermal energy sources.

Implementing heat recovery systems not only reduces operational costs through more efficient solutions like

water-based cooling with energy recovery, but also enables secondary use of waste heat in various sectors. This recovered heat can supply urban heating networks, residential buildings, public facilities, industrial processes, and even sustainable agriculture. Innovative concepts are increasingly being deployed, such as using data centre heat to warm greenhouses, support fish farming, and other agricultural applications.

The annual energy demand profile of servers is relatively stable and independent of outdoor temperatures. However, the total electricity demand of a data centre varies with external temperatures due to cooling system



behaviour. In summer, electricity demand peaks due to compressor-based cooling systems, while in winter, demand drops thanks to free-cooling.

Importantly, the energy demand profiles of data centres and district heating networks are complementary. The connection capacity reserve of data centres during winter can be effectively used to power heat pumps or other equipment supplying district heating. Summer operation of WHR equipment can also be achieved under shared power allocation scenarios.

Securing an energy connection is a prerequisite for building a data centre. Reusing the same connection for heat pump systems can significantly optimise

CAPEX compared to alternative waste heat sources that require dedicated energy infrastructure.

However, to ensure uninterrupted operation, critical systems in the data centre must always have priority access to power when shared connections are used.

Locating data centres in large urban areas with existing district heating infrastructure creates additional opportunities for large-scale heat recovery. Deploying such solutions can help reduce carbon emissions and achieve decarbonisation goals. The required technology is widely available, making this approach feasible, efficient, and mutually beneficial.

Despite the clear technical and environmental benefits, investors and operators face significant hurdles in implementing WHR projects. These challenges are often more economic and logistical than technical:



High capital expenditure (CAPEX) and payback periods

The initial investment in heat exchangers, pumps, extensive insulated piping, and potentially a dedicated WHR plantroom is substantial. Without clear revenue streams or strong incentives, the payback period can be long, making the business case difficult to justify based on internal operational savings alone.



Misalignment of load profiles

There is a fundamental seasonal paradox. Community heating demand peaks in winter, which is precisely when modern data centres can use highly efficient “free cooling” methods, minimising their own energy costs. The incentive for the data centre operator to export heat is therefore lowest when the community’s need is highest. Conversely, in summer, when the data centre’s cooling costs are highest, there is minimal demand for external heating.



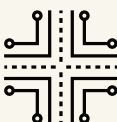
Complexity of contractual and business models

Establishing a fair price for waste heat is complex. The data centre operator seeks to cover infrastructure costs and generate revenue, while the heating network provider needs a price competitive with other heat sources. This requires complex, often bespoke, contractual agreements that must account for variable demand, electricity price volatility (for heat pumps), and long-term risk allocation.



Security and access

Granting a third-party heat network operator physical access to a secure data centre site for connection and maintenance poses a potential conflict with the facility’s primary duty to protect its clients’ IT infrastructure and data.



Lack of external infrastructure

The most significant barrier is often the absence of a nearby district heating network. Many large data centres are built in rural or suburban areas for reasons of Planning Policy, land availability and security, far from the dense urban centres where district heating is most viable. This geographical mismatch makes the cost of connective piping prohibitively expensive.



Uncertainty for heat off-takers

District heating operators require a reliable, consistent heat source to build a business case for their own infrastructure investment. They face uncertainty regarding factors outside their control, such as the data centre’s IT load growth (which may not materialise as planned), server technology refreshes that could reduce heat output, and periodic maintenance shutdowns that interrupt the heat supply.



Technical and regulatory hurdles

Many existing district heating networks are older, high-temperature systems (even up to 120°C in Wien, Austria), whereas data centres provide low-grade heat (30-50°C). While heat pumps can “upgrade” this heat, there can be technical limitations and efficiency losses, especially for very high-temperature networks. Furthermore, navigating licensing requirements for thermal capacities, planning permissions, and varying national regulations adds layers of complexity and delay.

The strategic potential of waste heat recovery

Waste heat recovery from data centres holds significant potential across Europe and could play a key role in transforming the energy sector and reshaping the heat market across the continent. According to a McKinsey report from October 2024, the installed capacity of data centres in Europe is 10 GW, with current energy consumption around 62 TWh/year. By 2030, this is expected to exceed 150 TWh/year. These estimates are confirmed by DC Byte data from Q2 2025, which reports a total capacity of 37.2 GW for data centres in Europe (including operational, under construction, and planned facilities), with 9.7 GW currently in operation.

Much of this expansion is concentrated in the traditional “FLAP D” hubs (Frankfurt, London, Amsterdam, Paris, Dublin), which today hold about 62% of Europe’s data centre capacity. However, as FLAP D faces grid constraints, the fastest growth is now moving to regions with abundant low carbon power and flexible grids (notably the Nordics, Iberia, and parts of Eastern Europe). All this growth requires enormous electricity supply (estimates suggest €250–300 billion in data centre build out by 2030) and presents a huge opportunity for waste heat reuse.

This strategic potential is being realised in various ways across the EU, tailored to local energy landscapes and regulatory environments.

This paper focuses on three different regions:

Poland

Poland is a rising data centre market (Tier 2 EU status) with a booming Warsaw hub (60%+ of the country’s capacity) and growing clusters in Kraków and Poznań. The current operational capacity is estimated at ~200 MW, up from 72 MW in 2014 (PMR data). Market forecasts predict 500 MW by 2030 and ~1.1 GW by 2035, with annual electricity consumption reaching 9.31 TWh (according to PSE’s development plan for 2025–2034). Poland’s legacy energy mix is carbon intensive (heavy coal use and one of Europe’s largest district heating systems), so using waste heat would deliver outsized decarbonisation.

In fact, Poland has the EU’s second-largest district heating network after Germany, often fuelled by lignite and natural gas. This creates a strong motivation to capture data centre heat: each megawatt recovered in Warsaw’s heat network can directly replace coal or gas burning. The government and industry are increasingly recognising this synergy.

The Nordics (Denmark, Sweden, Finland)

These nations are pioneers in integrating data centres into mature district heating systems. In Odense, Denmark, a landmark project with Meta's hyperscale data centre uses large-scale ammonia heat pumps to upgrade low-grade heat (around 27°C) to the 70-75°C required by the local grid, eventually providing carbon-free heat for over 12,000 homes. This project not only displaces coal (the plant supports Fyn's plan for 100% renewable heat by 2030) but also illustrates the scalability of the approach. More Danish sites are pursuing similar setups. The overall effect is that excess data centre heat in Denmark is now considered a mainstream resource: a majority of data centre operators there intend to reuse it, and the success in Odense (and elsewhere in Scandinavia) has sparked other projects and public - private partnerships.

In Stockholm, Sweden, the "Open District Heating" initiative allows multiple data centres to sell their excess heat into one of the world's largest district heating networks, with the goal of heating 10% of the city by 2035. In Finland, a project between Microsoft and Fortum in the Helsinki region is set to become the world's largest, supplying approximately 40% of the district heating for 250,000 people.

Ireland

Ireland is currently the largest national data centre market in Europe, with the share of data centres in total electricity consumption rising from 5% in 2015 to 21% in 2023 (30.6 TWh/year) - making it the highest per-capita data centre load in Europe. As a country with an emerging district heating market, Ireland's Tallaght District Heating Scheme in Dublin is a key pilot project. It uses waste heat from an Strategic potential web services data centre to warm public buildings and soon, residential apartments.

This not-for-profit utility (Heat Works) is unique in Ireland/UK and is essentially treating the data centre as a clean heat source. Ireland's example shows how even in countries without extensive legacy heat networks, data centre heat can retrofit into municipal schemes, especially where high efficiency heat pumps and collaboration (local government, utilities, hyperscalers) are deployed.

Across Europe, from the policy-driven mandates in Germany to the market-integrated models in the Nordics, data centres are increasingly being viewed as strategic energy assets. The potential is vast, but its successful implementation hinges on overcoming local challenges related to infrastructure, business models, and regulatory frameworks.

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Net Zero Carbon Design

Net zero carbon in data centres

A Net Zero Carbon (NZC) building is one that balances its total greenhouse gas emissions to as close to zero as possible. This is achieved through a combination of highly energy-efficient design, the use of on-site or off-site renewable energy sources, and strategies to minimize the carbon associated with the building's materials and construction processes.

The concept extends beyond just operational energy (the energy used to run the building) to include embodied carbon - the emissions generated during the entire lifecycle of the building's materials.

For data centres, achieving Net Zero Carbon requires a paradigm shift away from PUE as the sole arbiter of sustainability. A true NZC approach must adopt a holistic carbon balance methodology, providing a comprehensive accounting of environmental costs and benefits.

