RAMBOLL

Developing sustainable data centres

A strategic roadmap to achieve net zero carbon and reduce environmental impact

2025

Table of contents

Lead Author
Ed Ansett, Ramboll

Ramboll contributors
Joe Sheehan
Ryan Colquhoun
Ehsan B Haghigli
Robert Cairns
James Morton
Lars Ostenfeld Riemann
Andrea Merkle
Robert Nussey
Katrine Oline Aavitsland Lund
Luke Neville
Amey Karnik
Sam Hinton
Torben Kulasingams
Jonathan Martins

Additional contributors
Claire Ansett (Xylo Systems)
Peter Gross (PMG Associates),
Andy Lawrence (Uptime Institute)
Gerard Thibault (IDCS)

How to meet surging demand for data centres

Executive summary

Data centres provide vital services to society. They improve productivity, efficiency, and connectivity between people, and drive economic growth.

Data centre computing demand is surging. Global demand for data centre power is projected to grow at approximately 16% annually from 2023 to 2028, 33% faster than from 2020 to 2023. It will reach about 130GW by 2028[1], representing approximately 3% of global electricity consumption.

The fastest growing segment of compute growth are AI workloads, accounting for approximately 60% of total growth in data centre power demand from 2023 to 2028[2].

The rapid build out of data centres will negatively impact climate and nature unless we do something about it now.

An actionable roadmap with achievable targets

This paper brings together an extensive range of sustainability-related interventions, offering actionable guidance to owners, developers, operators, and consultants. The growth trajectory of this critical infrastructure necessitates a holistic, integrated approach to decarbonisation and natural resource management that will mitigate the impact of this critical infrastructure on the climate and biodiversity. In this paper, Ramboll presents a roadmap to reduce the environmental impact of data centres and make these mission critical facilities more sustainable.

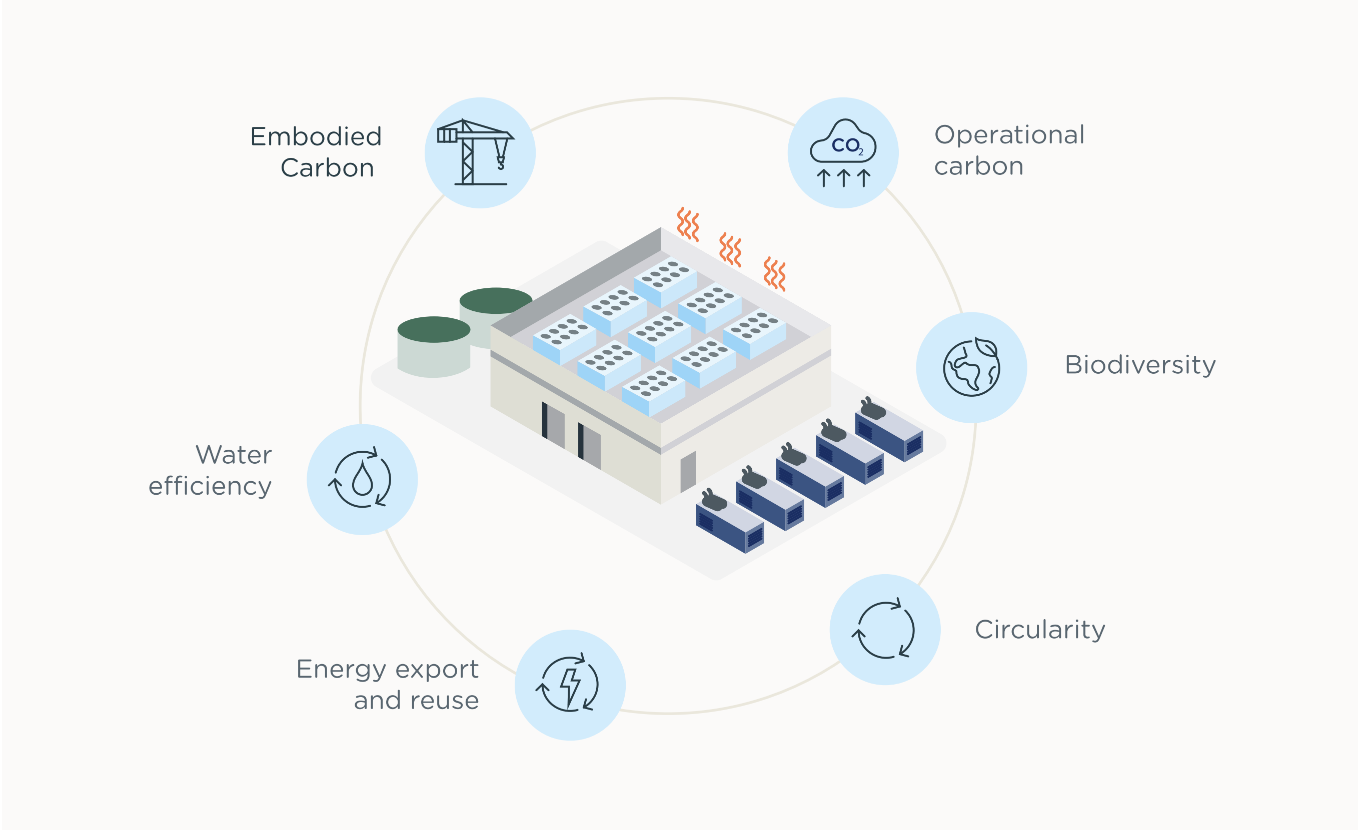
Due to the large quantities of energy consumed, operational carbon is the dominant component of total carbon in data centres. Reducing operational carbon involves improving energy efficiency, selecting power sources with low emission factors, managing IT load efficiently, and leveraging carbon offsetting. An operational carbon benchmark of net zero is achievable through optimised energy efficiency, energy reuse and export, demand response, and finally carbon offsetting.

In terms of embodied carbon, data centres are highly carbon-intensive, primarily due to the high concentration and capacity of the mechanical, engineering, and plumbing (MEP) systems. Addressing this through design and operational changes is crucial to reduce embodied carbon and achieve long-term sustainability goals. The proposed initial embodied carbon (A1-A5) benchmark of 1,500kgCO_2/m^2 is based on example data, however it should be noted that data is currently limited, and this target should be reviewed and adjusted.

The sole physical byproduct of data centre energy consumption is heat, which has historically been wasted and released to atmosphere. Data centres are in an excellent position to export what would otherwise be wasted heat energy by connection to adjacent heat off takers where infrastructure allows. Although heat export does not directly reduce the operational carbon of a data centre, it can potentially have a positive system effect by reducing heating energy demand in the area that benefits from the heat network. The suggested benchmark for heat export is as mandated by the German Energy Efficiency Act based on the EU Energy Efficiency Directive (2023/1791)[4], progressively increasing from 10% from July 2026 to 20% in July 2028 for new data centres.

Figure 1

Data centre sustainability dependencies



Data centres are uniquely positioned to provide grid support through demand response. Designing for and participating in utility demand response has the potential to increase electricity grid stability and reduce overall grid carbon emissions by reducing peak energy demand.

The construction and operation of data centres has a substantial environmental impact. It is vital to integrate biodiversity considerations in data centre design, construction and operation. Early planning, site selection, urban integration, and supply chain assessment are essential components to mitigate biodiversity impact and promote environmental sustainability. The potential effect on biodiversity, both directly at the site and indirectly in the supply chain, must also be addressed. The proposed biodiversity metric is 10% net gain[3].

Through the use of materials and resources in both construction and operation, data centres can create negative impacts on resource use and waste production. By implementing circular economy principles, data centres can minimise their environmental footprint, reduce operational costs, and enhance resource efficiency. The proposed circularity benchmark for data centres is that all materials are reused, reusable or recyclable, with zero output to landfill or incineration.

Data centres consume large quantities of water where a water-based cooling strategy is adopted. This can be of particular concern in water-stressed areas around the world. Compressor-based cooling systems use less water but more power, than water-based cooling, consequently resulting in increased operational carbon. A balance must therefore be found between water use and energy consumption based on relative environmental merits. The proposed benchmark is overall water neutrality which is generally achievable with appropriate water reduction and reuse strategies.

This paper brings together all of the factors that affect the sustainability of a data centre, proposing actions for data centre owners, developers, operators, and professional consultants to minimise carbon and environmental impact.

Introduction

The following areas are considered and explored, with a view to enabling data centre stakeholders to reduce negative impacts on climate and nature:

- Embodied carbon
- Operational carbon
- Biodiversity
- Circularity
- Energy export and reuse
- Water efficiency

Carbon

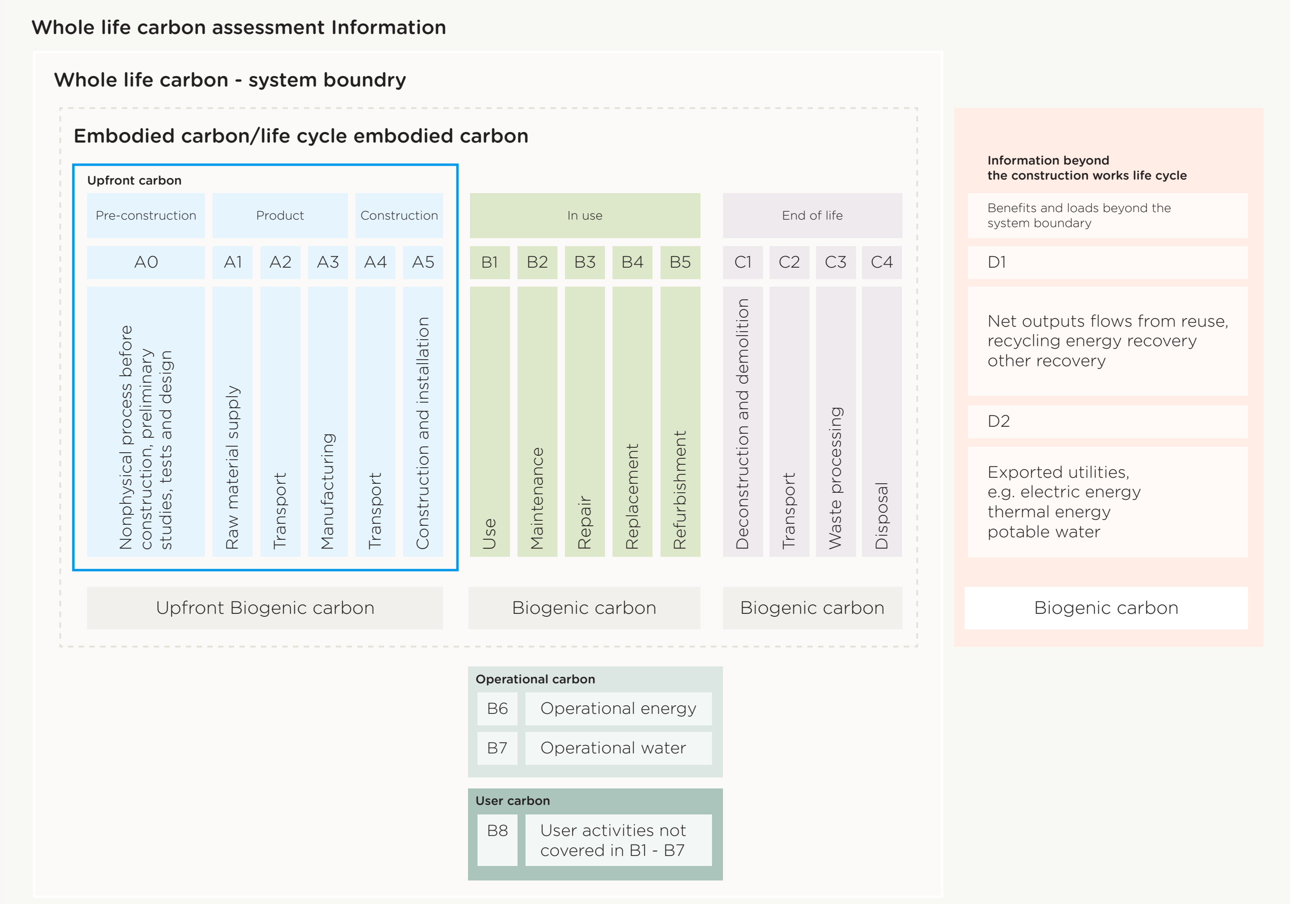
Operational carbon and embodied carbon together constitute the whole life total carbon footprint of a data centre. The quantum and ratio of operational and embodied carbon can vary significantly based on design, construction materials, energy sources, cooling techniques and efficiency measures taken.

Operational carbon includes emissions from energy consumed during the data centre's use, predominantly power to the data centre, water use, and other activities.

Embodied carbon describes material-related emissions and is divided between:

- Upfront embodied carbon - raw material extraction, production and construction activities up to practical completion of a building
- In-use embodied carbon from maintenance and repair of components and systems during the operation
- End-of-life carbon arising from decommissioning through to disposal

Figure 2
Whole carbon life cycles stages ▼



Source: RICS Professional Statement, 2nd edition, 2023

Biodiversity

Considering biodiversity impacts of data centres involves integrating conservation and ecosystem-sensitive practices into planning, design, construction, and operation. This approach aims to minimise the negative impact on ecosystems, protect existing natural habitats, and promote diversity of species within and around the data centre. By drawing design inspiration from nature's systems and structures, biomimicry can enable innovative, low-impact solutions. Equally important is supply chain biodiversity which refers to the consideration and protection of biodiversity throughout the entire lifecycle of products and services – from raw material extraction to production, distribution, and disposal – ensuring that impacts are understood, mitigated and transparently managed.

Circularity

Circularity refers to designing, constructing, operating, and deconstructing buildings in a way that minimises waste generation and resource consumption, and maximises the reuse, recycling, and recovery of materials. It is based on the principles of the circular economy, which aims to keep resources in use for as long as possible, reduce the use of virgin resources, extract the maximum value from them, and recover and regenerate materials at the end of their lifecycle.

Energy reuse and export

Energy reuse and export refer to strategies that enhance energy efficiency and reduce carbon emissions by storing and reusing energy that can be exported back to the grid or transferred to waste heat off takers. These practices reduce negative environmental impact, reduce energy costs, and can generate additional revenue for data centre operators.

Water

Water efficiency refers to strategies for minimising water consumption of data centres in their operational phase. Conserving water resources is crucial in areas facing scarcity or drought. The processes inside a data centre which have significant water consumption requirements depends on the cooling, humidification and ventilation strategies adopted.

Policy drives requirement for transparency

Governments worldwide are increasingly emphasising the need for sustainable data centres due to their significant environmental impact. These policies include stricter regulations on energy efficiency and carbon emissions and provide incentives such as tax credits and subsidies for adopting renewable energy technologies. Furthermore, they encourage circular economy initiatives to reduce waste and promote recycling. These evolving policies aim to significantly reduce the environmental footprint of data centres and promote more sustainable operations.

In Europe for example, Corporate Sustainability Reporting Directive (CSRD) regulation requires enhanced transparency and sustainability reporting. As a result, data centres must prioritise energy efficiency, use of renewable energy, and their overall environmental impact.

This directive is driving data centres to implement more sustainable practices and technologies, with an increased focus on assessing and documenting various operational aspects, such as energy usage, carbon emissions, water, and waste management.

Photo: Daniel Shearing

01

Embodied carbon

Referring to Figure 2 (see page 9), the upfront carbon stages (A1 to A5) account for all carbon up to practical completion of the building. This includes raw materials extraction and manufacture (A1 to A3) which are usually the most significant source of carbon impact, transport to site (A4) and construction related emissions (A5).

In-use stages (B1 to B5) represent the use stages of a building and accounts for fugitive emissions, mostly from refrigerant leakages (B1), maintenance (B2), repair (B3), replacement (B4) which is significant over the data centre lifespan for components that are regularly replaced – particularly MEP equipment – and refurbishment (B5).