This balance weighs three key components:

Embodied Carbon

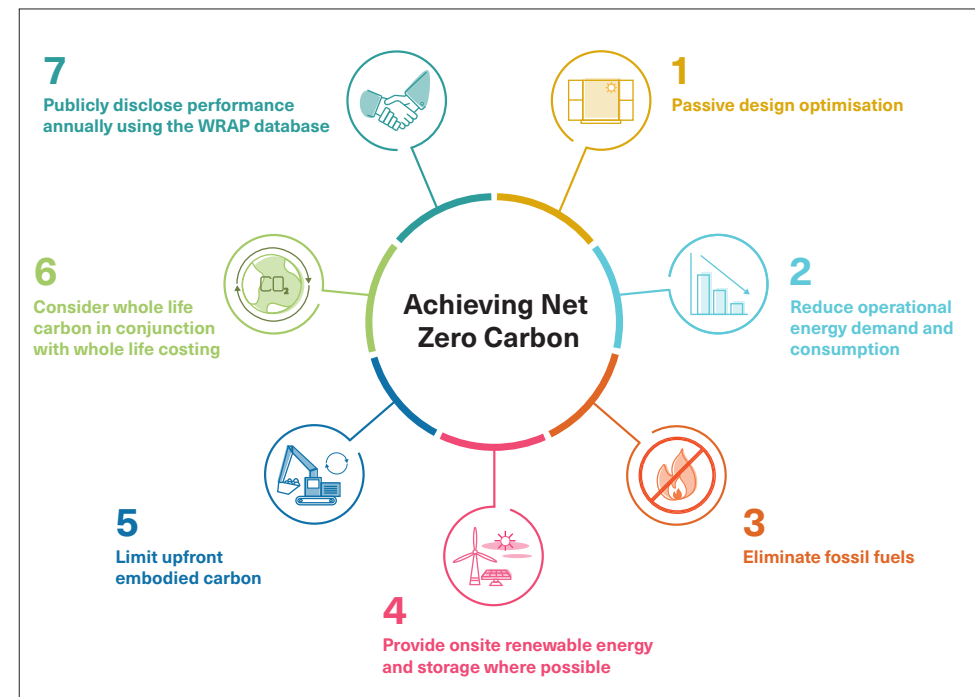
The upfront carbon investment required to manufacture, transport, and install the facility and its systems.

Operational Carbon

The emissions from the energy consumed to power and cool the facility.

Displaced (Offset) Carbon

The societal carbon savings achieved by strategies like WHR, which offset the need for conventional heating in the wider community.

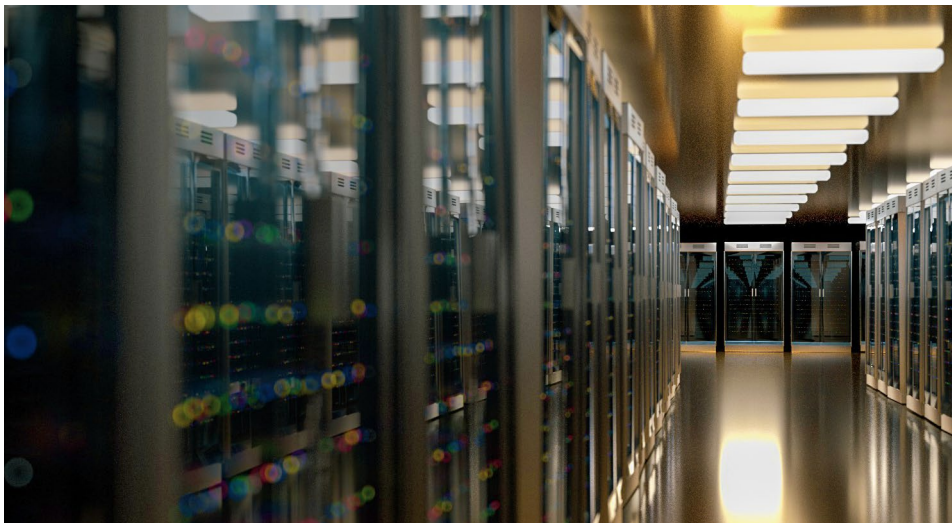


Waste heat recovery in data centres

Integrating waste heat recovery into data centre cooling architecture

The method of integrating waste heat recovery (WHR) into a data centre is fundamentally dictated by the facility's primary cooling architecture. This section outlines the baseline cooling technologies and details the specific mechanical and architectural modifications required to enable heat reuse for two common archetypes: air-cooled and water-cooled data centres.

The chapter focuses on impact of 10MW of waste heat recovery on power usage effectiveness (PUE) in 30MW IT load air-cooled and water-cooled data centre. 3 scenarios have been investigated, which vary in the number of months that WHR is used per year, which were: Scenario 1 - 12 months, Scenario 2 - 6 months, and Scenario 3 - 3 months. 100% IT utilisation is assumed.



Before examining WHR integration, it is essential to establish the baseline systems.



Air-cooled systems

In many contemporary hyperscale data centres, cooling is achieved through direct or indirect air handling systems. A common design involves large air handling units (AHUs) located in the mechanical corridors adjacent to the data halls or a “penthouse” structure that forms a pathway for the air above the data halls. These systems draw in outside air, which is then filtered and, if necessary, cooled through evaporative or adiabatic processes before being supplied to the cold aisles of the data hall. Hot air from the IT equipment is exhausted from the hot aisles and either recirculated or removed from the building. This approach leverages “free cooling” for a significant portion of the year, relying on mechanical cooling (such as DX or chilled water) only during peak ambient temperatures.

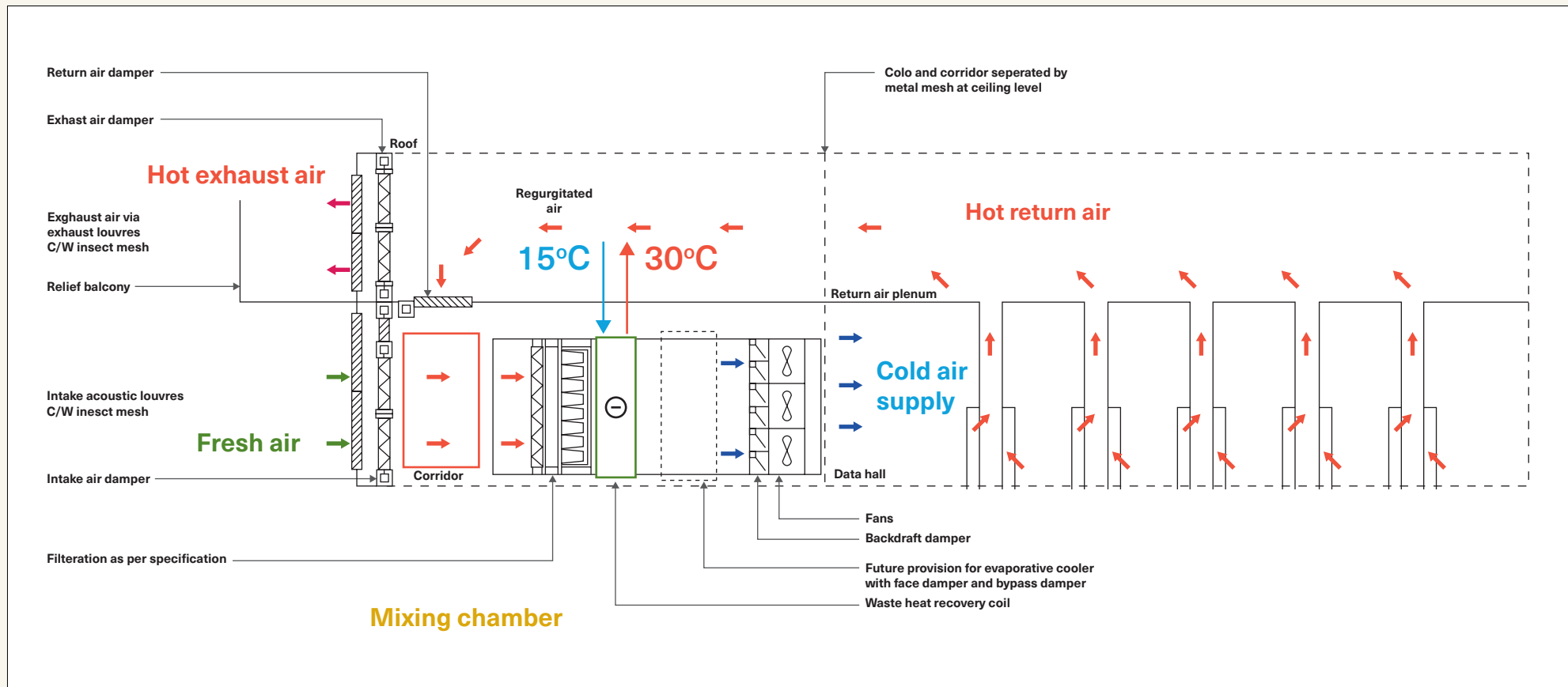


Water-cooled systems

Traditional enterprise and colocation data centres, as well as increasingly high-density facilities, utilize chilled water systems. A central chiller plant generates chilled water, which is then circulated to Computer Room Air Handlers (CRAHs) within the data hall. These CRAHs use the chilled water to cool the air that is then circulated to the IT equipment. The heat absorbed by the chilled water is returned to the chiller plant, where it is transferred via the refrigeration cycle to a condenser water loop. This condenser water is then pumped to external heat rejection equipment, such as cooling towers or dry coolers. The advent of direct-to-chip and immersion liquid cooling modifies this approach by capturing heat directly into a liquid medium at the server level, often at higher temperatures, which can then be managed by a Cooling Distribution Unit (CDU) and rejected to the facility's water loops.

Waste heat recovery integration in air-cooled data centres

In air-cooled facilities, the waste heat is diffuse, contained within a large volume of air exiting the servers at temperatures typically around 40°C. Capturing this heat requires introducing a large surface area heat exchanger into the primary exhaust air path.



Scenario 1: Penthouse design with integrated heat recovery coil



System description

A large, finned-tube heat recovery coil, circulating a water/glycol mixture, is installed within the air path of the penthouse structure. It is positioned upstream of the main data hall evaporative cooling media and supply fans.



Operational principle

When there is an external demand for heat, the water/glycol mixture is circulated through the coil. The hot exhaust air from the data hall, passes over the coil fins, transferring its thermal energy to the liquid. This process pre-cools the air before it reaches the evaporative media. If the heat recovery provides sufficient cooling, the water circulation to the evaporative media can be shut down entirely for that period, resulting in significant water and pump energy savings. The heated water/glycol mixture is then pumped to a waste heat recovery plant where it can be used, for example, to supply a district heating network.