End-of-life embodied carbon stages (C1 to C4) accounts for deconstruction of the building (C1), then disposal, recycling and management of the waste materials (C2 to C4).

Comparisons made in this section assume the sub-structure, superstructure and envelope of the data centre are included. MEP primarily describes the mechanical and electrical systems required to create a functional data centre including cooling plant, power plant and distribution. Compute, network and storage devices
are excluded.

While few embodied carbon assessments are currently available for data centres, existing data (see Figure 3) suggests that they are highly carbon intensive and have a significantly higher carbon content compared to comparably sized office and industrial buildings.

Based on a sample project assessment, Figure 4 shows the comparative dominance of MEP systems over all other building elements. This includes structure, building envelope and MEP systems.

Not only do data centres account for approximately 100% higher embodied carbon than a comparable Category A fit out office building of the same size approximately 60% of the upfront embodied carbon is derived from the MEP systems as shown in Figure 5. The percentage of emissions from MEP will be significantly higher when the whole life cycle is considered.

Figure 3

Upfront embodied carbon benchmarks ▼

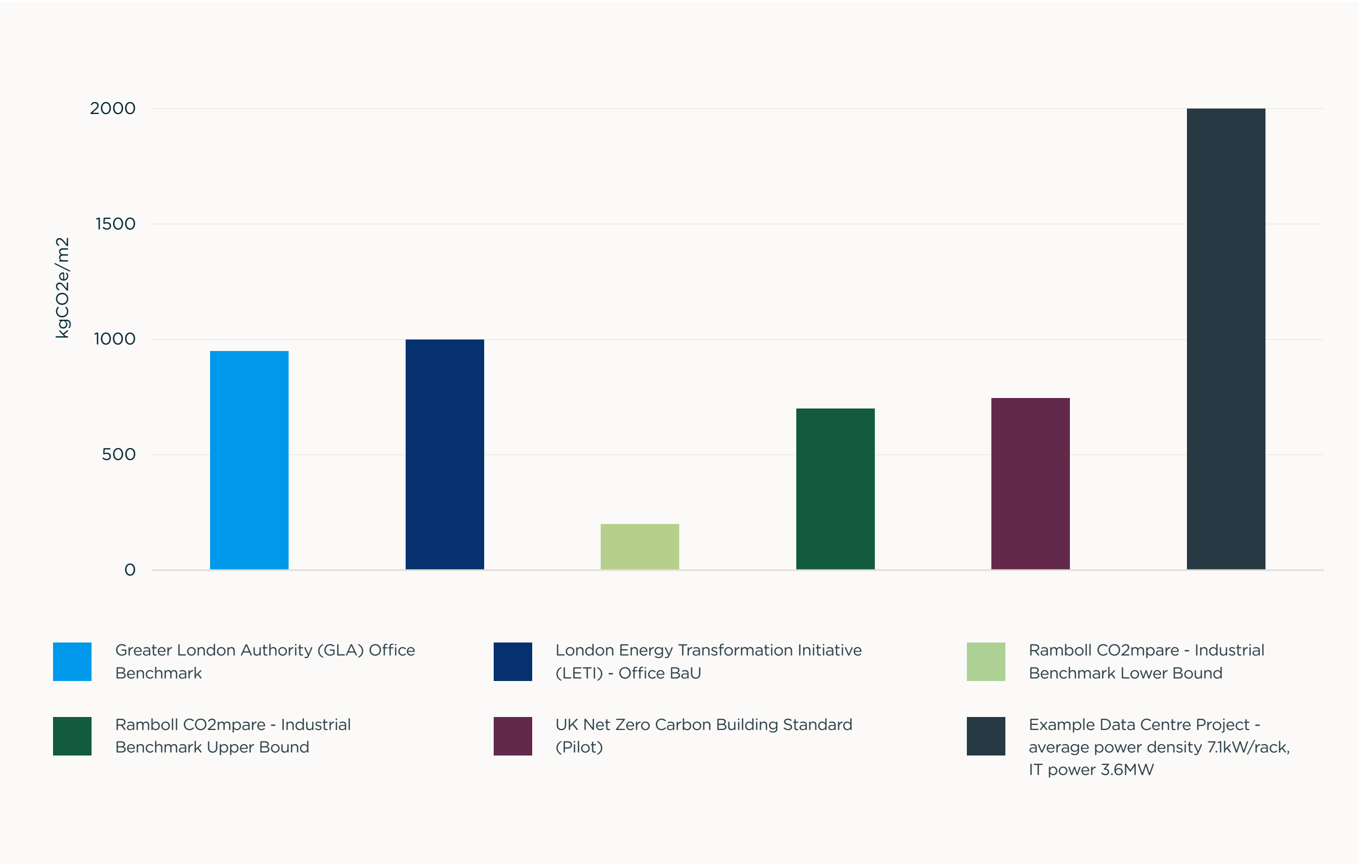


Figure 4

Whole life (A-C) embodied carbon benchmarks ▼

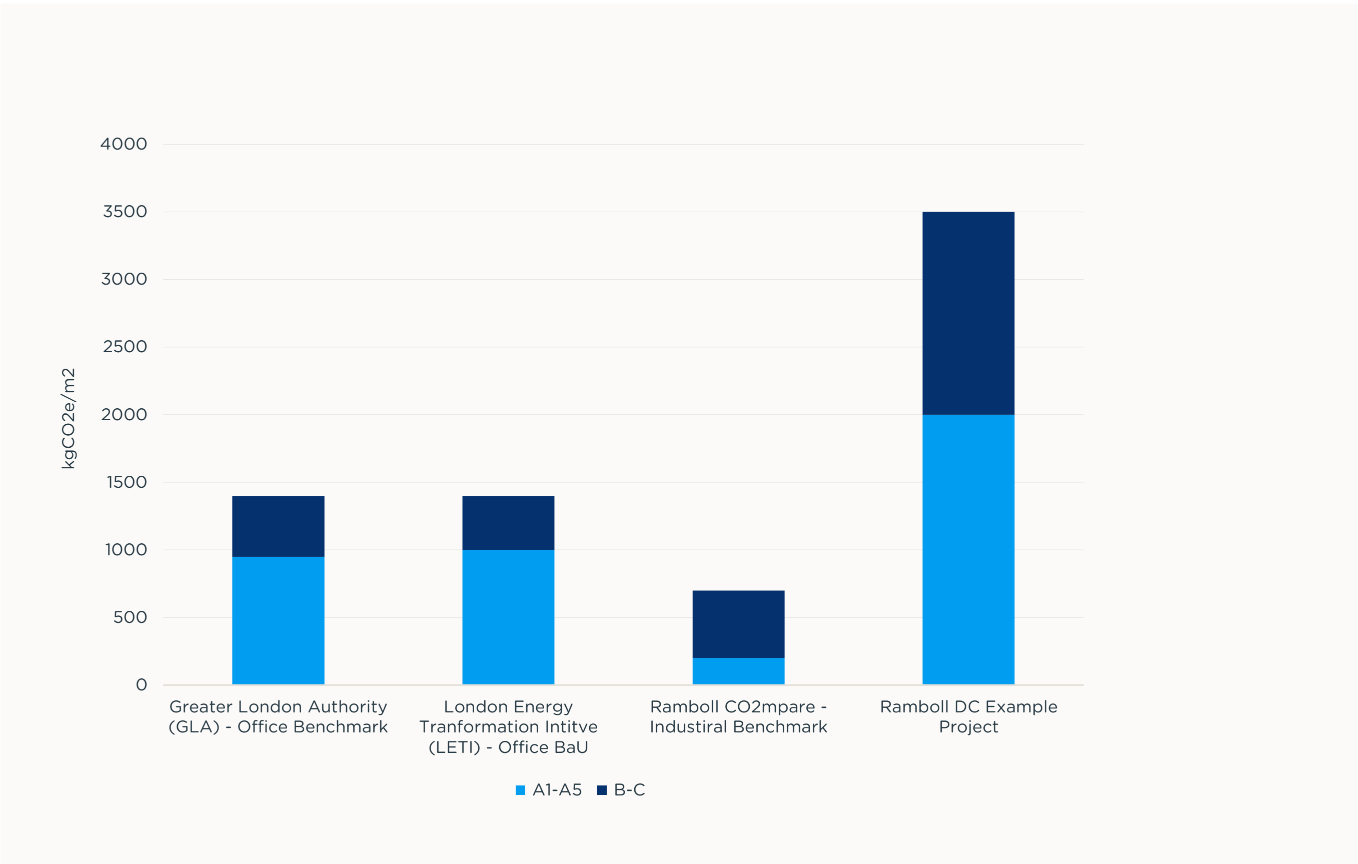
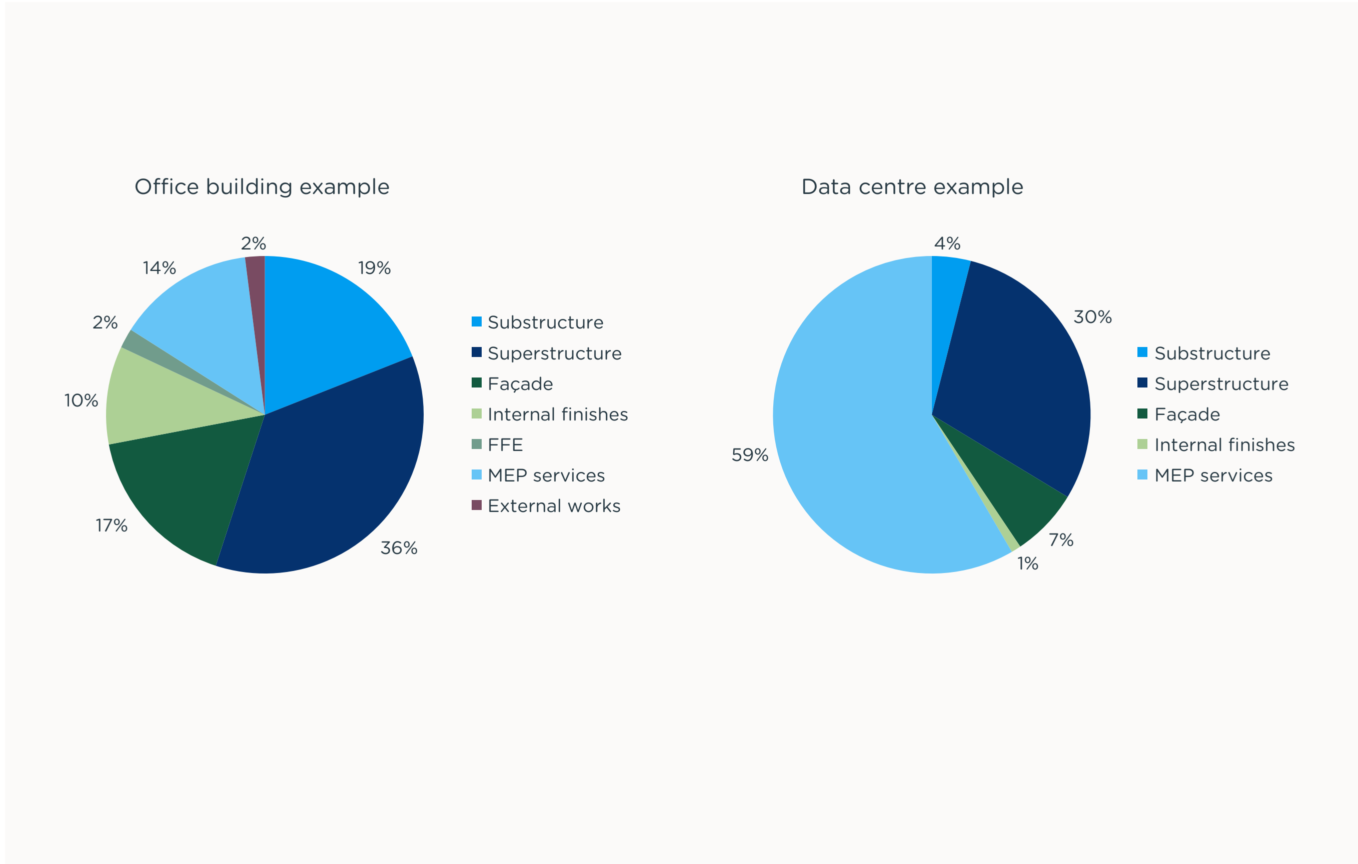


Figure 5

Whole life embodied carbon element comparison ▼



For a typical office building, concrete can account for approximately 40-60% of the embodied carbon, although this figure can vary considerably based on factors such as the building's structure (e.g. reinforced concrete frame c.f. steel frame), the amount of concrete used, and the specific mix of concrete. Whereas steel may account for approximately 20-30% of the total embodied carbon. Again, this figure can vary based on the type of structural system, the quantity of steel used, and the specific types of steel products employed.

Consequently, companies such as Google, Meta, Amazon, and Microsoft have joined the Sustainable Steel Buyers Platform, organised by the non-profit organisation RMI to encourage companies to facilitate low-emission steel procurement. These companies have also implemented or announced initiatives involving low carbon concrete.

Mass timber is also gaining popularity as a construction material in data centres in place of traditional materials like steel and concrete. Engineered timber products have high strength, making them appropriate for structural uses while having a significantly lower carbon factor than steel and concrete. This means that they can be suitable replacements for traditional structural materials and reduce embodied carbon.

Key factors affecting levels of embodied carbon

- MEP systems are the building element that accounts for the highest carbon intensity in data centres, with high numbers of carbon intensive plant units, particularly power and cooling equipment.
- MEP equipment service lives of 15-30 years mean multiple replacements over a 50 or 60 year building service life typically used in building LCAs. This means replacing the most carbon intensive components of the building multiple times, compared to the structure which would not normally be replaced.
- Refrigerant leakage (B1) could be highly significant due to the quantity of cooling units that may be required, especially if higher GWP refrigerants are used. Conversely where low GWP refrigerant can be used, a significant source of emissions can be avoided almost entirely.
- Structure can be carbon intensive in multistorey data centres due to the weight of the IT equipment. Floor slabs are almost always the highest carbon intensity components in structures. Additional floor systems like raised access floors can also add significant emissions.
- In terms of upfront carbon, the UK Net Zero Carbon Building Standard has a (A1-A5) limit of 745kgCO_2e/m^2 in 2025 for data centres, which seems unrealistic based on available examples.
- The embodied carbon of a typical greenfield data centre may be 2 to 3 times higher than a typical office, or as much as 5 times higher than a simple industrial building excluding machinery.

How to reduce embodied carbon in data centres

Mechanical, electical, civil, structural, and architectural measures to reduce embodied carbon include:

- Use of reduced carbon components such as low carbon concrete, steel, and mass timber
- Improving structural efficiency to reduce the amount of material required
- Prefabricated components to minimise waste
- Excluding raised floor designs
- Optimise operation and maintenance planning to extend service life and replacement
- Locally made materials to reduce transportation emissions
- Construction practices powered by renewable energy to reduce carbon emissions during the building phase
- Employ 3D printing technologies for construction to reduce waste and optimise material use
- Obtain LEED and BREEAM certification
- Reuse materials from decommissioned buildings or other sources
- Employ construction practices that minimise waste generation
- Prioritise durable materials with long lifespans
- Materials like natural stone, high-quality concrete, or treated timber extend service intervals and reduce replacement emissions
- Use materials with proven resistance to degradation
- Choose corrosion-resistant metals (e.g. galvanised steel), UV-stable plastics, or moisture-tolerant' finishes
- Design for maintainability
- Enable easy repair rather than full material replacement
- Avoid short-lived materials in high-wear areas
- Minimise use of soft flooring or low-durability paints where frequent replacements increase GWP.
- Consideration should be given to using BESS to replace the uninterruptible power supply (UPS) and emergency generators
- Deployment of low and medium voltage superconductors to reduce copper use
- End users may consider removing altogether or reducing use of on-site emergency power plant and rely instead on application failover between data centres
- Minimising in-use (B1 to B5) and end-of-life (C1 to C4) carbon – including the requirement for material (circularity) passports – paying particular attention to end-of-life material reuse and recycling

02

Operational carbon

Operational carbon encompasses the greenhouse gas emissions produced during the operational phase of the data centre. Based on the Whole Life Carbon framework, operational carbon is divided into three categories:

- B6: Energy use by the data centre throughout its operational life
- B7: Emissions associated with water use i.e. the energy used for water supply and treatment
- B8: Treatment of operational waste generated during the data centre's use.