Physical and operational implications

The primary physical implication is the significant increase in the size, weight, and structural complexity of the penthouse. The penthouse is likely to be made deeper to accommodate the coil bank and provide necessary access for maintenance. This may require additional structural steel and cladding, which directly increases the embodied carbon of the building. Operationally, the coil introduces a significant static pressure drop into the air path. The main data hall fans must work harder to overcome this resistance, leading to a continuous fan energy penalty whenever the data centre is in operation, regardless of whether heat is being recovered. If a waste heat recovery coil is introduced into operating facility, a possibility of replacing fans is also an option. Another option is to install face and bypass dampers to alleviate the pressure drop issue. Nevertheless, this operational carbon cost must be carefully weighed against the benefits.

Scenario 2: Mechanical corridor AHU with integrated heat recovery Coil



System description

Instead of being in a penthouse, the heat recovery coil is integrated directly into a larger, often custom-built, Air Handling Unit (AHU) located in a mechanical corridor or gallery adjacent to the data hall.



Operational principle

The principle is similar to the penthouse scenario. Hot air is removed from the data hall's hot aisle to the plenum placed above the data hall, then directed to the mechanical gallery where it passes through the AHU (across filters and the heat recovery coil) and is then either exhausted or passed through an evaporative cooling section before being returned to the cold aisle.



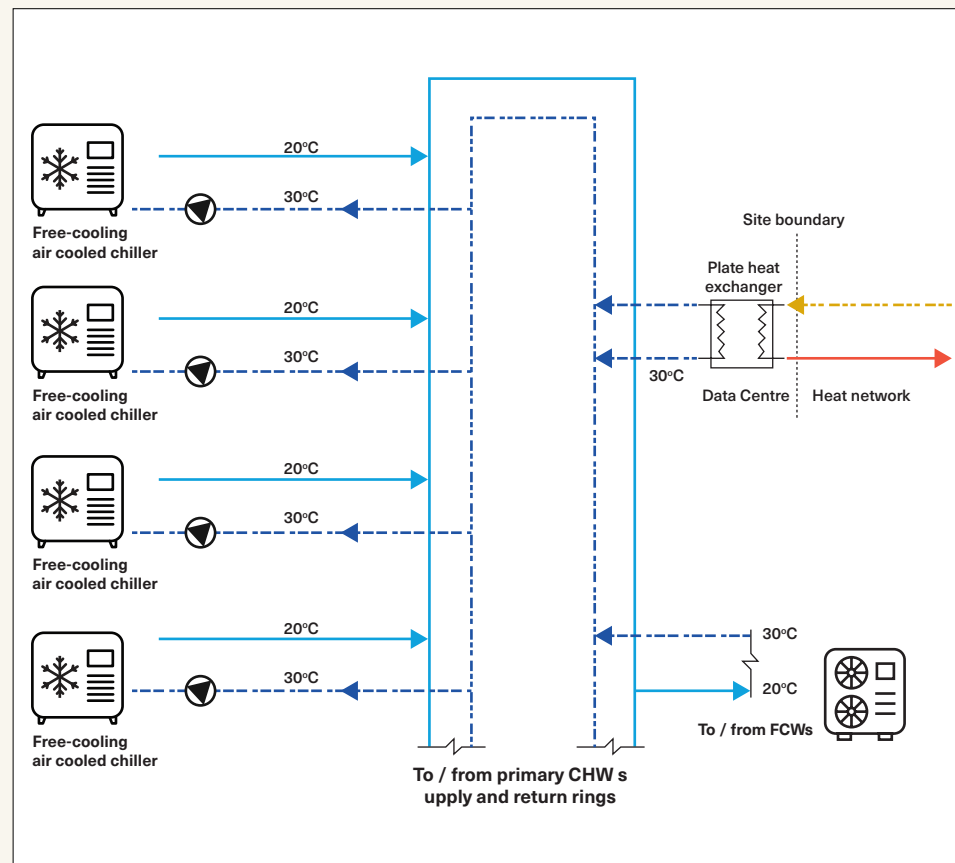
Physical and operational implications

This design requires a larger physical footprint for the AHUs themselves. The additional coil section increases the length and weight of each unit. Furthermore, this approach necessitates a more extensive and complex network of pipework. Large-diameter headers and risers must run through mechanical galleries to connect dozens of individual AHUs to a central plant, and this network may include underground distribution mains to transfer the recovered heat to a waste heat recovery plant. This extensive piping, along with the larger AHUs and more powerful fans required to overcome the coil pressure drop, represents a substantial embodied carbon investment.



Waste heat recovery integration in water-cooled data centres.

In water-cooled facilities, heat is already concentrated in a liquid medium, making recovery more thermodynamically efficient. The integration point is typically a liquid-to-liquid heat exchanger.



Scenario 3: Chilled water system



System description

The heat recovery system interfaces with the data centre's primary water loop, which typically operates at temperatures between 20°C and 30°C. In more advanced direct liquid-cooled facilities, a dedicated, warmer Technical Cooling System (TCS) loop might operate at even higher temperatures (around 40°C), making the heat more valuable. This warm facility water is piped to a dedicated waste heat recovery plant.



Operational principle

Inside the waste heat recovery plant room, the warm data centre water passes through one side of a large plate heat exchanger (PHX). On the other side of the PHX is the water from the external district heating network. Heat is efficiently transferred from the data centre loop to the district heating loop. This "low-temperature" heat (e.g., 35°C) is then piped to the district heating provider's Energy Centre, where large-scale, high-efficiency industrial heat pumps (such as multi-stage ammonia heat pumps) are used to "upgrade" the heat to the temperatures required for residential distribution, often in the range of 70-90°C. By providing this pre-heated water, the data centre significantly reduces the energy required by the district heating provider's heat pumps.



Physical and operational implications

This approach avoids modifications to the internal data hall cooling infrastructure. The primary physical additions are the dedicated waste heat recovery plant, the large PHXs, circulation pumps, and the extensive insulated underground pipework required to connect the data centre to the district heating network. The main operational energy penalty is the power required for the pumps that circulate the water through the heat recovery loop and PHXs. Due to the high specific heat capacity of water compared to air, the energy required to move a given amount of heat via liquid is significantly lower than via air, meaning this pumping penalty is generally less than the fan energy penalty in an equivalent air-cooled WHR system.



Strategies for utilising waste heat from data centres to supply district heating systems

The market offers a range of technological solutions that enable the efficient use of waste heat from data centres to support district heating networks.

Scalability is a further strength - waste-heat recovery installations can be tailored to small server rooms or hyperscale facilities, with investment size aligned to IT load growth. The modular nature of heat recovery-plant design allows incremental investment that grows with computing load rather than requiring full build-out upfront. But one of the key non-technical success factors remains the geographical proximity of the data centre to the district heating network. The closer the waste-heat source to the heat sink (that is, the piping connection into the DH network), the lower the investment cost of new pipework or heat-distribution infrastructure and the better the economics.

Beyond proximity, the load profile and scale of the heat network are equally critical non-technical factors determining the project's economic viability. Data centres are an ideal heat source precisely because their IT load and resultant waste heat output are remarkably stable, operating with a high, flat load factor 24/7. To achieve a fast return on investment, this constant heat supply

should be matched with a district heating network that has a high, stable baseload demand. This is why the scale and mix of the network are crucial. Large-scale, city-wide networks that serve a diverse mix of customers (residential, commercial, industrial etc.) are ideal. The varied demand profiles of these different users (e.g., offices and retail consume energy during the day, residential in the morning/evening) smooth out the network's total load, creating the high, constant baseload demand needed to absorb the data centre's output year-round. Conversely, WHR projects connected to smaller networks serving only residential properties are less economically viable. These networks have highly variable load profiles, with demand peaking sharply in winter and dropping in summer. Furthermore, they experience significant daily swings, with demand falling off during work and school hours. In this scenario, the expensive WHR plant would not use its full potential for long periods, failing to generate a return and diminishing the overall societal carbon benefit.

The required metrics include:



High-temperature heat pumps, which raise the temperature of waste heat from 20–50°C to 70–95°C, and in specialized configurations, even up to 120°C. This allows direct integration into urban heating systems. The seasonal coefficient of performance (SCOP) for heat pumps operating at supply temperatures of 70–85°C ranges from 3.5 to 4.5 kW/kW, meaning that each kilowatt of compressor input power can yield 3.5 to 4.5 kW of usable output. Efficiency depends on the required temperature in the district heating network and the temperature of the waste heat recovery loop.



High-efficiency circulation pumps, ensuring effective heat transfer.



Peak electric boilers (e.g., electrode or resistive types), which can be added to the system to meet the full annual heating curve when needed.



Air-to-liquid and liquid-to-liquid heat exchangers, used to capture heat directly from the air or cooling liquid within the data centre.



Thermal energy management systems, which enable dynamic control of heat flow based on demand. These systems integrate recovered heat from server cooling into district heating networks, adjusting the amount of heat recovered to match the operational parameters of the network.

Case studies - Air-cooled data centre

Introduction

This case study analysis examines the integration of a Waste Heat Recovery (WHR) system into a common hyperscale air-cooled data centre architecture. The baseline facility represents a modern, highly efficient design that leverages free cooling for a significant portion of the year. During periods of higher ambient temperature, this free cooling is supplemented by a direct or indirect evaporative/adiabatic cooling system to meet server inlet temperature requirements.