The electricity demand from data centres is projected to experience significant growth, currently driven primarily by the rise of AI digital technologies. The International Energy Agency (IEA) expects global electricity consumption for data centres to double by 2030, reaching around 945 TWh, and forecasts a 15% annual growth rate in data centre electricity consumption from 2024 to 2030[5].

Grid emission factor

The grid emission factor (GEF) quantifies the amount of carbon dioxide equivalent (CO_2e) emissions produced per unit of electricity consumed from the power grid. It provides a measure of the greenhouse gas (GHG) emissions associated with the generation of electricity supplied by a national or regional grid, expressed in kilograms (kg) of CO_2e per kilowatt-hour (kWh) of electricity consumed.

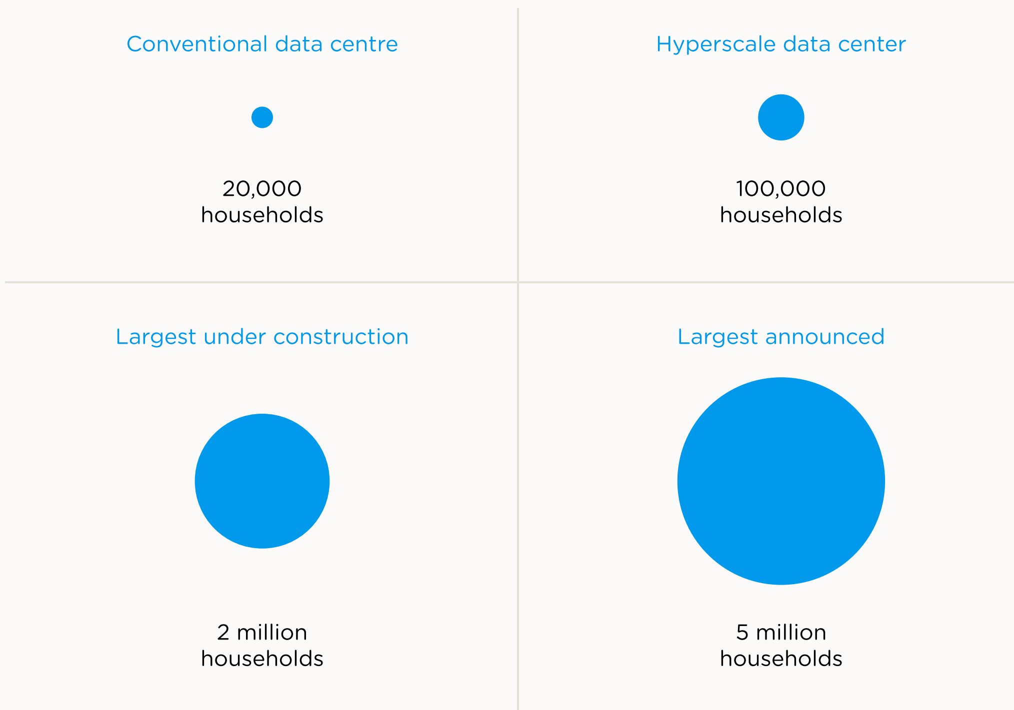
It is the generation fuel mix of the grid that predominantly determines its GEF. Grids with a high percentile fossil fuel in their fuel mix are inherently disadvantaged in terms of their sustainability since they have the highest operational carbon, see Figure 7.

Countries with a high GEF face the most significant challenges in terms of carbon intensity. Figures 8,9, 10 and 11 illustrate the current GEFs across example countries in Europe, the Americas, Asia Pacific and the Middle East.

Each country has its own challenges, arising from the generation fuel mix which in turn is a key factor in its approach to decarbonisation[6,7] Those countries with the highest GEFs face the most significant challenges in terms of carbon reduction.

Figure 6

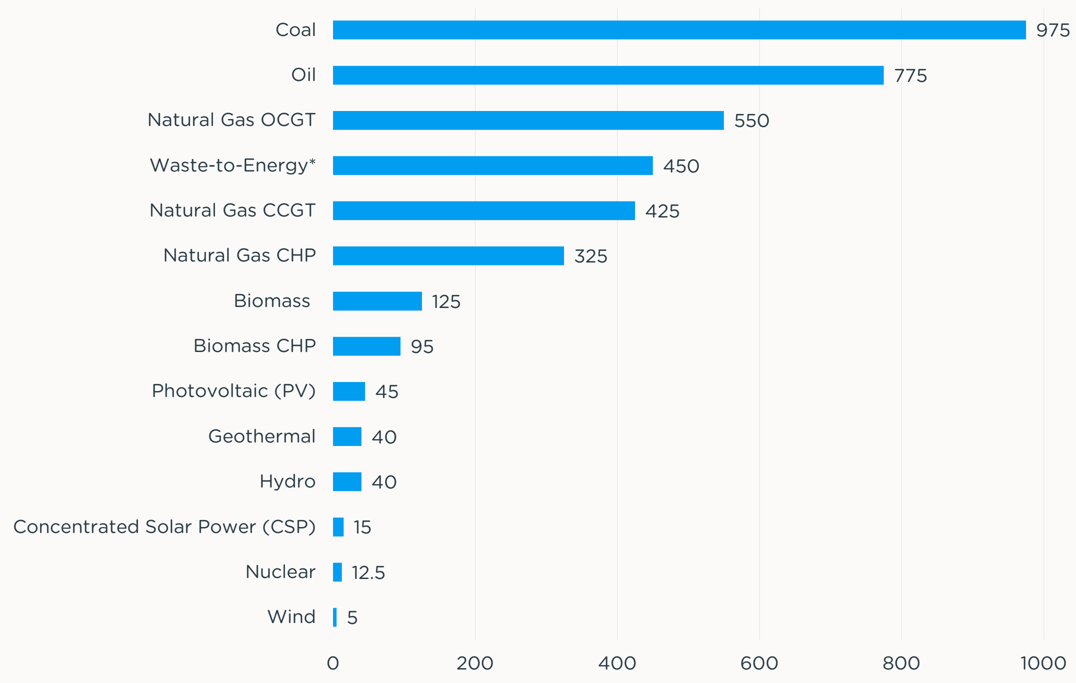
Data centre electricity consumption in household equivalents ▾



Source: IEA

Figure 7

Generation source average emissions (gCO_2e /kWh) ▾



Source: IEA

Notes on fuel types

Fossil Fuels
- Coal - high emissions due to the carbon intensity of coal
- Oil - high emissions generally used for peaking power
- Natural Gas - lower emissions compared to coal and oil but still significant

Wind – low emissions, primarily from manufacturing, transportation, and installation

Solar – low operational emissions, with most emissions from manufacturing and installation

Hydro – low emissions, primarily from construction of dams and reservoirs

Geothermal – low emissions, primarily from drilling and operation of wells

Nuclear – low emissions, with some from mining, fuel processing, and waste management

Biomass - can be carbon-neutral if sustainably sourced, but emissions vary based on feedstocks and combustion efficiency

Waste-to-Energy Plants – emissions depend on the type of waste, technologies used for combustion and pollution control

Figure 8

Grid emission factors for Europe (kgCO_2e/kWh)

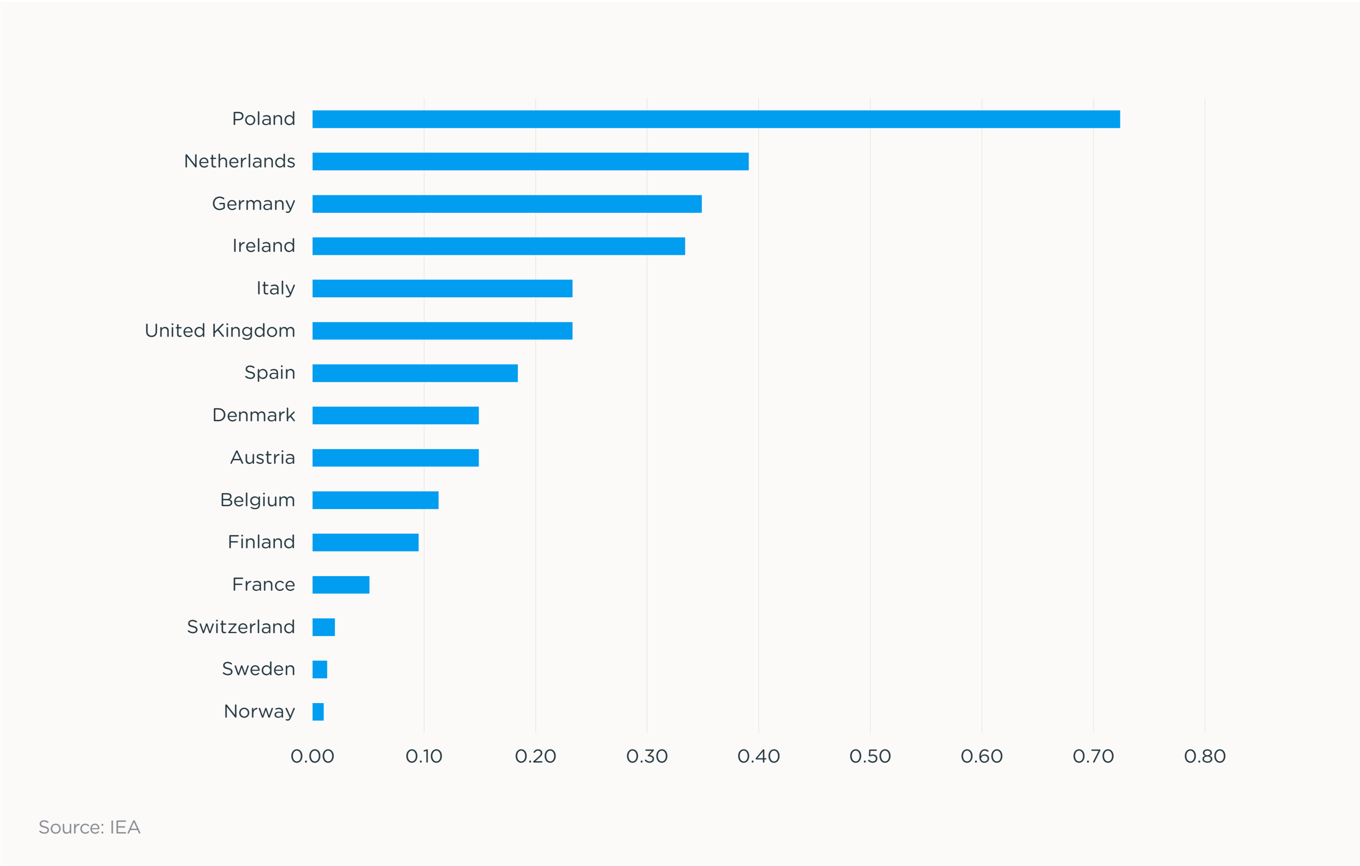


Figure 9

Grid emission factors for the Americas (kgCO_2e/kWh)

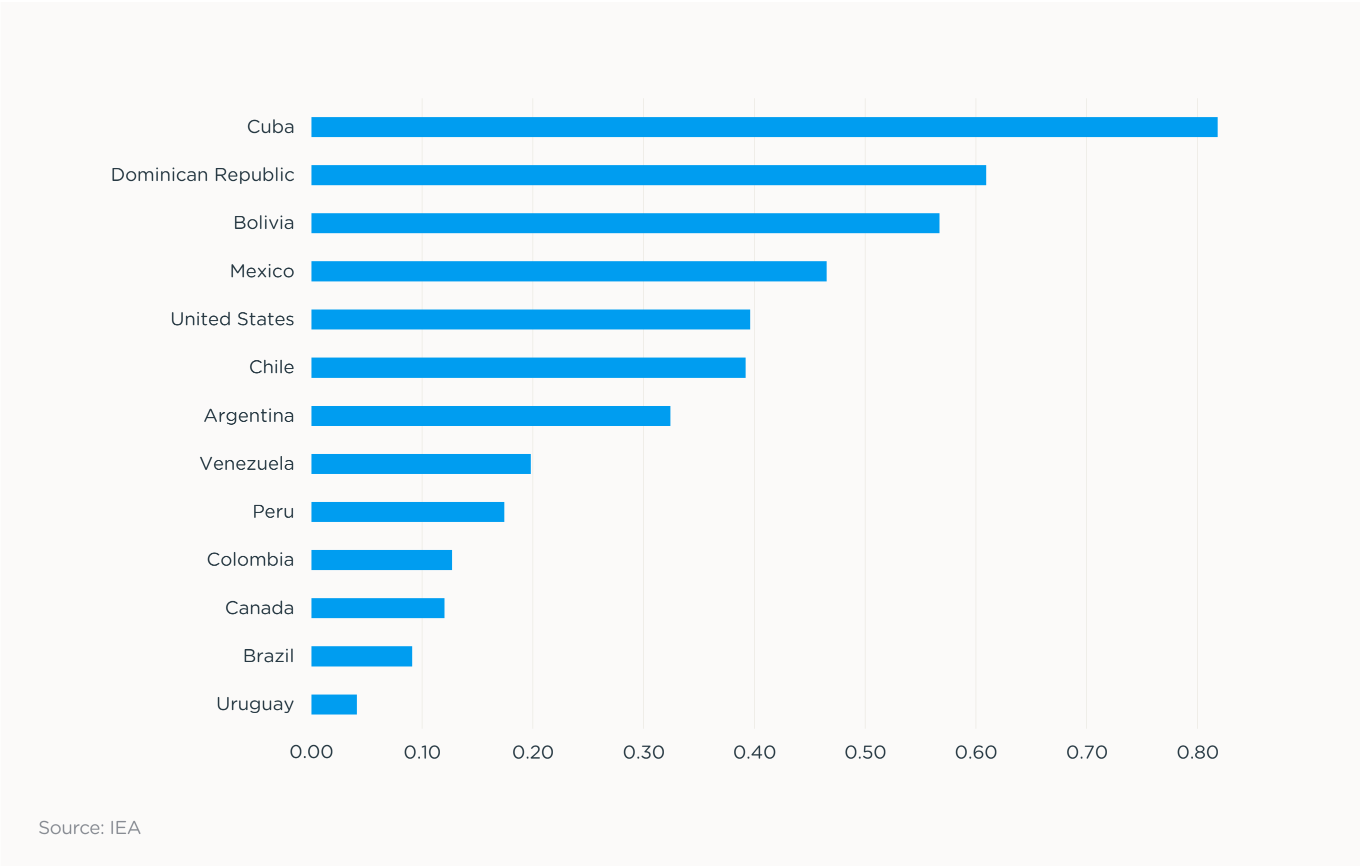


Figure 10

Grid emission factors for Asia Pacific (kgCO_2e/kWh)