This baseline design, while achieving a very low Power Usage Effectiveness (PUE) of 1.127, does so at a significant environmental cost: high water consumption, reflected in the baseline Water Usage Effectiveness (WUE) of 1.008. This scenario exemplifies the classic PUE-WUE trade-off, a persistent challenge in the data centre industry where achieving high energy efficiency often necessitates high water consumption. This heavy reliance on water-based systems also introduces secondary environmental impacts, such as the required use of water treatment chemicals (e.g., algaecides, biocides) and the subsequent discharge of this via “cooling water blowdown”.

The central hypothesis of this case study is to determine the net operational impact of this intervention. It seeks to quantify whether the energy savings from the evaporative cooling pumps are sufficient to outweigh the 10% parasitic fan energy supply increase.

The engineering intervention modelled in this analysis, as per the project assumptions, is the introduction of a large, finned-tube heat recovery coil into the primary exhaust air path.



This intervention creates a new operational dynamic with a critical trade-off:

The benefit

The WHR coil captures thermal energy from the hot recirculated air, functioning as a sensible cooling component. This allows the evaporative cooling media and its associated water circulation pumps to be deactivated whenever the WHR system is operational. This yields a dual benefit: direct energy savings from the idled pumps (positively impacting PUE) and a significant reduction in water consumption (positively impacting WUE).

The drawback

The introduction of a large coil into the air path inherently increases system resistance, creating an additional static pressure drop. The main data hall fans must work harder to overcome this resistance, resulting in a continuous parasitic fan energy penalty, assumed here to be a 10% increase in fan power. This penalty negatively impacts the facility's PUE.

Case study 1 – Denmark

In Denmark, with its clean grid (243g CO₂e/kWh), the 12-month CUE improves minimally, from a baseline of 0.2738 to 0.2715. For this location, the operational carbon saving is negligible. This finding strongly reinforces the report's primary thesis: for data centres on green grids, the true carbon benefit is not operational (CUE) but societal, found in the displaced carbon from the heat off-taker. The justification for the project in Denmark is therefore rooted in water conservation (WUE).

This table below presents the performance metrics for the air-cooled facility in Denmark:

	PUE	WUE	CUE
Baseline (no WHR)	1.1266	1.008	0.2738
WHR Scenario 1 (12 months)	1.1172	0.432	0.2715
WHR Scenario 2 (6 months)	1.1236	0.817	0.2730
WHR Scenario 3 (3 months)	1.1254	0.930	0.2735

Case study 2 – Poland

In Poland, the WHR intervention provides a significant improvement. Operationally, the PUE improves from 1.1266 to 1.1173 (Scenario 1), confirming the project is a net-energy positive. Simultaneously, the WUE sees an improvement, falling from 1.008 to 0.440, a ~56.3% reduction. This solves the baseline PUE-WUE trade-off and mitigates water-related environmental impacts.

The critical differentiator for Poland is the “carbon multiplier” effect from its high-carbon grid (736 g CO₂e/kWh). The 12-month CUE improves from 0.8292 to 0.8223. This absolute CUE reduction (0.0069) is approximately 3 times greater than the reduction seen in Denmark for the exact same mechanical upgrade. This means the project delivers not only a significant societal carbon benefit (ERF) but also a meaningful operational carbon reduction (CUE), amplifying its value in a carbon-intensive region.

This table presents the performance metrics for the air-cooled facility in Poland:

	PUE	WUE	CUE
Baseline (no WHR)	1.1266	1.008	0.8292
WHR Scenario 1 (12 months)	1.1255	0.938	0.8284
WHR Scenario 2 (6 months)	1.1236	0.826	0.8269
WHR Scenario 3 (3 months)	1.1173	0.440	0.8223

Case study 3 – Ireland

Like the other locations, the Ireland case study demonstrates a clear operational success. The PUE improves from a baseline of 1.1266 to 1.1172 in the 12-month scenario, proving the energy savings from idled pumps outweigh the parasitic fan energy increase.

The most significant gain is in water conservation. The annualized WUE is reduced from 1.008 to 0.431, a ~57.2% reduction. This result is transformative, as it resolves the facility's PUE-WUE trade-off and curtails water-based pollution.

From a carbon perspective, Ireland's grid (255 g CO₂e/kWh) is relatively clean, like Denmark's. As a result, the operational CUE improvement is minimal, moving from 0.2873 to 0.2849. As with Denmark, the project's justification in Ireland is not operational CUE savings but the crucial gains in water efficiency (WUE) and the potential for large-scale societal carbon offsetting via the Energy Reuse Factor (ERF).

This table presents the performance metrics for the air-cooled facility in Ireland:

	PUE	WUE	CUE
Baseline (no WHR)	1.1266	1.008	0.2873
WHR Scenario 1 (12 months)	1.1254	0.929	0.2870
WHR Scenario 2 (6 months)	1.1236	0.816	0.2865
WHR Scenario 3 (3 months)	1.1172	0.431	0.2849

Like the other locations, the Ireland case study demonstrates a clear operational success. The PUE improves from a baseline of 1.1266 to 1.1172 in the 12-month scenario, proving the energy savings from idled pumps outweigh the parasitic fan energy increase.

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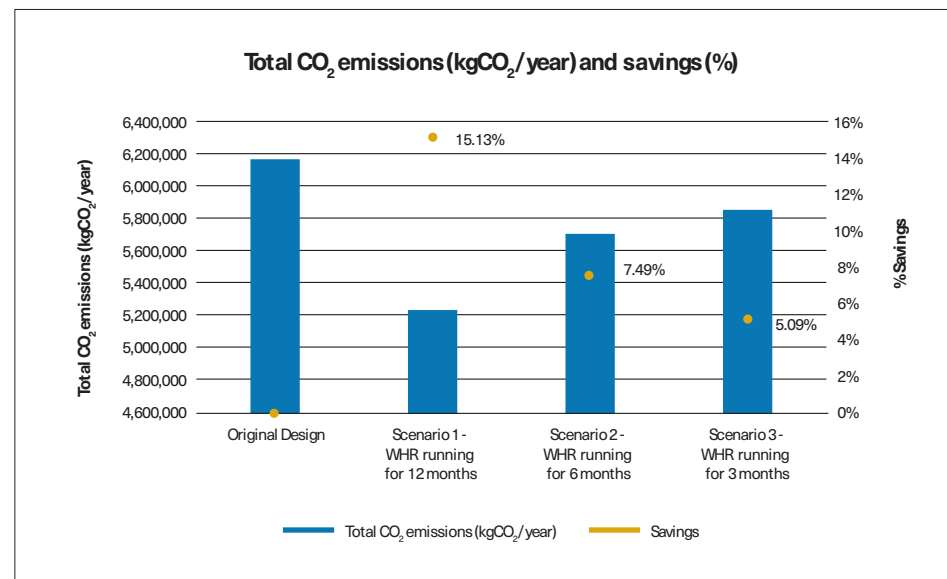
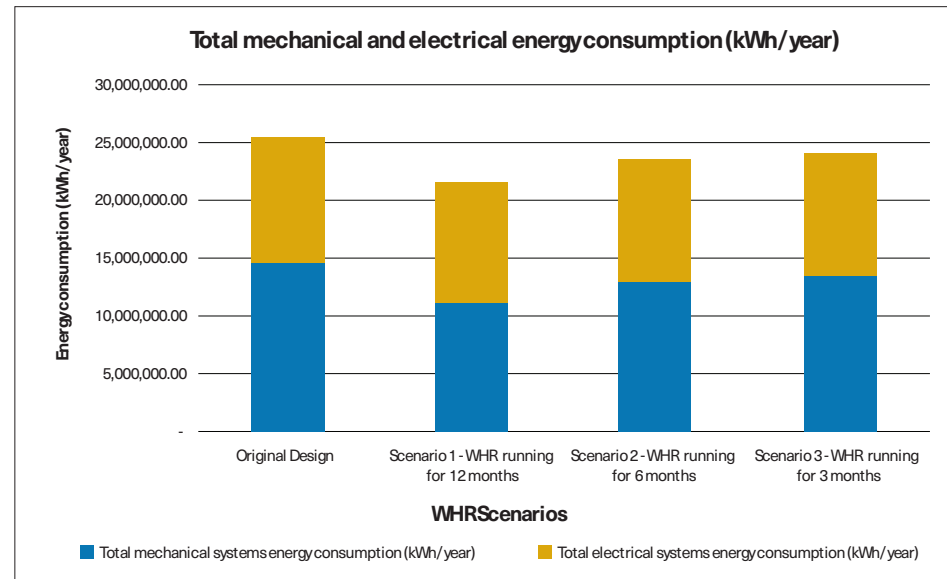
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Caste studies - Water-cooled data centre

Case study 1 – Denmark

For the water-cooled facility in Denmark, implementing WHR for the full year reduces the PUE from a baseline of 1.236 to 1.205. This scenario delivers annual energy savings of 3,193 MWh. Shorter WHR periods yield proportionally lower benefits. A 6-month operation saves 1,251 MWh, while a 3-month operation saves just 639 MWh.

This efficiency gain results in annual CO₂ savings of 935,113 kg. Given Denmark's highly decarbonised grid, these savings are primarily driven by the significant reduction in total energy consumption rather than a high carbon multiplier effect. This scenario demonstrates that even in a green energy landscape, optimizing data centre efficiency through WHR provides substantial carbon benefits.