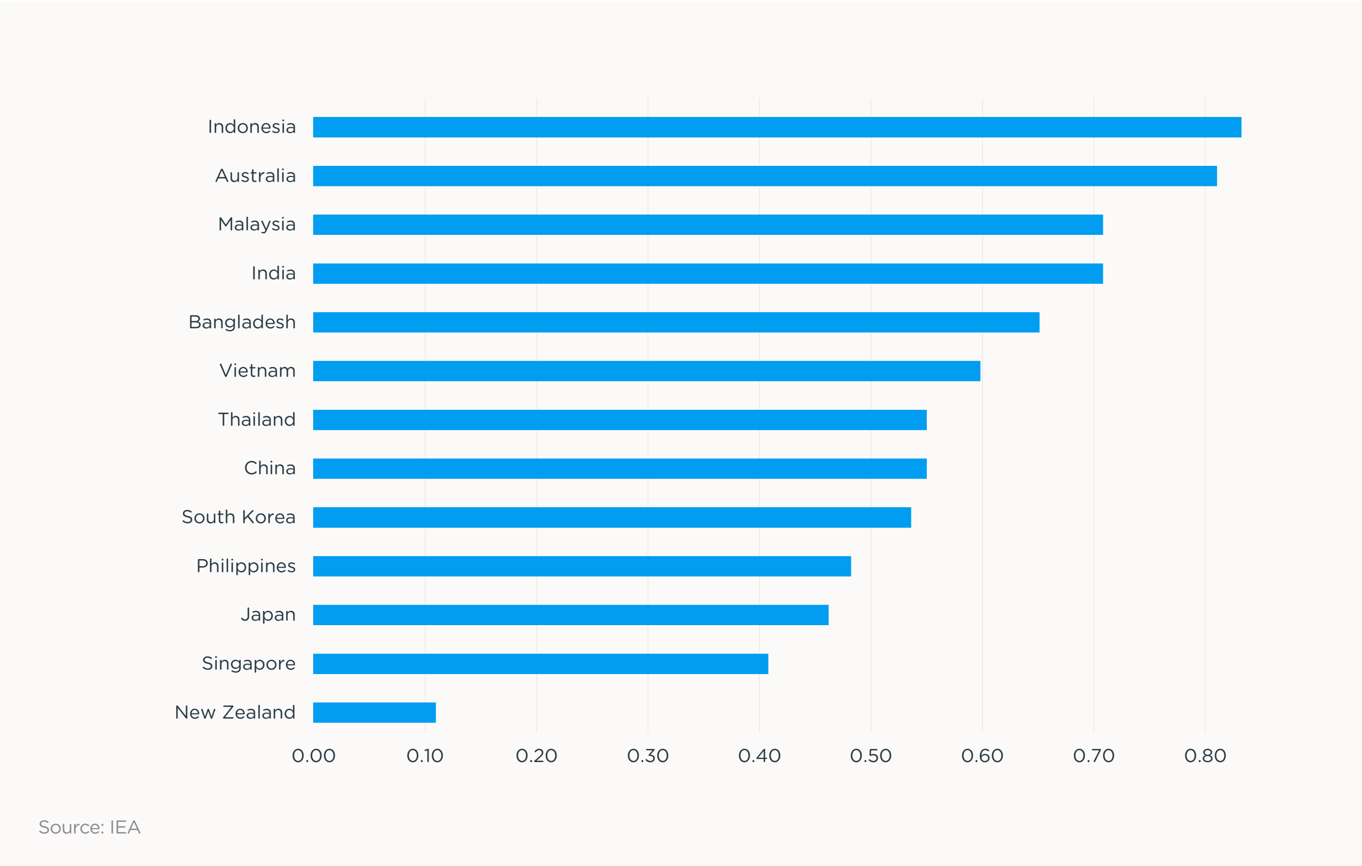
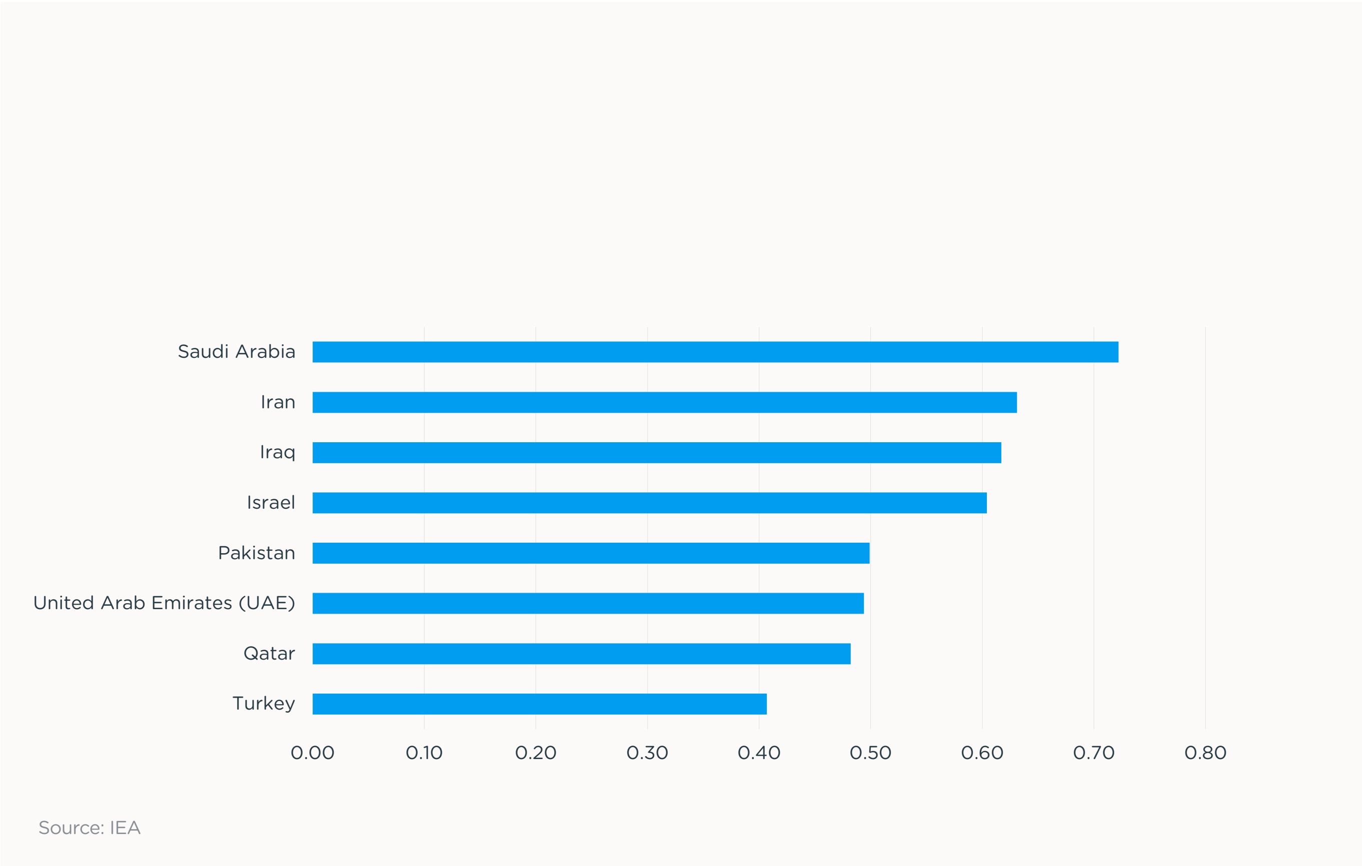


Figure 11

Grid emission factors for the Middle East (kgCO_2e/kWh)



Time of day grid emission factors

In some countries the GEF can vary significantly depending on the mix of renewable sources like solar and wind impacting generation levels throughout the day, meaning emissions are typically lower during daylight hours when solar power is high, and can fluctuate based on the country's specific energy mix.

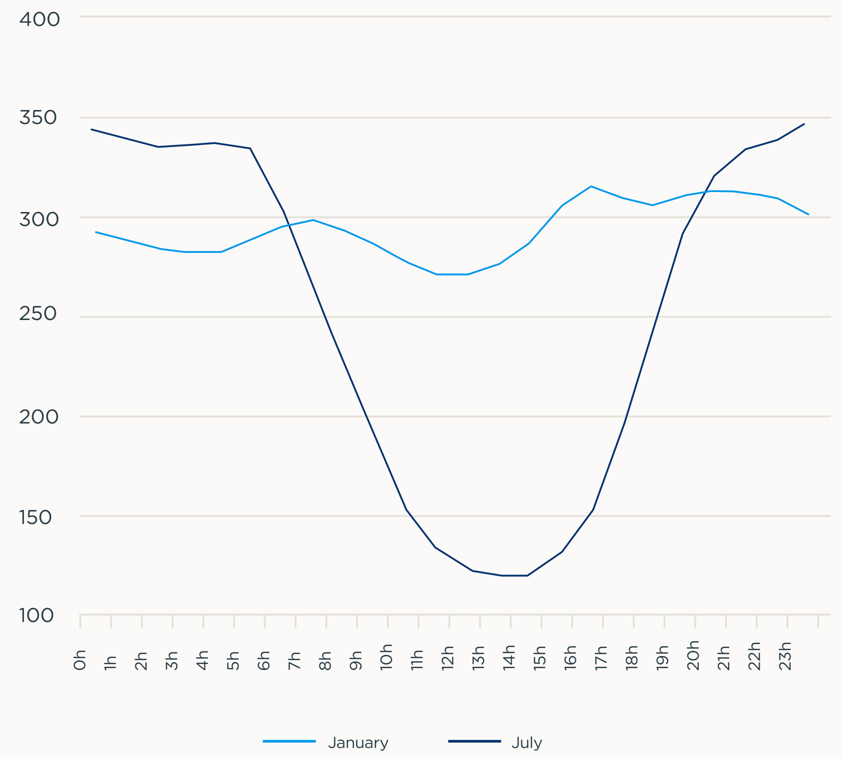
For example, Germany has substantial time of day GEF variations as indicated in Figure 12. Many countries have relatively low daily GEF variations, whilst others – particularly those in temperate climates – are subject to seasonal variations.

For some types of data centres, it is possible for end users to take account of time varying emission factors and seasonal variations. IT loads can then be migrated to geographic locations where the GEF is lower to reduce operational carbon emissions.

However, co-location and retail data centres have no influence on end user customer energy use and therefore do not have the ability to mitigate operational carbon through IT load migration

Figure 12

Average hourly CO_2e intensity of electricity generation in Germany, January – July 2024



Source: IEA

Off-grid generation and microgrids

Off-grid generation, where the data centredraws power from its own dedicated power source or as part of a microgrid, is growing. In such cases the data centre is unaffected by the GEF and has the following benefits:

- Enhanced energy security and reliability
- Utilising renewable energy sources reduces carbon emissions
- Using carbon capture, utilisation, and storage (CCUS) can significantly reduce CO_2e emissions.
- Lower operational costs by reducing dependency on costly fluctuating grid electricity prices

The benefits of data centres operating as part of a microgrid include:

- A reliable alternative power supply
- Integrating with renewable energy sources and advanced energy management systems reduces operational carbon and operating cost
- Scalability providing greater flexibility
- Contributes to grid stability by providing demand response
- Transmission and distribution efficiency losses are practically eliminated.

Fuel cells

The most common types of commercial fuel cells used for data centres are the proton exchange membrane fuel cell (PEMFC) and the solid oxide fuel cell (SOFC).

Where fuel cells provide the primary power supply to the data centre, the electrical utility grid acts as a back-up. As such, fuel cells could feasibly replace both the emergency generators and UPS in the data centre.

Hydrogen fuel cells generate electricity and emit only water and heat as byproducts, thereby producing zero operational carbon emissions. When hydrogen is produced from renewable sources such as wind or solar it can reduce the carbon footprint of the data centre. The modular nature of fuel cells allows for scalable solutions tailored to the specific energy needs of data centres, ensuring a flexible and robust power supply.

The operational carbon footprint of a green hydrogen fuel cell is typically near-zero, assuming the hydrogen is wholly produced using energy from curtailed renewable energy sources. The primary emissions in the lifecycle occur during hydrogen production (if not sourced from renewables) and transportation rather than during the fuel cell operation.

Solid oxide fuel cells are typically powered using natural gas to produce minimal NO_x and SO_x emissions improving air quality and decreasing environmental impact. The operational carbon footprint of a natural gas-powered SOFC is considerably lower than traditional combustion-based power generation systems, but it still involves significant carbon emissions due to the carbon content of the natural gas fuel. The efficiency of the SOFC helps reduce the carbon footprint per unit of energy produced, but it does not eliminate it entirely unless it is used in conjunction with carbon capture.

A further benefit of all types of fuel cells is the significant reduction of noise emissions.

Gas generators

Natural gas generators are increasingly used as a primary source of power for data centres. Widespread availability and established infrastructure make natural gas accessible for off-grid applications. Compared to other fossil fuels, natural gas combustion results in lower emissions of pollutants such as SO_x, NO_x and particulate matter.

Although cleaner than other fossil fuels, natural gas produces significant carbon emissions. At scale, these can be used in conjunction with carbon capture, utilisation, and storage (CCUS) which typically captures around 90% of the carbon emissions from the generators.

Alternative sustainable fuel sources for primary power gas generation include biomethane, green hydrogen, yellow hydrogen (made through electrolysis using solar power), syngas, renewable natural gas (biomethane), ethanol, and methanol.

On-site gas generation for data centres poses several challenges, primarily due to GHG emissions and pollutants. It also involves high costs related to fuel, maintenance, significant space for infrastructure, potential reliability issues, safety and efficiency concerns. Navigating regulatory complexities can be demanding, requiring strict compliance and permitting.

SMRs

Small modular reactors (SMRs) are nuclear reactors that are designed to be smaller and more flexible than traditional large-scale reactors. With typical capacities ranging from 10MW to 300MW, SMRs are being considered for data centre off grid generation due to delays in obtaining grid power and increased reliability of electricity supply.

SMRs have a low carbon emission factor and have no direct emissions during operation. Lifecycle emissions of 10-20gCO_2e/kWh are associated with construction, fuel production, and decommissioning.

Contemporary reactors have improved load following characteristics and provide a continuous and reliable power supply. Modern SMR designs also incorporate advanced safety features and passive cooling systems that can enhance the safety profile compared to traditional large reactors.

SMRs do however come with significant challenges related to their high cost including having to pay 100% of the operational fuel cost upfront. Other issues include prolonged regulatory permitting, cost and space associated with shielding, waste management, and ongoing public concern related to safety of operations, which are exacerbated if the data centre requires redundant power by duplicating SMRs.

Carbon offsetting

Carbon offsetting is an additional tool for organisations that wish to offset the impact of residual emissions after applying the energy and carbon reduction measures addressed in the earlier sections.

The most common approaches to offsetting have involved nature-based solutions like reforestation, forest conservation (afforestation), peatland restoration or investment in blue carbon projects such as wetland restoration. There is however a growing focus on investment in projects focused on renewable energy generation, direct air capture technologies, methane capture and destruction, and more sustainable fuels production such as sustainable aviation fuel.

By selecting projects which have material relevance to their operations and activities, data centre operators can contribute more widely to their social and environmental commitments. Their projects can be used to promote the development of renewable energy projects or deliver social impact for communities through projects which also bring energy infrastructure resilience. Reforestation projects also enhance biodiversity, improve air and water quality, and support local communities by creating jobs and fostering sustainable development.

It is important to note that carbon offsetting does not reduce carbon emissions associated with a data centre's operations and isn't reflected in carbon emissions reporting as a reduction. It does however play a part in achieving net zero goals, neutralising residual emissions as part of an overall net zero strategy.

In all cases, it is important that carbon offsetting is validated by reputable bodies such as the Verified Carbon Standard, the Gold Standard established by WWF, the Clean Development Mechanism managed by the United Nations, Climate Action Reserve, or the American Carbon Registry.