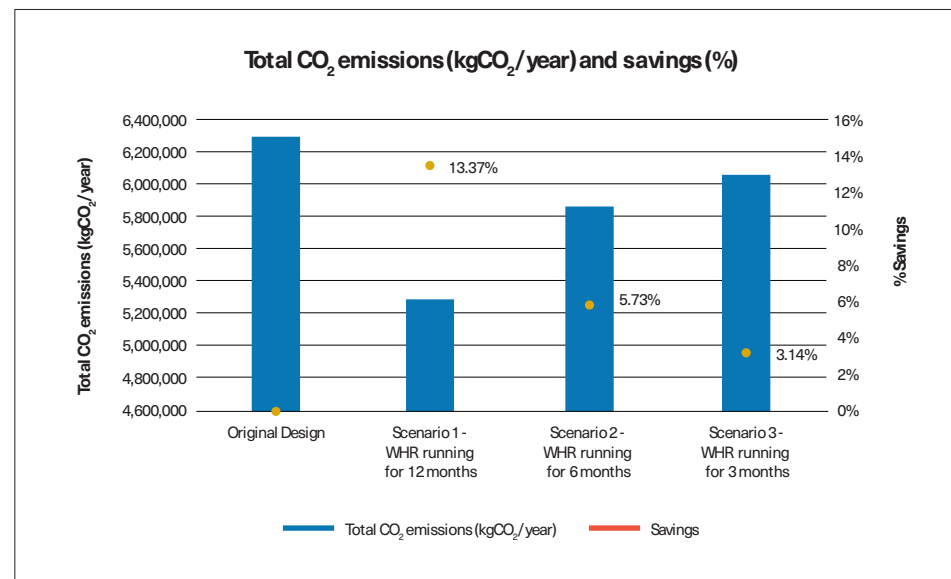
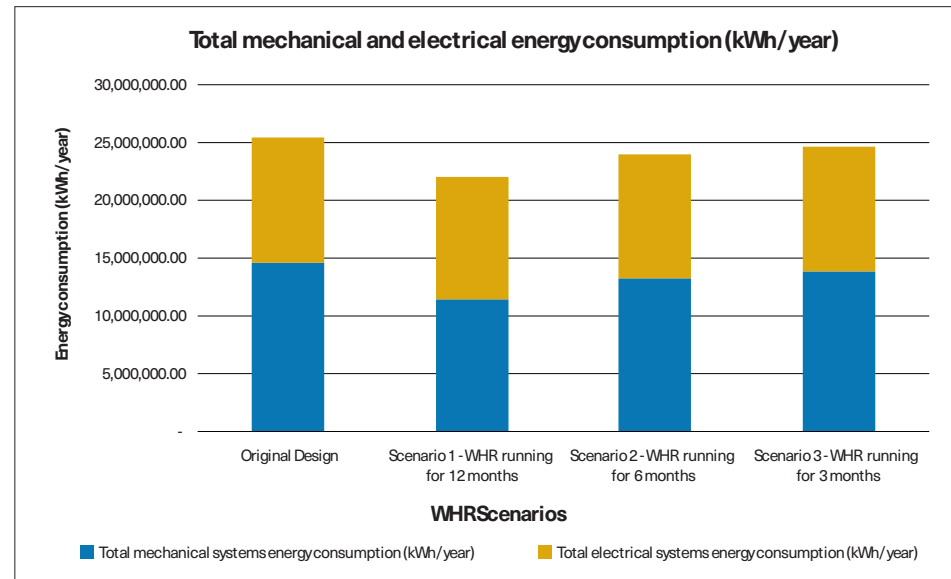


	Original Design	Scenario 1 - WHR running for 12 months	Scenario 2 - WHR running for 6 months	Scenario 3 - WHR running for 3 months	Scenario 1 - WHR running for 12 months - % saving	Scenario 2 - WHR running for 6 months - %saving	Scenario 3 - WHR running for 3 months - %saving
Total mechanical systems energy consumption (kWh/year)	14,604,285.23	11,138,611.25	12,950,537.69	13,521,163.26	23.73%	11.32%	7.42%
Total electrical systems energy consumption (kWh/year)	10,832,748.23	10,450,222.36	10,580,538.70	10,621,578.91	3.53%	2.33%	1.95%

Total CO ₂ emissions (kgCO ₂ /year)	6,181,199.13	5,246,086.57	5,718,051.56	5,866,686.35
Total CO ₂ savings (kgCO ₂ /year)	-	935,112.57	463,147.57	314,512.79

Case study 2 – Poland

Implementation of 12- month WHR yields a PUE improvement from 1.242 to 1.210. This scenario delivers the highest energy savings of all locations at 3,401 MWh annually. Due to the carbon-intensive nature of Poland's electricity grid, the resulting CO₂ savings are a remarkable 2,503,237 kg per year. This figure, which is over 2.5 times greater than the savings achieved in Denmark for a similar PUE improvement, starkly illustrates how a high grid carbon factor acts as a powerful multiplier, amplifying the environmental benefits of energy efficiency measures. It underscores the strategic importance of deploying such technologies in regions where the grid is still heavily reliant on fossil fuels.





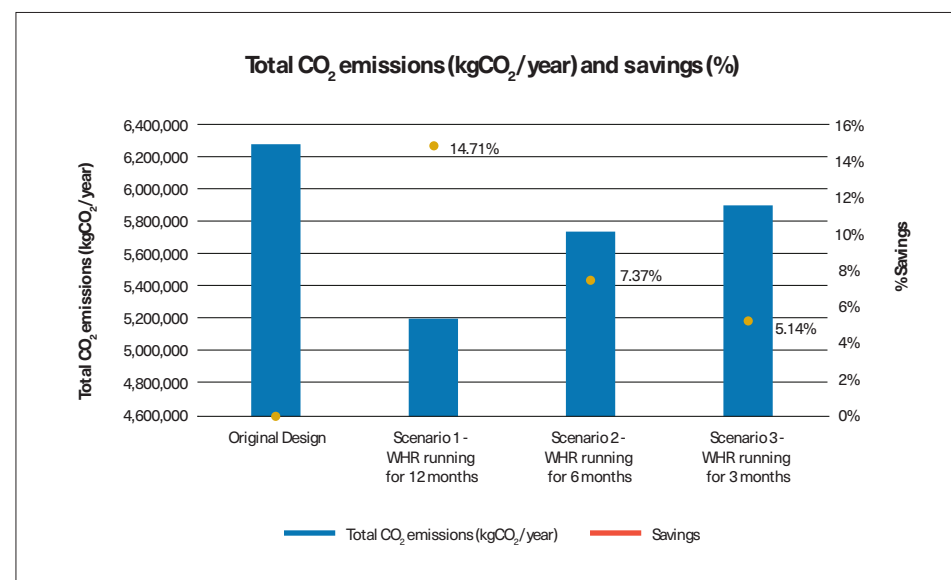
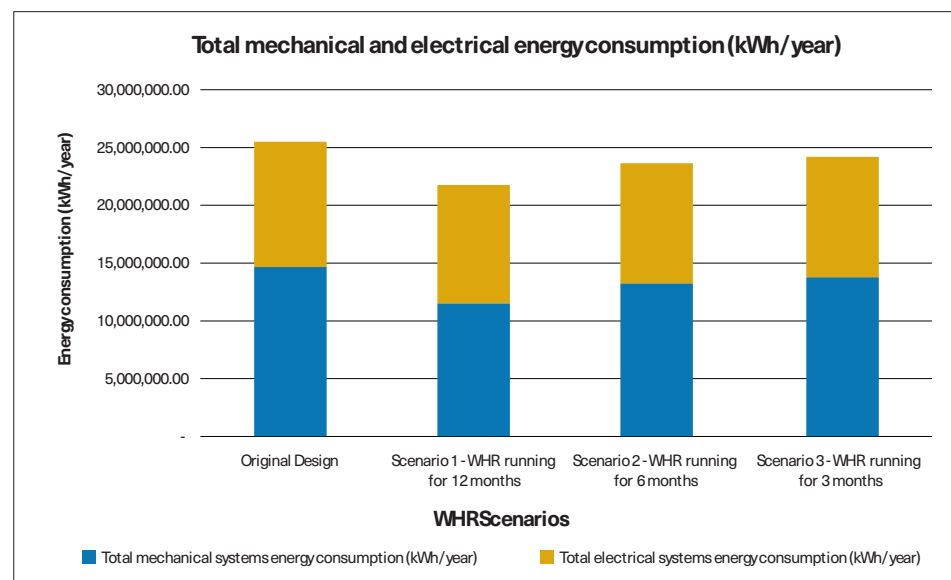
	Original Design	Scenario 1 - WHR running for 12 months	Scenario 2 - WHR running for 6 months	Scenario 3 - WHR running for 3 months	Scenario 1 - WHR running for 12 months - % saving	Scenario 2 - WHR running for 6 months - %saving	Scenario 3 - WHR running for 3 months - %saving
Total mechanical systems energy consumption (kWh/year)	14,604,285.23	11,431,349.54	13,244,821.31	13,859,632.00	21.73%	9.31%	5.10%
Total electrical systems energy consumption (kWh/year)	10,832,748.23	10,604,546.17	10,734,973.65	10,779,191.71	2.11%	0.90%	0.49%

Total CO ₂ emissions (kgCO ₂ /year)	18,721,656.63	16,218,419.24	17,649,129.09	18,134,174.25
Total CO ₂ savings (kgCO ₂ /year)	-	2,503,237.39	1,072,527.54	587,482.38

Case study 3 – Ireland

The Irish location shows balanced performance between the values for Denmark and Poland. Irish scenario shows a PUE reduction from 1.238 to 1.206 with 12-month WHR. This scenario results in annual energy savings of 3,302 MWh and CO₂ savings of 954 tonnes. This value is comparable to Denmark's, reflecting Ireland's relatively cleaner grid compared to Poland. A 6-month operation saves 1,435 MWh and 478 tonnes of CO₂, while a 3-month operation saves 868 MWh and 333 tonnes of CO₂.

Nonetheless, the results still represent a significant reduction in operational carbon and demonstrates the universal applicability of WHR in reducing a data centre's direct environmental impact, regardless of the grid's carbon intensity.





	Original Design	Scenario 1 - WHR running for 12 months	Scenario 2 - WHR running for 6 months	Scenario 3 - WHR running for 3 months	Scenario 1 - WHR running for 12 months - % saving	Scenario 2 - WHR running for 6 months - %saving	Scenario 3 - WHR running for 3 months - %saving
Total mechanical systems energy consumption (kWh/year)	14,604,285.23	11,462,682.25	13,204,356.28	13,732,634.72	21.51%	9.59%	5.97%
Total electrical systems energy consumption (kWh/year)	10,832,748.23	10,233,604.82	10,358,868.50	10,396,863.04	5.53%	4.37%	4.02%

Total CO ₂ emissions (kgCO ₂ /year)	6,486,443.53	5,532,553.20	6,008,622.32	6,153,021.93
Total CO ₂ savings (kgCO ₂ /year)	-	953,890.33	477,821.21	333,421.60

Power usage effectiveness analysis overview

PUE analysis overview

The implementation of WHR directly reduces the load on the mechanical cooling plant, leading to lower energy consumption and a corresponding improvement in the annualized PUE.

Across all three locations, the annualized PUE improves as the duration of WHR increases. The 12-month scenario provides a PUE improvement of approximately 2.5% in Poland and 2.6% in both Ireland and Denmark. Extending WHR from 3 months to 12 months progressively lowers the Annualised PUE and increases both mechanical and electrical energy savings across all three locations.

A key finding from the analysis is that only the 12-month WHR scenario successfully reduces the peak mechanical load and, consequently, the peak PUE. This indicates that shorter-duration WHR, while beneficial for annual energy consumption, is insufficient to impact the system's performance on design days (i.e., the hottest days of the year).

Poland starts with the highest baseline PUE (1.242), likely due to a climate that demands more from the mechanical cooling system. Consequently, it also sees the largest absolute reduction in PUE when WHR is applied year-round. Ireland and Denmark have milder climates, resulting in slightly better baseline PUE values and similar levels of improvement from WHR.

The 3-month WHR scenario offers only a marginal PUE improvement (less than 1% in all locations), suggesting that short-duration heat recovery has a limited impact on overall facility efficiency, even though it still provides a benefit.

Location	Original PUE	PUE (12-Month WHR)	PUE (6-Month WHR)	PUE (3-Month WHR)
Poland	1.242	1.210	1.228	1.234
Ireland	1.238	1.206	1.224	1.230
Denmark	1.236	1.205	1.224	1.230

The 12-month scenario provides a PUE improvement of approximately 2.5% in Poland and 2.6% in both Ireland and Denmark.



Annual energy savings

Tables presented in each of case studies demonstrate that the savings are most pronounced in the mechanical systems, as WHR directly offloads the work required from the air-cooled chillers.

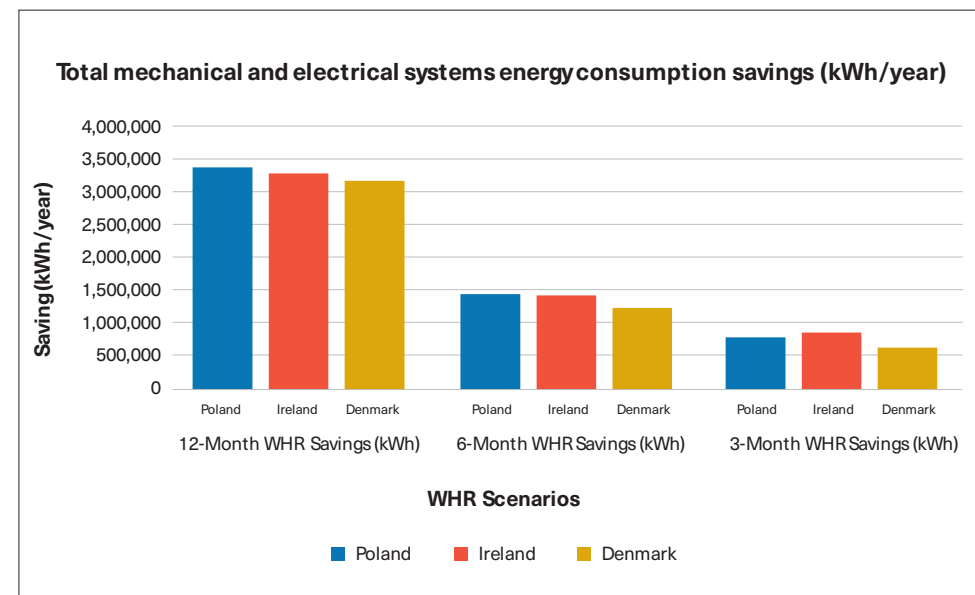
Energy savings scale almost linearly with the duration of WHR. The 6-month scenario consistently delivers roughly 40-45% of the savings of the 12-month scenario, while the 3-month scenario provides about 20-25% of the full-year savings.

Poland shows the highest potential for energy savings in the 12-month scenario. This is because its climate likely requires the most cooling energy over a full year, so reducing that load via WHR yields the greatest benefit.

While PUE measures energy efficiency, Carbon Usage Effectiveness (CUE) provides a more direct measure of a data centre's sustainability by quantifying its carbon emissions relative to its IT energy consumption. Developed by The Green Grid, CUE is calculated as the ratio of the total CO₂ equivalent emissions caused by the data centre's total energy consumption to the energy consumption of the IT equipment.

Table and chart shown below present total mechanical and electrical systems energy savings (kWh/year), based on WHR duration period:

Location	12-Month WHR Savings (kWh)	6-Month WHR Savings (kWh)	3-Month WHR Savings (kWh)
Poland	3,401,138	1,457,238	798,210
Ireland	3,301,673	1,434,735	868,462
Denmark	3,193,335	1,251,092	639,427



An ideal theoretical CUE is 0, indicating a carbon-neutral operation. The total CO₂ emissions in the numerator are a composite figure, derived from several key components:

Grid electricity emissions

This is the largest contributor and is calculated by multiplying the total facility energy consumption by the local electricity grid's carbon emission factor (e.g., in kg CO₂e per kWh). This factor varies dramatically by region.

On-site fuel combustion

This includes emissions from the periodic testing of backup diesel generators, a critical procedure to ensure reliability. The calculation is based on the volume of diesel consumed, its energy density, and its specific carbon factor.

Fugitive emissions from refrigerants

Cooling systems (chillers) contain refrigerants with a high Global Warming Potential (GWP). An estimated annual leakage rate (e.g., 3%) is multiplied by the total refrigerant charge and its GWP to determine the equivalent CO₂ emissions.

The analysis of CUE further underscores the critical importance of local grid conditions. The Poland facility exhibits a significantly higher Annualised CUE (0.137) compared to Ireland (0.062) and Denmark (0.055) in the baseline scenario. This is a direct result of Poland's carbon-intensive electricity grid, which has a high proportion of coal-fired generation. In contrast, the grids in Ireland and Denmark are significantly cleaner.

Consequently, the absolute CO₂ savings achieved through the energy efficiency gains of WHR are substantially greater in Poland. Any reduction in electricity consumption (the primary component of operational carbon) has a magnified benefit. This demonstrates that the total carbon benefit of any PUE improvement is amplified in regions with less green power generation, making CUE an essential metric for evaluating the true environmental impact of a data centre project.

The impact of waste heat recovery implementation on embodied, operational, and displaced carbon

Introduction

This section focuses on impact that implementation of 10MW waste heat recovery system has on embodied, operational and displaced carbon values for 30MW IT load air-cooled and water-cooled data centres.

The implementation of any waste heat recovery system, while promising operational and societal carbon savings, requires a significant upfront investment in physical infrastructure. This infrastructure carries an “embodied carbon” footprint, representing the greenhouse gas emissions associated with the materials and manufacturing processes of its components. A credible carbon balance analysis must begin by quantifying this initial carbon cost.

The total embodied carbon is calculated as the Global Warming Potential (GWP) for these stages and is expressed in kilograms of carbon dioxide equivalent (kgCO₂e).

Data for embodied carbon coefficients will be sourced from publicly available, reputable databases and manufacturer-specific documents to ensure transparency and accuracy. The primary source for generic materials will be the Inventory of Carbon & Energy (ICE) database, a widely used resource in the construction industry. Where available, these generic values will be superseded by more specific data from Environmental

Product Declarations (EPDs). EPDs are third-party verified documents that provide standardized environmental impact data for specific products. For complex mechanical, electrical, and plumbing (MEP) equipment where EPDs are not available, estimations will be based on the methodology outlined in CIBSE Technical Memorandum 65 (TM65), which calculates embodied carbon based on a product’s material composition.



The following table summarizes the key embodied carbon coefficients used in this analysis.

Material	Component application	Embodied carbon (kg CO ₂ e/kg)	Source
Steel (Carbon)	Structural sections (Beams, columns)	1.22	EPD (Nucor)
Steel (Carbon)	Hot-dip galvanized pipe	1.41	EPD (Corbec)
Steel (Stainless)	Plate heat exchanger plates	2.50	ICE Database
Copper	Pipework and coil tubes	4.98	EPD (Cupori 110)
Aluminum	Coil fins	8.24	ICE Database
Bronze/brass	Valves and fittings	4.50	ICE Database

Embodied carbon analysis

To calculate the total embodied carbon values associated with implementation of waste heat recovery installation, a high-level bill of materials has been developed for each case study. The quantities are based on engineering assumptions for a 30MW data centre aiming to recover 10MW of waste heat.