Power purchase agreements

Power purchase agreements (PPAs) are contracts between electricity generators and purchasers, typically electricity consumers or utility companies, that stipulate the terms under which electricity will be generated and sold. They have become a vital tool in the development and financing of renewable energy projects. PPAs offer numerous benefits, but they also come with potential limitations that must be carefully considered.

One of the major advantages of PPAs is their ability to provide long-term price stability for electricity consumers. By locking in a fixed rate for electricity over the duration of the agreement – typically 10 to 25 years – consumers can protect themselves from the volatility of energy markets and anticipated rises in electricity prices. This is particularly advantageous for large energy consumers such as data centres which benefit from predictable energy costs.

PPAs also play a crucial role in facilitating the development of renewable energy projects. For project developers, having a long-term contract with a reliable off taker assures them of a steady income, which makes it easier to attract investors. Consequently, PPAs enable the construction of more renewable energy.

Two disadvantages of PPAs are their complexity and the long-term commitment required from both parties. Since PPAs typically span decades, electricity consumers may be bound to terms that could become less favourable over time due to changing market conditions or advancements in technology.

Some PPAs can be risky financial contracts, whereby the contract places the financial burden on the consumer if the electricity price falls. Most customers tend to buy more power than they need, to ensure all the carbon is offset when grid emission factors are high. If the price falls, they must pay the supplier the price difference and will be required to continue to buy at a higher price.

Collecting and reporting data using PPAs involves integrating information from various sources, ensuring measurement accuracy, adapting to changing regulatory requirements, and managing technological and infrastructure limitations. Additionally, there are concerns about data security and the complexities of financial reporting, which requires coordination among multiple stakeholders. Real-time monitoring and verification add to the challenges, especially in remote power generation locations.

Power and cooling efficiency

Most legacy data centres utilise conditioned air to cool IT equipment which has lower heat transfer efficiency compared to liquid cooling. Whilst liquid cooling, or at least hybrid liquid-air cooling, has now become the norm for AI workloads, addressing inefficiencies in both new and legacy air-cooled systems remains important.

The main metric used to measure data centre power and cooling efficiency is power usage effectiveness (PUE) which is defined as the ratio of total energy used by the data centre relative to the total energy used by the IT equipment.

For air cooled systems, the key features that improve PUE include:

- Effective airflow management strategies, such as hot aisle and cold aisle containment and blanking plates within racks, to prevent the mixing of hot and cold air, allowing the system to operate at the highest possible temperature, thereby enhancing cooling efficiency
- Rear door heat exchangers
- Airside or water-side economisers to take advantage of favourable outdoor conditions to provide free cooling, reducing reliance on mechanical cooling systems
- Variable-speed drives on cooling fans, pumps, and chillers to adjust their speed based on actual cooling demand
- Increasing server inlet temperatures to reduce cooling requirements without compromising the performance, reliability or energy consumption of the IT equipment

The key to improving PUE is to increase operational temperatures to allow the reduction or complete removal of mechanical refrigeration systems. Liquid cooling systems allow this as they can currently operate at much higher temperatures than air cooled systems. It should be noted that this may not always be the case particularly with increasing IT load densities as this tends to supress the required water temperatures for liquid cooled installations.

Other measures that improve PUE include:

- Liquid cooling, such as direct-to-chip liquid and immersion cooling
- Modular UPS systems that scale with IT load and offline UPS allowing operation at the highest efficiency
- Using offline eco-mode UPS systems
- Optimised airflow management
- Direct current power distribution to eliminate energy losses associated with converting alternating current
- Reducing the number of components in the design to minimise system losses
- MEP systems design optimisation for loss reduction

From an IT perspective the following practices will reduce operational energy use:

- Maximised virtualisation to consolidate workloads
- High efficiency IT hardware
- Invoking sleep states
- Load migration to low GEF locations

How to reduce operational carbon

- The location where data centres are built plays a crucial role in driving down operational carbon. It's evident that strategic placement of data centres in locations optimised for renewable energy access, favourable climates, and low GEF is essential for minimising operational carbon emissions.
- Reducing operational carbon in data centres primarily involves improving energy efficiency and obtaining power from renewable energy sources.
- The most challenging issues exist in areas where the data centre primary source of power has a high GEF.
- Power purchase agreements that source power directly from renewable energy providers do not immediately improve the grid GEF, however such contracts drive increased renewable energy sources onto the grid and aide decarbonisation.
- Off grid data centres are gaining traction using, dedicated renewables, fuel cells and SMRs.
- Natural gas generation is a good option in areas with a relatively high GEF particularly if blended with green hydrogen.
- For data centre end users that can control the IT load additional options include reducing energy consumption through efficient switched mode power supplies and dc-dc converters, server consolidation, implementing CPU sleep states and time-of-day load shifting (shedding) to low GEF geographies.

Operational carbon metrics

Operational carbon associated with electricity use is calculated as:
CO2e emissions (kg CO2e) = Direct data centre energy consumption (kWh) × GEF (kg CO2e/kWh)

Operational carbon associated with water use is calculated as:
CO2e emissions (kg CO2e) = Carbon use from water supply and treatment

03

Biodiversity

Biodiversity is the variety and variability of life on Earth, including diversity within species, between species, and of ecosystems[8], and it is becoming an increasingly critical concern for businesses worldwide, including data centres. As the industry expands rapidly, biodiversity is emerging not only as an environmental concern but also recognised as a material risk[9].

This section explores biodiversity considerations in the construction and operation of data centres, focusing on:

- Site selection
- Urban integration and mitigation measures
- Embodied ecological impact (EEI)
- Measuring biodiversity

While energy consumption, carbon emissions, and reliance on non-renewable backup power are widely recognised environmental impacts for data centres, biodiversity is often overlooked and misunderstood despite its critical role in ecosystem health and climate resilience.

Data centres can contribute to biodiversity loss through direct and indirect pathways, including land use change, habitat fragmentation, resource extraction, and pollution. Poorly planned landscaping may also introduce invasive species, further disrupting local ecosystems.

However, biodiversity is not only impacted by data centre development, itis also essential to their long-term sustainability. Diverse ecosystems provide critical services such as ambient air cooling, water regulation, erosion control, and soil health, which support the operational resilience of data centres.

Protecting and restoring natural habitats during data centre development not only prevents ecological degradation but also enhances local ecosystem services, supports regulatory compliance, and contributes to broader sustainability goals.

Photo: Kouji Tsuru

Site selection

According to Synergy Research Group, global data centre capacity is doubling every four years, with 120-130 new hyperscale facilities expected to come online annually[10]. As this rapid expansion continues, site selection emerges as a critical point of intervention for biodiversity protection.

However, data centre site selection is often constrained by practical factors such as proximity to power infrastructure, fibre connectivity, water availability, and urban demand centres. These constraints frequently push developments into ecologically sensitive or space-limited areas where the risk of biodiversity loss is heightened.

Once operational, data centres often require bulk diesel storage to support backup generators, which can further impact local ecosystems through land use, pollution risk, and increased infrastructure. As power demands grow, so too does the need for larger or additional fuel storage, reinforcing the importance of strategic site planning that takes account of both operational resilience and environmental sensitivity.

To minimise these impacts, developers should avoid high-value ecological areas wherever possible. This includes:

- Conducting early-stage ecological surveys to identify protected species, habitats, and ecological corridors
- Engaging landscape architects and ecologists early in the design process to influence site layout and mitigation strategies
- Considering brownfield or previously developed land with low biodiversity value to reduce the need for habitat clearance.

Urban integration

Data centres are increasingly constructed in or near urban areas, where land availability, proximity to infrastructure and access to end-users are key drivers. However, these urban settings present unique biodiversity and environmental challenges, particularly due to limited space, reduced vegetation, and intensified heat emissions.

One of the most pressing issues in these environments is the urban heat island (UHI) effect, where built-up areas experience elevated temperatures due to heat-absorbing surfaces and a lack of vegetation. For data centres, this results in higher cooling demands, energy consumption, and operational costs. While conventional buildings can reduce heat emission through envelope design, data centres primarily eject heat through external cooling systems. Data centres in the UK typically eject 20MW-100MW of heat directly to atmosphere at full load, further intensifying local UHI effects.

To address these challenges, early-stage planning should integrate nature-based solutions[11] that both mitigate UHI and support biodiversity. These include:

- Green roofs and living walls to provide insulation, reduce heat absorption, and support pollinators
- Strategic planting of native trees and vegetation to provide natural cooling through shade and transpiration
- Stormwater management through healthy soil systems and permeable landscaping, reducing runoff and erosion
- Use of vegetation types suited to local climate and soil conditions, ensuring resilience and ecological value

Data centres are increasingly constructed in or near urban areas, where land availability, proximity to infrastructure and access to end-users are key drivers.

Embodied ecological impact (EEI)

Embodied ecological impact (EEI)[12] refers to the impact on biodiversity and ecosystems embedded within the entire lifecycle of materials, equipment, and services. EEI is similar to that of embodied carbon, but instead of focusing on greenhouse gas emissions, it considers the biodiversity loss and ecological degradation associated with supply chains.

To fully understand a data centre's biodiversity footprint, it is essential to assess the biodiversity impacts embedded in its supply chain from raw material extraction and manufacturing to transportation and disposal. This includes:

- Mining and extraction of rare earth elements and metals used in IT and MEP systems, which often occur in biodiversity hotspots
- Land use change and habitat disruption linked to upstream suppliers
- Water use, pollution, and waste generated during component manufacturing

Data centre developers and operators will need to place more emphasis on understanding their nature depedencies and risks, and could face increasing requirements for transparency across their supply chain, including:

- Sustainability reporting that includes biodiversity metrics
- Supplier engagement to promote biodiversity-conscious sourcing
- Lifecycle assessments that incorporate ecological as well as carbon impacts

Measuring biodiversity

As biodiversity becomes a core component of environmental accountability, measuring it effectively is essential for data centre developers aiming to align with emerging global frameworks such as the Global Biodiversity Framework[13] or voluntary initiatives such as the Taskforce on Nature-related Financial Disclosures (TNFD)[14] and Science-Based Targets for Nature (SBTN)[15].

Traditional biodiversity assessments often focus on species inventories, the number and prevalence of species at a given site usually requiring extensive field surveys. While this remains important, modern frameworks emphasise a more holistic view of biodiversity, including:

- Ecosystem condition and function
- Species richness and abundance
- Ecological integrity and connectivity
- Dependencies and impacts across the value chain.

Developers in England are required to demonstrate a minimum 10% net improvement in biodiversity value post-development. This is typically measured using a statutory metric that considers habitat condition, distinctiveness, and area to provide a biodiversity unit value at a baseline and then at post-development, considering the net change. Similarly, Ramboll's Global Biodiversity Metric and Americas Biodiversity Metric[16] apply a similar approach and mitigation hierarchy principles to evaluate the extent and condition of ecosystems.

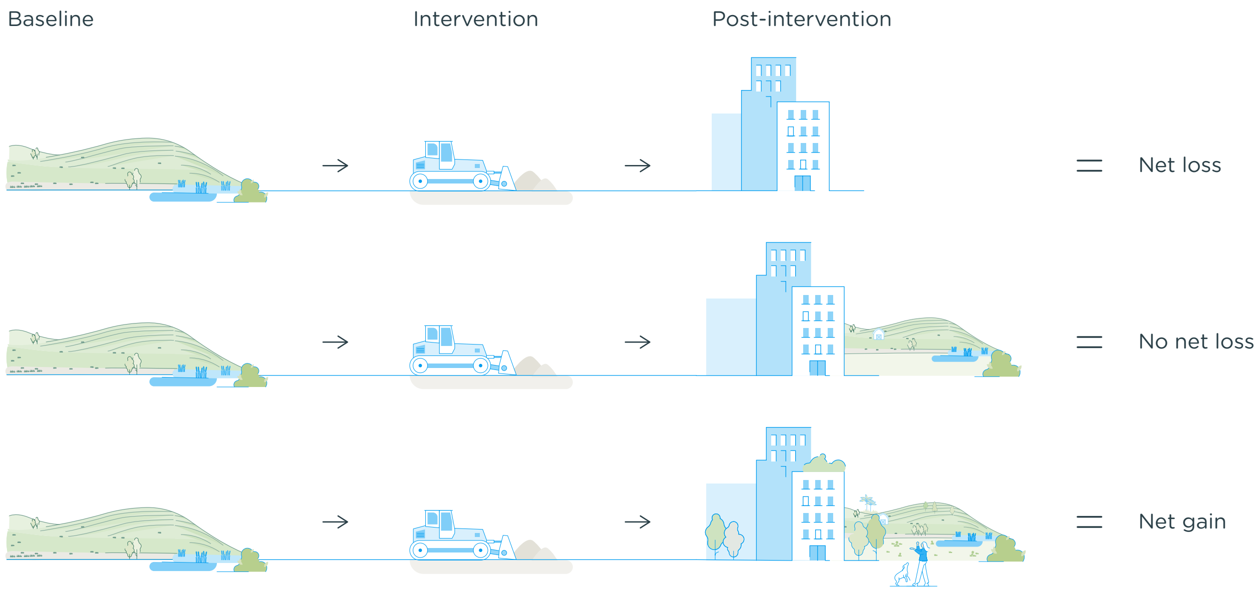
However, achieving biodiversity net gain on-site can be challenging, especially in space-constrained urban or industrial locations. In such cases, developers may need to purchase offsite biodiversity units or statutory credits to compensate for residual losses and meet regulatory requirements. While offsets can play a role, frameworks like TNFD and SBTN stress the importance of prioritising avoidance and minimising biodiversity loss before relying on compensation.

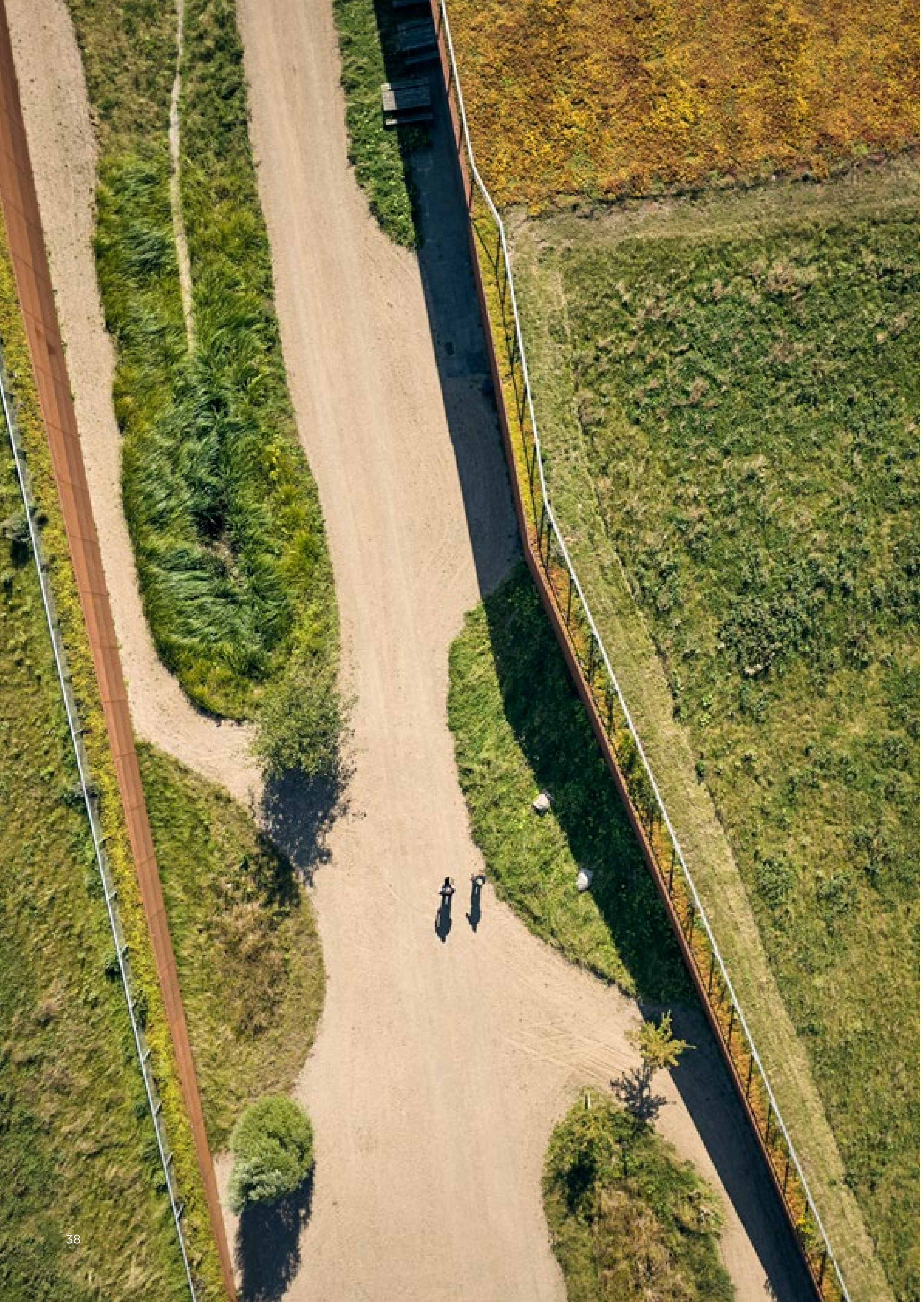
To ensure meaningful outcomes, biodiversity metrics should be:

- Integrated early in the planning and design process
- Aligned with science-based targets and nature-related risk assessments
- Transparent and verifiable, enabling consistent reporting and stakeholder trust

While not yet mandated, aspirational goals for no net loss or net positive outcomes within supply chains should be grounded in transparent, science-based practices to avoid greenwashing and ensure meaningful conservation outcomes.