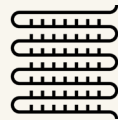
Air-cooled data centre

For the air-cooled data centres, the primary additional components are the heat recovery coils and the associated structural and distribution systems. Depending on the design, a heat recovery coil can be placed either inside of the AHUs located in the mechanical corridor adjacent to the data hall, or introduced into the air path at the penthouse level above the data hall. Both solutions require additional pipework, accessories (valves, strainers, sensors etc.) and steel structure to support these additional elements.



To provide a high-level analysis, a breakdown of the main components of the waste heat recovery system has been done with the assumptions listed below.

For the solution with AHUs placed in the mechanical corridor, it is assumed that 30 AHUs are required, each handling approx. 1.2MW of IT load, with all of these being fitted with heat recovery coils. For the penthouse solution, a similar coil size has been assumed.

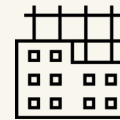


Heat recovery coils

Assuming a standard coil of this size requires approximately 145 kg of copper (tubes) and 200 kg of aluminum (fins):

Total copper mass:
30 x 145kg = 4,350kg

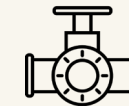
Total aluminum mass:
30 x 200kg = 6,000kg



Structural steel (Penthouse/AHU support)

The additional weight and size of the coils and plenums require reinforced structural support. An estimated 1.5 tonnes of additional structural steel sections per coil location is assumed.

Total steel mass:
30 x 1,500kg = 45,000kg



Pipework and valves

Pipework include flow and return headers and smaller branch connections to each coil. This includes an estimated 500m of DN300 pipe, 1,000m of DN150 pipe, and associated valves and fittings.

Total pipe mass (Galvanized steel):
approx 45,000kg

Total valve mass (Bronze/brass):
approx 2,000kg

Water-cooled data centre

For the water-cooled scenario, the infrastructure is more centralized, consisting of large plate heat exchangers and the associated primary pipework. For the sake of the study it is assumed that these elements are located in the dedicated plantrooms, placed on the roof of the data centre building, similarly as entire mechanical plant.



Plate Heat Exchangers (PHXs)

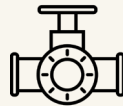
To handle a 10MW load with redundancy, five 2MW stainless steel gasketed plate heat exchangers are assumed. Based on one of the manufacturer's data sheets, each unit has a dry weight of approximately 1,420 kg (predominantly stainless steel plates – assumed as 85% of the entire exchanger and a carbon steel frame – assumed 15% of the entire exchanger).

Total stainless steel mass:

5 x 1,420kg x 85%: approx 6,035kg

Total carbon steel mass (frames):

5 x 1,420kg x 15%: approx 1,065kg



Pipework and valves

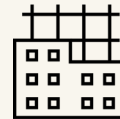
This system requires connections to the plate heat exchangers and large-diameter pipework connecting the data centre's WHR plantrooms to the dedicated mechanical plantroom owned by the heat network provider. It is estimated as 20m of DN200 and 400m of DN350 carbon steel pipework:

Total pipe mass (Galvanized Steel):

approx 40,000kg

Total valve mass (Bronze/Brass):

approx 4,000kg



Structural steel (Pipework support)

The additional secondary carbon steel structure weight is based on the mass per length indicators (100 kg/m for vertical supports and 75 kg/m per horizontal supports) what results in total steel mass of 46,480kg.

Total embodied carbon investment

The completed calculation, presented in table below reveals that the water-cooled WHR system has a total embodied carbon footprint of 147.5 tonnes of CO₂ equivalent (tCO₂e), which is approximately 26% lower than the 198.5 tCO₂e for the air-cooled system.

This result, where the water-cooled system has a lower carbon footprint despite a comparable total mass, stems from the material composition. The high-level analysis demonstrates that the type of material can be a more powerful determinant of embodied carbon than the total mass. A simple comparison based on the total weight of the two systems would be misleading because it would treat each kilogram of material as having an equal carbon impact.

The air-cooled system's profile is dominated by a large mass of highly carbon-intensive aluminum for the coil fins. In contrast, the water-cooled system's mass is primarily composed of steel pipework and heat exchangers, which have a much lower carbon intensity per kilogram. This highlights that a material-specific analysis is crucial for accurately assessing the embodied carbon of different solutions.

Scenario	Component	Total Mass (kg)	Embodied Carbon (tCO ₂ e)
Air-cooled Data Centre	Structural steel	45,000	54.9
	Heat Recovery coils (Copper)	4,350	21.7
	Heat recovery coils (Aluminum)	6,000	49.4
	Pipework (Galvanized steel)	40,000	63.5
	Valves and fittings (Bronze/Brass)	2,000	9.0
	Total for air-cooled	102,350	198.5
Water-cooled Data Centre	PHXs (Stainless steel)	6,035	15.1
	PHXs (Carbon steel frames)	1,065	1.3
	Pipework (Galvanized steel)	40,000	56.4
	Valves and Fittings (Bronze/Brass)	4,000	18.0
	Structural steel	46,480	56.7
	Total for water-cooled	97,580	147.5

Carbon offset potential

The true environmental benefit of waste heat recovery lies in the reduction of external carbon emissions from the wider community, where users would otherwise rely on conventional heating systems. This “offset carbon” is a critical component of a holistic carbon balance. The magnitude of this carbon offset is highly dependent on the specific mix of heating technologies being displaced in a given region.

This analysis quantifies the potential carbon offset by assuming a data centre recovers and exports 43,800 MWh of thermal energy annually. This recovered heat is used to supply a number of equivalent dwellings, displacing their need for existing heating systems. The total carbon savings are calculated by weighting the emissions from four primary heating sources - natural gas boilers, coal boilers, oil boilers, and electric air source heat pumps (ASHPs) - according to the prevalent residential heating fuel mix in each target country.



Facebook, Luleå, Sweden © Lindman Photography

Case study 1: Poland

Poland's heating sector is heavily reliant on fossil fuels, particularly solid fuels.

While a significant portion of urban households (over 52%) are connected to district heating networks, these networks are themselves predominantly coal-fired. For individual households, solid fuels like hard coal remain a primary heating source (32.8%), followed by natural gas (14.5%). The use of oil and electricity for primary heating is less common.



For this analysis, the displaced heating load is modeled with the following estimated fuel mix for individual dwellings:

- Coal: 60%
- Natural gas: 25%
- Oil: 10%
- Electricity (Heat pump): 5%

Based on the 43,800 MWh of recovered heat, the potential carbon savings from displacing each fuel type individually are calculated. These figures are then weighted by the residential fuel mix to determine the total blended carbon offset. The grid carbon intensity for Poland is taken as 736 kgCO₂e/MWh.

By supplying recovered heat to residential users in Poland, a data centre could displace an estimated 14,222 tonnes of CO₂e annually. The exceptionally high savings are a direct result of displacing carbon-intensive heating sources, particularly coal, which dominates both individual heating and the fuel mix for district heating networks.

Displaced heat source	100% displacement savings (tonnes CO ₂ e/year)	Residential fuel mix (%)	Weighted annual savings (tonnes CO ₂ e/year)
Coal boiler	16,916	60%	10,150
Natural gas boiler	9,325	25%	2,331
Oil boiler	12,880	10%	1,288
Electric heat pump	9,060	5%	453
Total weighted savings		100%	14,222

Case study 2: Ireland

Ireland's residential heating sector has historically relied on a mix of oil and natural gas.

As of 2022, oil remains the most common fuel type (38.9%), closely followed by natural gas (32.7%). Solid fuels like coal and peat still play a role (approx. 16%), while the share of electric heating, including heat pumps, is growing but remains smaller (approx. 12%).



The following fuel mix is used for this analysis:

- Oil: 39%
- Natural gas: 33%
- Coal/solid fuel: 16%
- Electricity (Heat pump): 12%

The carbon savings for displacing electric heat pumps are recalculated using a grid carbon intensity for Ireland of 255 kgCO₂e/MWh. This is significantly lower than the generic value used in the initial calculation, reflecting Ireland's increasing share of renewable electricity.

In Ireland, a data centre exporting its waste heat could achieve an estimated annual carbon offset of 11,190 tonnes of CO₂e. The savings are substantial due to the continued reliance on fossil fuels, particularly oil and natural gas, for home heating.

Displaced heat source	100% Displacement savings (tonnes CO ₂ e/year)	Residential fuel mix (%)	Weighted annual savings (tonnes CO ₂ e/year)
Oil boiler	12,880	39%	5,023
Natural gas boiler	9,325	33%	3,077
Coal boiler	16,916	16%	2,707
Electric heat pump	3,191	12%	383
Total weighted savings		100%	11,190

Case study 3: Denmark

Denmark has a mature district heating market that supplies over 65% of households. For dwellings with individual heating systems, there has been a significant shift towards renewables.

The 2023 fuel mix for the residential sector shows a diverse landscape where heat pumps and biomass are as prevalent as gas boilers.



The mix for individually heated homes is as follows:

- Natural gas: 27%
- Oil: 9%
- Electricity (Heat pump and resistive): 33%
- Biomass: 31%

The carbon savings for displacing electric heating are recalculated using a Danish grid carbon intensity of 243 kgCO₂e/MWh. Biomass is assumed to be carbon-neutral in this context, providing no additional offset.

For Denmark, the weighted annual carbon offset is estimated at 4,680 tonnes of CO₂e. While still significant, this figure is considerably lower than in Poland or Ireland. This is a direct result of Denmark's advanced energy transition: its electricity grid is cleaner, and its heating sector has already substantially moved away from fossil fuels towards district heating, biomass, and heat pumps.