Figure 13
Biodiversity net gain ▼





How data centres can work with biodiversity

- Biodiversity has a critical role to play in ecosystem health and climate resilience
- The operational resilience of data centres is impacted by biodiversity as diverse ecosystems can provide ambient air cooling, water regulation, erosion control, and soil health
- Site selection is critical, developers should avoid high-value ecological areas and conduct early-stage surveys to assess land
- Urban integration of data centres produces biodiversity challenges, but these can be mitigated through integrating nature-based solutions in early-stage planning
- The Embodied ecological impact (EEI) of data centres throughout their lifecycle is increasingly coming into focus
- Biodiversity net gain requires developers in England to show a minimum 10% increase in biodiversity
- Metrics should be integrated early, aligned with wider industry standards, and verifiable

04

Circularity

Circularity is an essential aspect of sustainability that requires systems to minimise waste, and maximise the reuse of materials, to create a closed-loop system where resources are continuously reused. For data centres, this means that when every component that goes into a data centre reaches the end-of-life stage, it is decommissioned, deconstructed, and reprocessed.

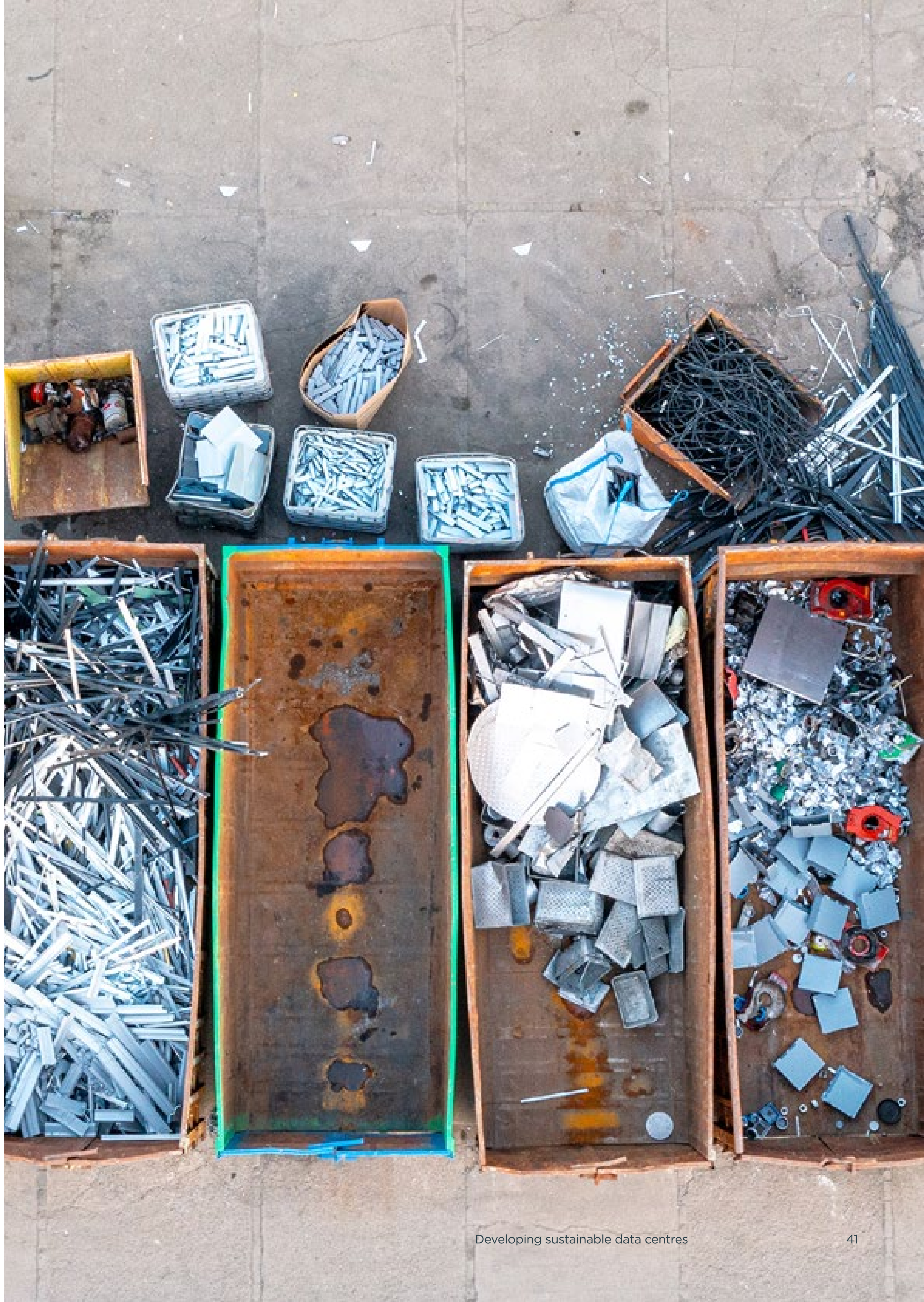
Data centre circularity should be a key focus area for circularity efforts due to the relative magnitude of embodied carbon, and the extent of precious metals and rare earth elements used. Continuous extraction means finite resources become increasingly scarce leading to higher costs and supply chain vulnerabilities. Much of the electronic equipment used in data centres is high in rare earth elements and precious metals, particularly gold, silver, platinum, tantalum, lithium, cobalt, copper and nickel. Several of these finite elements are at critical depletion levels due to limited supply, geopolitical issues, and excess demand resulting in increased costs.

The mining and extraction processes required to source rare earth elements and precious metals often lead to habitat destruction pollution, deforestation and biodiversity loss. Manufacturing data centre equipment involves pollution from industrial processes, such as the release of hazardous chemicals and greenhouse gases. Disposal leads to waste ending up in landfills and oceans, causing pollution and harming wildlife.

The circular economy approach provides a remedy to these impacts, as reusing materials will avoid the excessive consumption of natural resources. Circularity passports are central to this effort.

Circular economy policy demands

Achieving a circular economy is recognised as essential by an increasing number of governments. In March 2020 the EU introduced the Circular Economy Action Plan[18] which is intended to transition the EU to a circular economy where resources are used sustainably, and waste is minimised.



Circularity passports

A circularity passport or material passport is designed to ensure transparency and facilitate the repair, refurbishment, reuse, recycling, and safe disposal of materials and components.

It is a digital or physical document that provides detailed information about the lifecycle, composition, origin, and circularity potential of products or materials.

A circularity passport provides information on:

- Material content such as the types of materials and potential chemicals used in the product, their recyclability and potential for reuse
- Product origin, data on the entire lifecycle of the product, from raw material extraction, manufacturing, and usage to end-of-life options
- Metrics on the environmental impact of the product, including energy consumption, emissions, and resource use
- Guidelines on how to disassemble, reuse, recycle, or safely dispose of the product and its components
- Details on how to maintain and repair the product to extend its lifespan and minimise waste.
- Information on relevant certifications, standards, and compliance that indicate the product's environmental and circular credentials

Benefits of circularity passports include:

- Enhanced transparency about products, allowing stakeholders to make more informed decisions on product specification and replacement
- Facilitation of repair, refurbishment, reuse and recycling, improving resource efficiency and circularity across value chains
- Assisting companies meet legal requirements and industry standards for environmental and circularity practices
- Encouraging adoption of sustainable practices by providing guidelines on maintaining, repairing, and recycling products

Approach to design

Designing data centres for circularity involves integrating sustainable and resource-efficient practices across various aspects of the design, operation, and end-of-life stages such as to minimise resource use and maximise value retention, through both the development of the asset and during demolition.

Circularity aspects to consider

Design principles

- Use modular components that can be upgraded, replaced, or scaled up/down based on IT load changing requirements
- Design for deconstruction to minimise waste and enable the reuse or recycling of building materials, components, and technology
- Select materials that are long-lasting, reusable, recyclable, and have a lower environmental impact
- Obtain certifications such as LEED, BREEAM, Green Mark or other sustainable standards to guide design and construction processes.

Energy efficiency

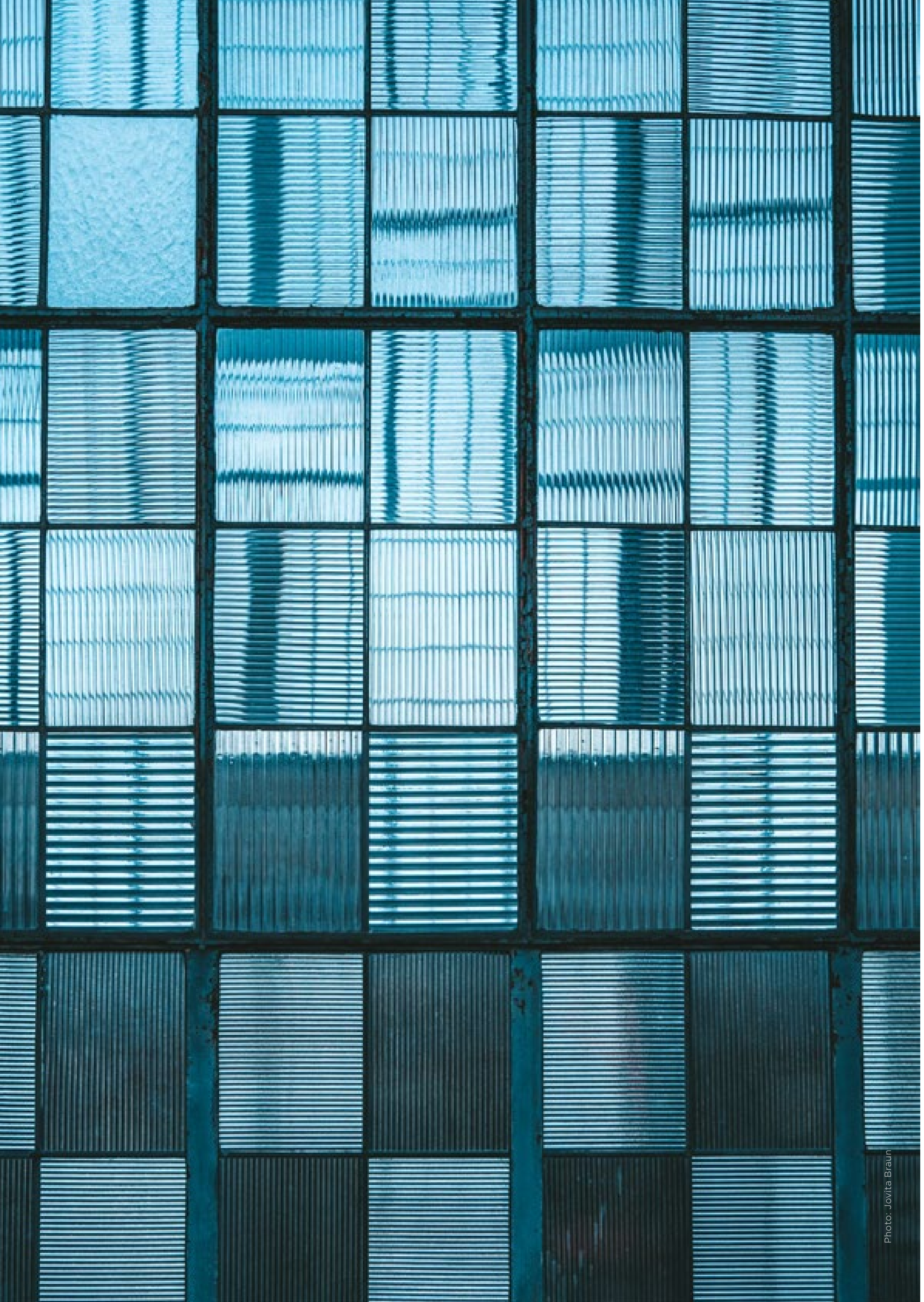
- Incorporate renewable energy sources such as solar, wind, or geothermal power
- Utilise cooling solutions such as liquid cooling, hot/cold aisle containment, and free air cooling to reduce energy consumption
- Adopt energy-efficient designs to reduce power consumption throughout the product's life
- Capture and reuse waste heat from IT equipment for other internal reuse or heat export.

Water conservation

- Design cooling systems that minimise water usage
- Provide systems to recycle cooling water and use greywater for non-potable applications
- Rainwater use for cooling and other facility needs

End of life and waste management

- Plan repurposing, refurbishing, reusing, and recycling components to promote the use of secondary materials, i.e. materials that have been reclaimed, reprocessed, or recycled from waste products, and are used to replace or supplement virgin raw materials
- Conduct lifecycle assessments to understand the environmental impact of materials and target where to incorporate circular practices from the start
- Select components that are straightforward to disassemble to reuse or recycle
- Select manufacturers that reuse, recycle or refurbish end-of-life equipment
- Minimise using materials that are difficult to reuse or recycle or pose environmental hazards



How to achieve circularity in data centres

- Evaluate current practices to identify opportunities for implementing circular design principles
- Integrate circular economy concepts into the initial design and planning stages and specify a requirement for manufacturers to provide circularity passports
- Select materials and suppliers that align with circular economy values
- Apply sustainable practices and materials during the construction phase
- Continuously monitor and optimise operations to ensure resource efficiency and help to mitigate the associated environmental impact of resources
- Develop strategies for decommissioning, reusing, recycling, and repurposing equipment and materials

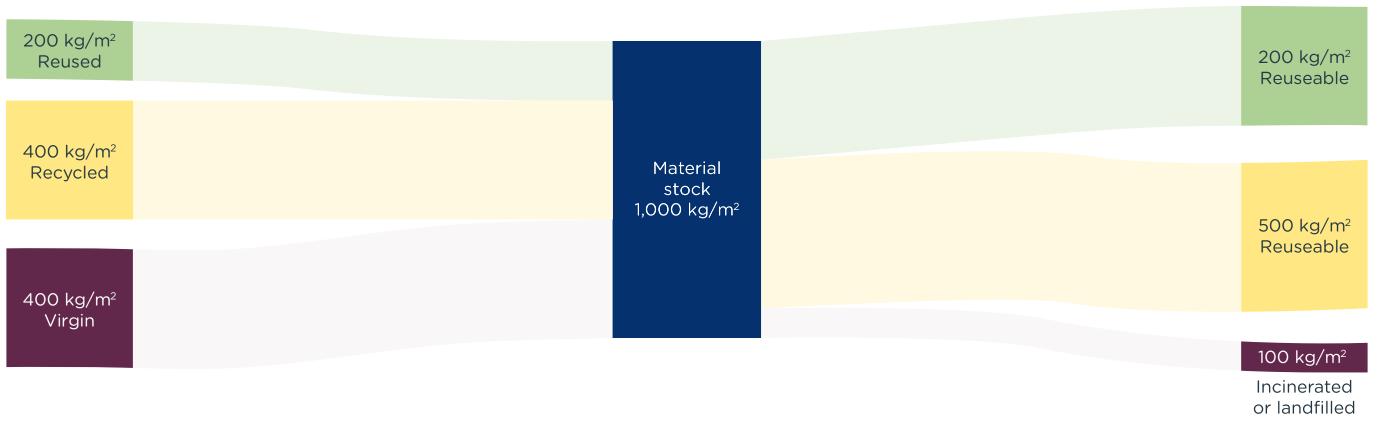
Measuring circularity: importance of consistent metrics

When measuring circularity, a consistent set of metrics is important to allow for performance comparison across projects and the identification of trends where certain constraints or design choices may hinder it. These metrics relate to material intensity, reused material, reusable materials, and recycled content.

The recommended metrics in this section align with the requirements of ISO 59020 Circular Economy and the UK Greater London Authority Circular Economy Statements[19] and are best applied to structural elements of the data centre. They can be applied to the architectural and MEP elements also, albeit subject to a far greater number of data points due to the many types of components used compared to structural elements.

Figure 14

Combined metrics - proportions of input and output materials



Material circularity

Material intensity is a measure of the mass of material per square metre of a building defined as the material stock (kg), and the gross internal floor area (m^2) and provides a useful indication of the total mass of materials being used in a design.

Reused materials are products which are utilised again with minimal processing. This can occur at various levels, such as reusing entire buildings, structures, or individual components and materials. It is a crucial strategy within the circular economy because it maintains the high value of materials and reduces the reliance on new resources. The percentage reused proportion of materials is the total mass of reused materials divided by the mass of the total materials used.

Reusable materials are products or components that can be utilised again for their original intended purpose. These materials are generally designed with deconstruction in mind to ease future reuse. Once they reach the end of their lifecycle, they can be reused in their current form, or undergo minor repairs, typically without requiring any significant additional processing. The percentage of reusable materials is calculated as the mass of reuseable material stock divided by the mass of the total materials used.

Recycled content is an additional metric based on material intensity to evaluate the circularity of a structure. The quantity of recycled materials can be expressed as kg/m^2 and provides a valuable way to demonstrate the amount of virgin material used in a project.

Rare earth elements

In terms of rare earth elements which are particularly relevant to MEP systems, the following metrics can be considered:

Recycling rate: the percentage of rare earth elements (REEs) that are recycled from the total amount used. A higher recycling rate indicates better circularity.

Reuse rate: the proportion of REEs that are reused rather than discarded or sent for recycling. Like recycling, higher reuse rates suggest enhanced circularity.

Virgin material replacement rate: the extent to which recycled or reused REEs replace virgin REEs in new products.

Resource efficiency: evaluating how efficiently REEs are used in products, including minimising waste during manufacturing and maximising their lifecycle through reuse and recycling.

End-of-life collection rate: this metric measures how well systems collect products containing REEs at the end of their lifecycle for recycling or reuse.

Ramboll worked with Meta and a district heating company to use surplus heat from their hyperscale data centre to heat more than 12,000 homes in nearby Odense, Denmark.

05

Energy export and reuse

Data centres can export and reuse energy to generate additional revenue and improve efficiency. Demand response programs typically aim to shift or reduce electricity consumption during peak periods, thereby reducing the need for high-emission power plants to operate, and promoting more efficient energy use.

Demand response and other grid services

The data centre industry is uniquely positioned to participate in demand response (DR), and by doing so, will reduce grid carbon emissions and generate additional income for data centre owners. Unlike conventional DR service providers, data centres have an inherent ability to provide multiple stacked DR services from the same location.

In addition to DR services, data centres can further diversify their participation through energy arbitrage, capacity market commitments, and other local or regional grid services, maximising both revenue and operational flexibility. Energy arbitrage involves buying electricity when prices are low and selling or using stored energy. Data centres can participate by using their battery systems to store cheap off-peak power and discharge during peak price periods. Capacity market participation means committing back-up power assets to be available to the grid.

Demand response (DR) is the adjustment in demand relative to grid generating capacity, designed to address supply and demand imbalance, high wholesale electricity prices and assist with grid reliability. The primary sustainability benefits associated with demand response are reduced Scope 2 emissions by mitigating marginal emissions during peak electricity periods.

The underlying objective is to actively engage customers in modifying their generation or consumption in response to pricing signals.

Companies participating in DR are paid according to the type of DR service they provide. Typically, DR services that are provided at the shortest notice, in real time, are more lucrative than day ahead services. The amount of revenue associated with DR services is dependent on the type of service, available power export capacity, location of the data centre, and prevailing pricing structure.

DR services contribute to greenhouse gas abatement by reducing the average carbon footprint and marginal emissions of the utility. The reduction in both types of utility emissions will also be reflected in a reduction of the data centre carbon footprint. The extent of GHG reduction will be determined by the utility GEF and the amount of energy exported.

Most utility events are short duration transient disturbances lasting less than a few seconds where the UPS energy store momentarily provides power during the utility event.

The data centre can provide demand response either from its UPS or its emergency power sources – or both.

UPS batteries and flywheels remain off load most of the time. Until recently, this was considered the inherent price to pay for the occasional time when they were needed to support the critical load. However, with the introduction of DR service incentives by utilities, there is an opportunity to utilise UPS energy storage to provide DR support services.

This has been recognised by UPS suppliers such as ABB, Eaton, Schneider, and Vertiv who have configured their UPS to provide grid support services. In principle, flywheels could also provide frequency support albeit only short duration FFR services.

The DR applications associated with UPS energy storage are frequency response services due to the speed in which UPS can respond but limited by the energy storage capacity of the UPS.

The types of DR frequency response applicable in general are shown in Table 1.

Table 1
UPS energy storage potential DR services ▾

DR Type	Batteries	Flywheels
FFR	Yes	Yes
FCR	Yes	No
FFR	Possibly	No

These case studies illustrate how data centres are successfully monetising battery storage while supporting grid stability.

Case study

01

Google's Saint-Ghislain data centre in Belgium installed a 2.75 MW/5.5 MWh battery system, reserving half for backup power and using the other half for grid services[20]. This allows participation in Belgium's balancing markets, creating a new revenue stream and reducing reliance on diesel generators. Launched in 2022, this project demonstrates how data centres can both maintain critical power reliability and actively contribute to grid decarbonisation.

02

In Dublin, Microsoft retrofitted its data centres with 255 MW of battery capacity integrated into the backup power systems[21]. These batteries provide fast frequency response to the Irish grid, helping stabilise frequency deviations while maintaining critical power reliability. By participating in grid services, the batteries generate additional revenue and reduce the need for fossil-fuel-based balancing power, directly supporting grid decarbonisation efforts.

03

In Sweden, Conapto's Stockholm data centres upgraded their UPS systems to participate in the Nordic FFR market, enabling grid support within milliseconds[22].

Investing in battery capability

Investing in battery capabilities for grid service can yield attractive returns for data centres. In the UK, data centres can generate approximately £30k to £80k per MW annually, with higher returns during volatile grid conditions[23]. Ramboll expects to recover investments in four to eight years and achieve around 13% to 17% annual returns in good cases.

It is increasingly important for data centres to adopt revenue stacking strategies, combining ancillary services with energy arbitrage and capacity market participation. This approach not only improves return on investment but also mitigates revenue volatility caused by changing market dynamics.

Like UPS, a data centre's power generation plant is idle almost all the time except for the occasional utility outage and periodic testing. Generators are even less utilised than UPS energy storage since they cannot respond quickly enough to start and accept load during a short duration utility event. Therefore, during these extensive periods of inactivity, these assets are non-productive.

Most data centre generators use conventional diesel fuel. However, there is increasing pressure from governments to consider alternatives to diesel engines. Consequently, whilst the installed base almost entirely comprises diesel reciprocating engines, the use of lower carbon NG engines and turbines is increasing.

From a GHG abatement perspective, both diesel and NG gas engines can be used to provide DR services under the appropriate circumstances. In other words, when their use in providing DR services has a net positive contribution to the reduction of grid GHG emissions. This is determined by the GEF associated with each application and the marginal emissions that could be avoided.

With diesel generators in particular, the predisposition to providing DR services is determined by the type of DR service under consideration, the type of engine and the type of fuel used i.e., gas-to-liquid (GTL), ultra-low-sulphur diesel (ULSD), and biofuels such as hydrotreated vegetable oil (HVO) in lieu of conventional diesel.

There may also be a case for running emergency generators in 'island mode' using alternative fuels such as ULSD, GTL or HVO. Each application should be assessed taking into consideration the difference in CO_2e between the grid emission factor and the emission factor of the diesel engine running on the alternative fuel type.

Fuel cells can be used to provide DR services. SOFCs are unsuitable to provide real time frequency support services due to their relatively slow load following capability. Whereas hydrogen proton-exchange membrane fuels cells are quicker in terms of load following ability and may be suitable for FFR, FCR and FRR frequency services. However, in principle SOFCs and PEMFCs are both able to provide load curtailment, load shifting and STOR services.

The various types of DR services that could be provided by emergency generators and fuel cells are indicated in Table 2.

Table 2
Generator and fuel cell potential DR services ▾

DR Type	Diesel Generators	Gas Generators	SOFC	PEM Fuel Cell
FFR	No	No	No	Yes
FCR	Yes	Yes	No	Yes
FRR	Yes	Yes	No	Yes
Load Curtailment	Yes	Yes	Yes	Yes
Load Shifting	Yes	Yes	Yes	Yes
STOR	Yes	Yes	Yes	Yes

Heat recovery and export

Data centres are already utilising waste heat recovery at the facility level. Absorption chillers can convert recovered waste heat into cooling, reducing reliance on electrically driven chillers and improving overall energy efficiency within the facility. In some cases, data centres located on, or near industrial parks may also benefit from combined heat and power systems installed nearby.

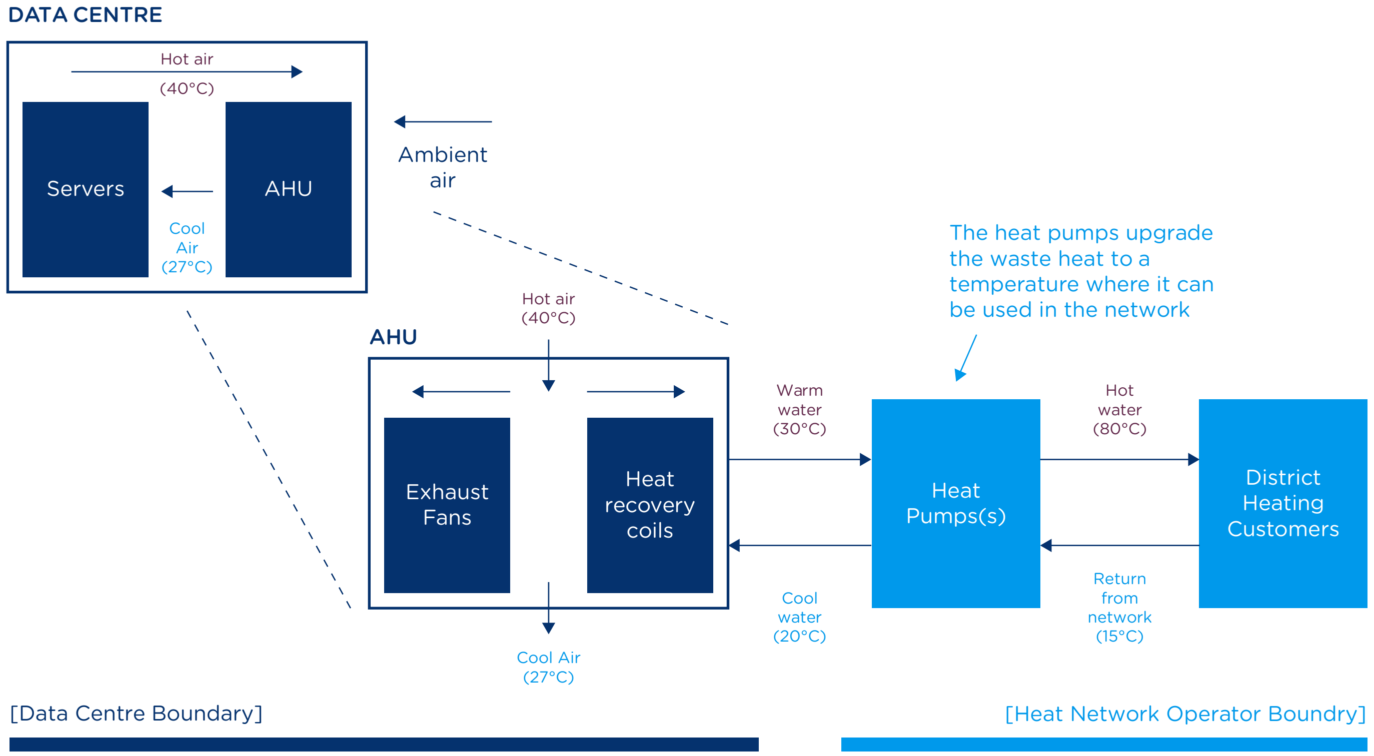
These systems generate electricity while capturing usable heat, which can be supplied back to the data centre for space heating or domestic hot water needs, further enhancing energy performance. By capturing waste heat from the main data hall cooling systems, a portion of the return water in hydronic cooling systems can be redirected through heat exchangers and water source heat pumps to provide heating to back of house areas in the data centre. Heat recovery methods similar to this and other low and zero carbon technologies are considered in BREEAM assessments and are required for the building to gain a BREEAM Excellent rating.

At a larger scale, data centres provide a steady and largely untapped source of low-grade waste heat, creating valuable opportunities for both on-site reuse and export to nearby heating networks. Inside the data centre, technologies like latent heat thermal energy storage allow waste heat to be captured and stored efficiently for later use, helping to reduce the need for additional energy to meet heating demands. For external applications, technologies such as air-source and water-source heat pumps can upgrade the temperature of waste heat, making it suitable for district heating networks. In one such example, Ramboll worked with Meta and a district heating company to use surplus heat from their hyperscale data centre in Tietgenbyen, Denmark to heat more than 12,000 homes in nearby Odense.

These approaches not only improve overall energy efficiency but also open new revenue streams by supplying surplus heat to local off takers.

Figure 15

Data centre waste heat recovery for district heating - air cooled systems ▼



By incorporating adsorption chillers, data centres can take this a step further, using waste heat to drive cooling processes, reducing reliance on electrically powered chillers, and improving both environmental and financial outcomes.

Figure 15 illustrates the limitations of heat recovery for legacy data centres, where heat is generated by the IT load at low grade (approximately 30°C) and therefore requires temperature elevation via heat pumps to enable its use in district heating or other off taker applications.