Displaced heat source	100% Displacement savings (tonnes CO ₂ e/year)	Residential fuel mix (%)	Weighted annual savings (tonnes CO ₂ e/year)
Natural gas boiler	9,325	27%	2,518
Oil boiler	12,880	9%	1,159
Electric heat pump	3,040	33%	1,003
Biomass	0	31%	0
Total weighted savings		100%	4,680

Conclusions on carbon offset potential

The data for Poland indicates the highest potential for CO₂ savings among the three locations.

The displacement of coal-fired boilers yields an annual saving of 10,150 tCO₂e. This value is numerically the largest on the chart and is more than 3.7 times greater than the next largest potential saving in Poland (from displacing natural gas boilers at 2,331 tCO₂e/year).

This significant differential underscores a key technical conclusion: the efficacy of WHR as a decarbonization tool is maximized in energy systems with a high penetration of carbon-intensive solid fuels. The high carbon content of coal means that its displacement provides a disproportionately large CO₂ abatement benefit per unit of thermal energy supplied.

In the Irish context, the analysis shows that the most substantial CO₂ savings are achieved by displacing liquid and gaseous fossil fuels. Specifically, displacing oil boilers results in 5,023 tCO₂e/year in savings, while displacing natural gas boilers yields 3,077 tCO₂e/year.



These figures reflect a residential heating sector that is heavily reliant on the direct combustion of these fuels. In contrast, the savings from displacing electric heat pumps are minimal (383 tCO₂e/year), which suggests that the carbon intensity of the electricity grid is lower than that of direct fuel combustion. Therefore, the primary decarbonization pathway for WHR in this environment is the substitution of fossil-fuel-based heating.

The data for Denmark shows a lower overall potential for CO₂ savings compared to Poland and Ireland. The most significant saving is derived from the displacement of natural gas boilers, at 2,518 tCO₂e/year. The zero value for oil boiler displacement indicates that this is not a prevalent heating source to be displaced, or that the alternative is already considered carbon-neutral (such as biomass).

This profile is indicative of a mature energy market that has already made substantial progress in decarbonizing its heating sector through technologies like district heating and renewables. In such a system, the additional or marginal carbon benefit of introducing data centre waste heat is reduced. The strategic value in this context is primarily in enhancing overall grid efficiency and displacing the remaining, smaller-scale fossil fuel installations.



This analysis confirms that from a societal carbon perspective, the most impactful data centre heat reuse projects will be those located in areas with the most carbon-intensive heating and electricity grids.

The analysis of displaced carbon emissions reveals several key conclusions:



Offset potential is location - dependent

Carbon intensity of the local electricity grid is the most powerful variable influencing the carbon offset calculation. This demonstrates that the long-term value of a WHR investment is intrinsically linked to the decarbonization trajectory of the host country's grid. A project that is highly beneficial today in a coal-heavy region may offer diminishing carbon returns as that grid transitions to renewables.



Displacing carbon - intensive fuels provides the greatest benefit

The largest carbon savings are achieved in regions where the existing heating infrastructure relies heavily on high-carbon fuels. Poland's dependence on coal makes it a prime candidate for high-impact WHR projects.



Grid carbon intensity is a key multiplier

Carbon offset from displacing electric heating is directly tied to the grid's carbon intensity. In Poland, with a carbon-heavy grid, displacing electric heat pumps offers savings comparable to displacing gas boilers. In Denmark, with its clean, wind-powered grid, the savings from displacing electric heat are much lower.



Advanced energy transitions reduce offset potential

As countries like Denmark successfully decarbonize their heating and electricity sectors, the additional carbon benefit of introducing data centre waste heat diminishes. In these regions, the value proposition shifts from pure carbon offsetting to improving overall energy system efficiency and displacing the last remaining fossil fuels.

Conclusion

The holistic carbon balance analysis conducted in this report provides a foundation for strategic decision-making in the design and deployment of sustainable data centres. The findings move attention to complex interplay of engineering design, local context, and societal benefit. Based on this analysis, several key conclusions and recommendations can be drawn for industry stakeholders.

Waste heat recovery is not a universally applicable panacea for data centre emissions, but rather a highly context-sensitive decarbonization strategy. Its viability as a net-positive carbon reduction measure is contingent upon a specific set of conditions being met.

The analysis conclusively demonstrates that a successful WHR project is defined by the confluence of several factors:



Proximity to a consistent heat demand

The high embodied carbon investment in WHR infrastructure can only be justified if the recovered heat is consistently utilized. The most effective model for achieving this is integration with large-scale district heating and cooling networks that can absorb the data centre's constant thermal output as a stable, renewable-compatible baseload. Standalone projects serving single users (e.g. a swimming pool or greenhouse) are valuable but may not provide the scale of demand needed to justify the investment for a hyperscale facility.



Local climate patterns

Colder climates with long heating seasons offer the greatest potential for heat reuse, maximizing the total annual thermal energy that can be supplied and, consequently, the total carbon emissions that can be displaced. Temperate climates offer fewer hours of demand, reducing the overall carbon benefit.



Grid carbon intensity and displaced heating fuel

The carbon savings are most profound when displacing direct fossil fuel combustion (e.g., natural gas boilers). When displacing electric heating systems like ASHPs, the net carbon benefit is a direct function of the grid's carbon intensity. In regions with carbon-intensive grids (Poland), this offset can be substantial. In regions with highly decarbonized grids (Denmark), the benefit is marginal, shifting the justification for WHR back to the displacement of remaining fossil fuels and enhancing overall energy system efficiency.

The insights from this report lead to actionable recommendations for key actors in the data centre ecosystem.

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For data centre designers and engineers



Adopt a holistic carbon balance approach

The design process must evolve beyond the optimization of PUE. A whole-life carbon assessment, integrating the embodied carbon of construction and MEP systems, the operational carbon of the facility and the potential societal carbon benefits of WHR, should become standard practice during site selection and concept design.



Quantify the fan power penalty

For air-cooled designs, the fan energy penalty associated with heat recovery coils is a significant and unavoidable operational cost. This must be meticulously calculated and disclosed in any feasibility study to avoid overstating the net energy benefits of the system.



Prioritize water-based heat recovery

Where feasible, cooling architectures that concentrate heat in a liquid medium should be prioritized. The analysis shows that recovering heat from a water loop is not only more energy-efficient operationally (leading to PUE improvements) but also carries a lower embodied carbon footprint compared to air-side recovery systems of equivalent capacity. (TBC, but that's what I am expecting from the results).

For policymakers and urban planners



Integrate data centre and energy planning

Municipal and regional planning authorities should actively work to co-locate future data centre developments with existing or planned district heating networks. Planning policy can be a powerful tool to overcome the geographical mismatch between heat sources and heat demand. Revisiting zoning policies to allow data centres to be sited closer to urban centres can reduce infrastructure costs and foster their perception as essential urban utilities.



Incentivise symbiotic partnerships

Governments should create financial and tax incentives to bolster the business case for both data centre operators and heating network providers. This could include grants for the capital expenditure on connective infrastructure, tax breaks on the energy used for heat recovery processes, or subsidies for the distribution of recovered heat, thereby de-risking the investment for all parties.



The ongoing surge in AI and high-performance computing is accelerating the industry's shift towards direct-to-chip and full immersion liquid cooling. These advanced cooling methods are significantly more efficient at heat capture than traditional air or water cooling, and critically, they do so at much higher temperatures. While air-cooled systems reject heat at 35-40°C, advanced liquid cooling systems can capture heat in a liquid loop at temperatures of 45°C, 50°C or even higher.

This trend has profound positive implications for the future of waste heat recovery



Higher-grade heat

The higher the temperature of the recovered heat, the more valuable it is. It requires less “upgrading” via heat pumps to reach the temperatures needed for district heating, significantly improving the overall coefficient of performance (COP) of the entire energy system.



Improved carbon payback

A higher-grade heat source reduces the energy consumption of the district heating provider's heat pumps, leading to greater displaced carbon emissions and further shortening the carbon payback period of the WHR investment.



New opportunities

High-temperature waste heat opens up possibilities for direct use in industrial processes or for driving absorption chillers, creating a circular cooling and heating economy within the data centre campus itself, as demonstrated by a supercomputer cluster in Germany.

As data centres evolve to handle the demands of next-generation computing, they will increasingly become concentrated sources of high-quality thermal energy. This trajectory strengthens the argument for their integration into urban energy infrastructure, positioning them not as parasitic energy consumers, but as anchor tenants in a decarbonized, circular energy economy. Future research must continue to model these evolving scenarios, ensuring that the design and regulation of tomorrow's data centres fully leverage their potential as valuable community energy assets.

The analysis is predicated on the assumption that a consistent 10MW heat demand exists for the duration of the heating season. This underscores the most significant non-technical barrier to widespread WHR adoption: the need for a reliable off-taker for the recovered heat. The high embodied carbon of WHR systems makes them an environmental and economic liability if they are underutilized.

A key challenge is the potential misalignment of load profiles. Data centre heat production is constant, 24/7, whereas residential heating demand varies significantly with season. As demonstrated by the successful project in Odense, Denmark, the solution lies in integrating data centres into large, diverse district heating networks. Such networks serve a mix of residential, commercial, and industrial users, which helps to smooth out the overall demand profile and provides the data centre with a stable baseload demand for its waste heat. Without such an integrated energy infrastructure, a data centre operator risks investing in a stranded asset that fails to deliver its promised carbon savings, turning a potential environmental benefit into a net loss.



Climate influences the carbon balance in two opposing ways

it dictates the length of the heating season (determining the potential for heat reuse) and the availability of free cooling (determining the baseline operational efficiency).

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