Figure 16 illustrates the advantages of deploying liquid cooling, either direct to chip or immersion systems, which generate heat of a higher grade (40°C to 60°C). This level of waste heat export has direct use applications and reduces the energy required to elevate to higher temperatures, increasing the efficiency of the system.

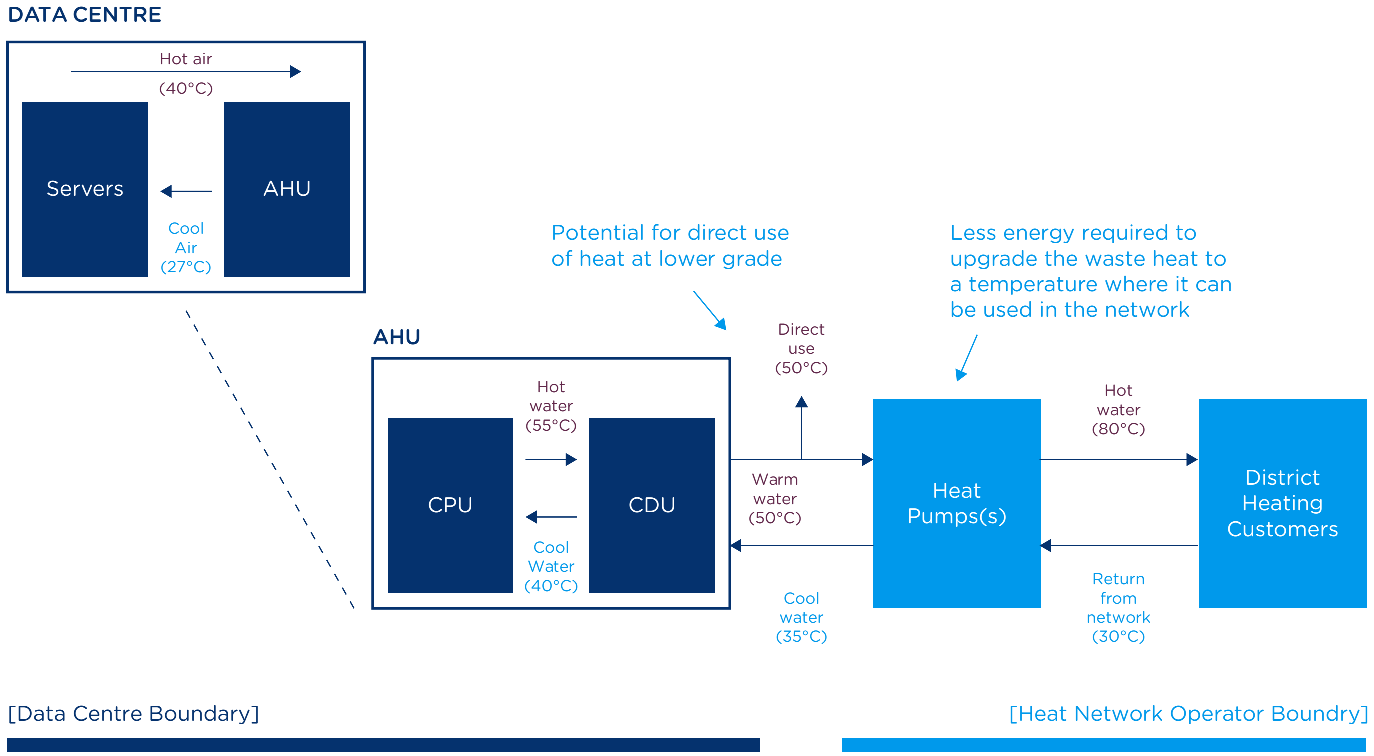
In instances where heat reuse or export is not possible, this type of system increases the envelope for free cooling to apply globally, eliminating the need for mechanical refrigeration process even at high ambient temperature locations.

Data centres are already utilising waste heat recovery at the facility level. By capturing waste heat from the main data hall cooling systems, a portion of the return water can be redirected through heat exchangers and water source heat pumps to provide heating to back of house areas in the data centre.

Data centre heat export can require expensive infrastructure, particularly when using low-grade waste heat, which often necessitates extra equipment to become usable. Economic viability is another issue, particularly in areas where there is limited local demand for the heat. This problem is further complicated by the fact that data centres are often located far from potential heat off takers.

FIgure 16

Data centre waste heat recovery for district heating - hybrid and water-cooled systems ▼



How to export and reuse energy from data centres

- Carbon savings associated with demand response can vary significantly depending on the time of day and the mix of power plants operating and can be offset against total carbon
- Revenues from demand response vary by country, export capacity, and type of scheme
- Carbon savings associated with heat reuse and export can be offset against total carbon
- Revenues from heat export vary by country and export capacity

Off-takers of heat export

- District heating
- On site heating
- Biomass energy production
- Aquaculture
- Hydroponic greenhouses
- Battery producers
- Commercial laundries

Measuring energy export and reuse

To measure the comparative reduction in carbon emissions of using waste heat to provide heating to an office for example, deduct the CO_2e of the grid energy that would otherwise have been used.

Similarly, the CO_2e saved from energy export to an off taker such as a district heating system is calculated by deducting the CO_2e of the grid energy that would otherwise have been used to provide the same amount of energy.

Carbon saving associated with demand response are calculated as follows:

Carbon Savings = (Baseline Consumption – Reduced Consumption) x GEF

Where carbon savings are measured in kg CO_2e, baseline consumption and reduced consumption as measured in kWh, and the GEF is measured in kg CO_2e/kWh.

06

Water use and efficiency

Data centres can consume large quantities of water if a water-based cooling strategy is adopted.

The type of cooling strategy used, and the location of the data centre are key factors in determining the level of water usage and water usage effectiveness (WUE). Each location presents its own advantages and challenges in terms of both water availability and consumption.

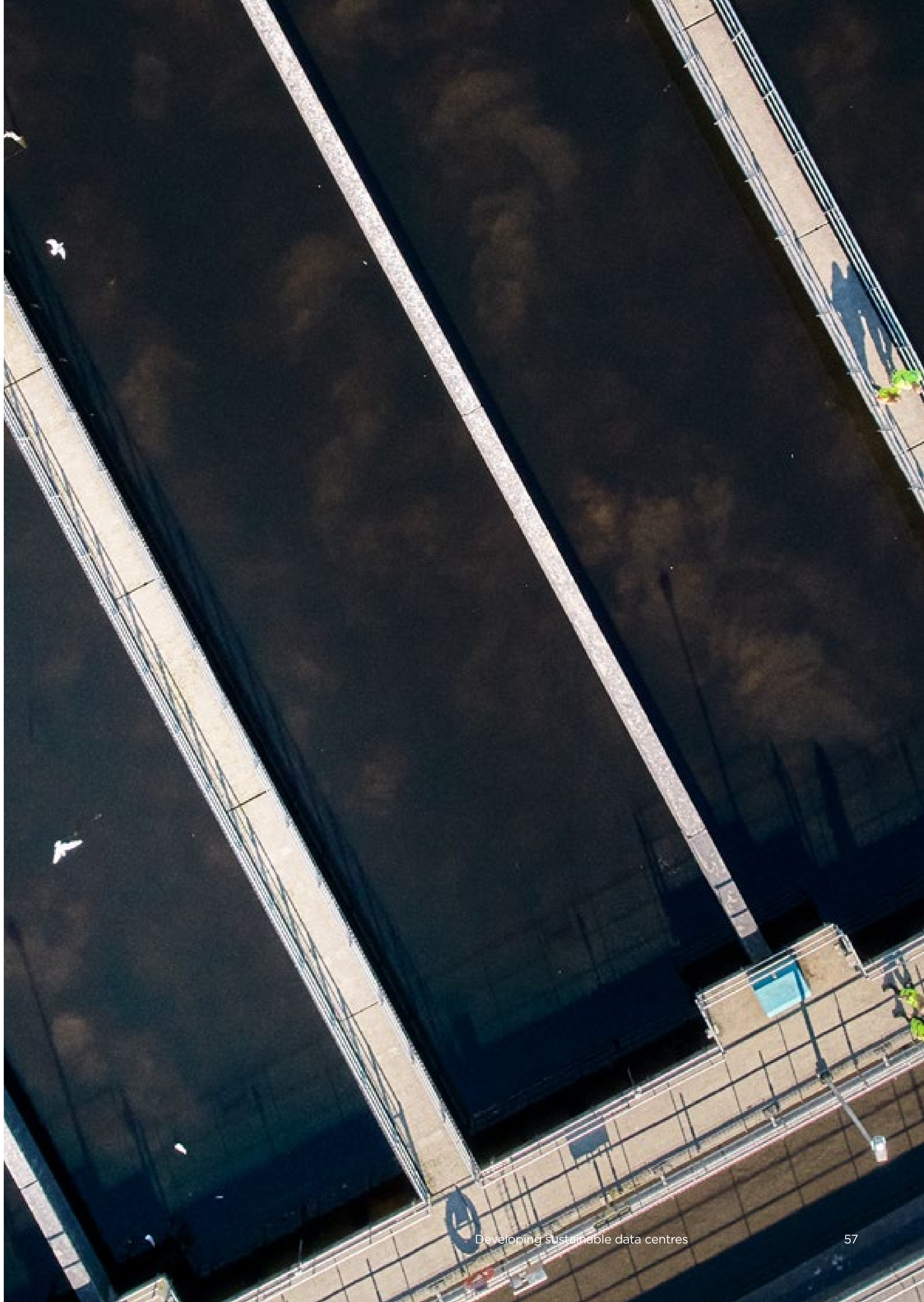
For approximately 20 years, the key metric in terms of data centre efficiency has been Power Usage Effectivness (PUE), often with water-based cooling systems, using direct or indirect air to carry the water-cooling effect into the data centre. Compared to an electric-based cooling systems such as air-cooled chillers and direct expansion, water-based systems use less electricity and therefore provide a lower PUE.

Over recent years the industry has seen an increased in the use of liquid cooling to enable higher rack power densities. It is anticipated that the use of liquid cooling, both direct to chip and immersion types, will continue to grow as IT power demand and rack densities increase.

This will add further pressure to minimise PUE. Consequently, it is likely that the use of water-based cooling will also increase.

Figure 17 illustrates the locations of data centres associated with the three largest hyperscale companies in water scarce areas.

A dilemma for the data centre operator is to determine the relative sustainability and cost benefits based on its location. If the data centre is in a water scarce area, this would tend toward an electric based cooling solution, whereas if the data centre is in an area with a high GEF such as Poland or Indonesia (Figures 8 and 10), where water is less constrained, it may be more appropriate to use a water-based cooling solution. There are however some areas such as much of Australia and Saudi (Figures 10 and 11) where the GEF is high, and the area is also water stressed.



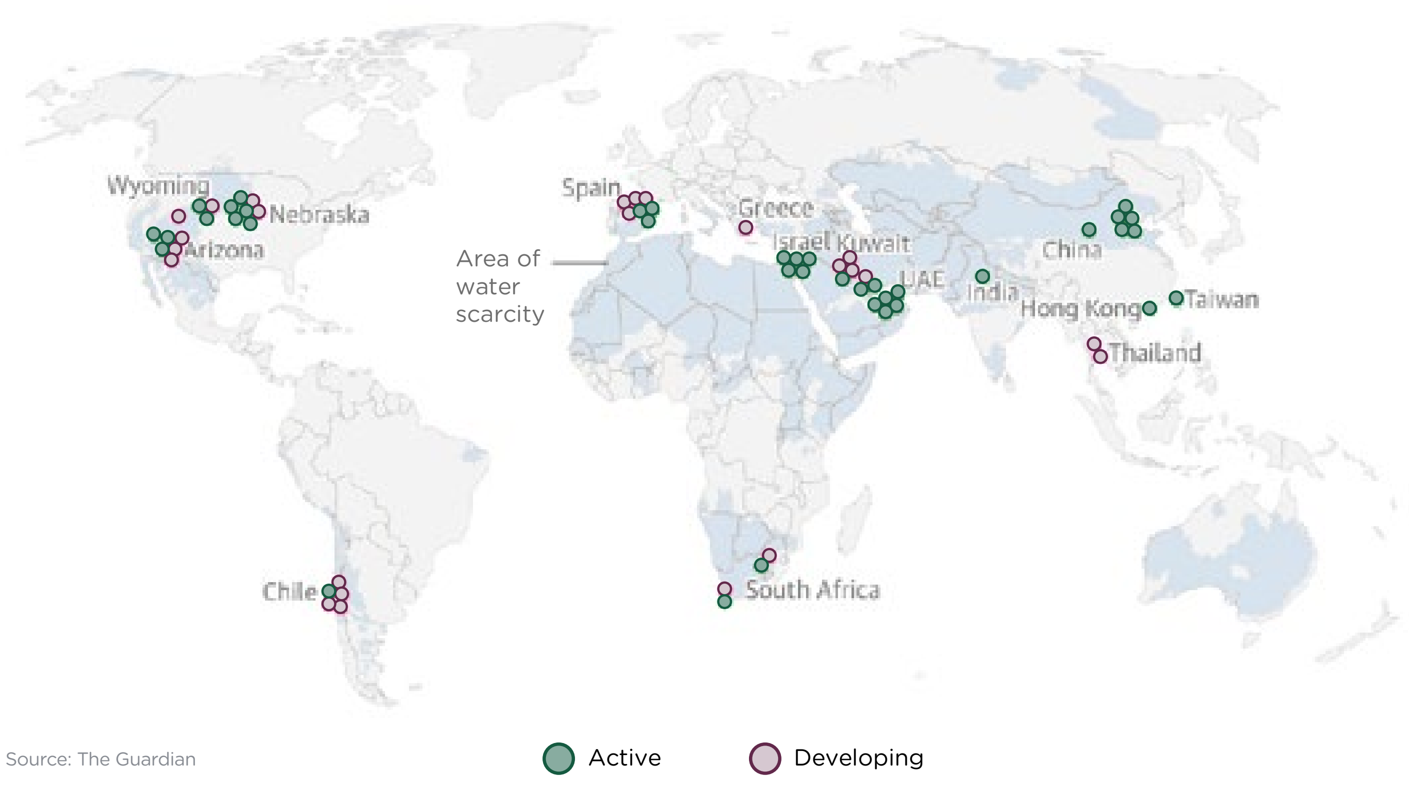
Water usage effectiveness (WUE)

The primary metric adopted by the data centre industry to measure water use efficiency is WUE, which quantifies the amount of water used for cooling annually in relation to the energy it consumes. This is expressed as litres per kilowatt-hour (L/kWh), reflecting the amount of water consumed for each unit of energy used by the IT equipment. A lower WUE value indicates better water efficiency, meaning the data centre uses less water for the given amount of energy it consumes.

WUE is a useful metric because it promotes efficient water use, highlights water consumption and therefore the associated environmental impact. It is also a good benchmarking tool and encourages reduced water consumption through the selected design solution and operational behaviour. However, WUE does not account for other environmental impacts, such as energy consumption, carbon emissions, or detrimental effects on local water and air quality conditions. Therefore, WUE provides a relatively narrow view and should be considered in the context of overall sustainability.

Figure 17

Data centres in areas of water scarcity



Source: The Guardian

Water-based heat rejection processes

Fundamentally there are two types of water-based heat rejection processes:

- Heat transfer
- Evaporative

Heat transfer cooling

Also referred to as 'once through', these systems require a body or source of water, often natural. Heat is exchanged with this water indirectly through a water-to-water heat exchanger from the data centre cooling medium. The water is heated and returned to the water body or source.

As the water itself is not exchanged there is no contamination of the water source however the returned temperature is elevated as illustrated in Figure 18. The extent of temperature increase depends upon the relative scale of the heat rejection power and the scale and mass of the water body.

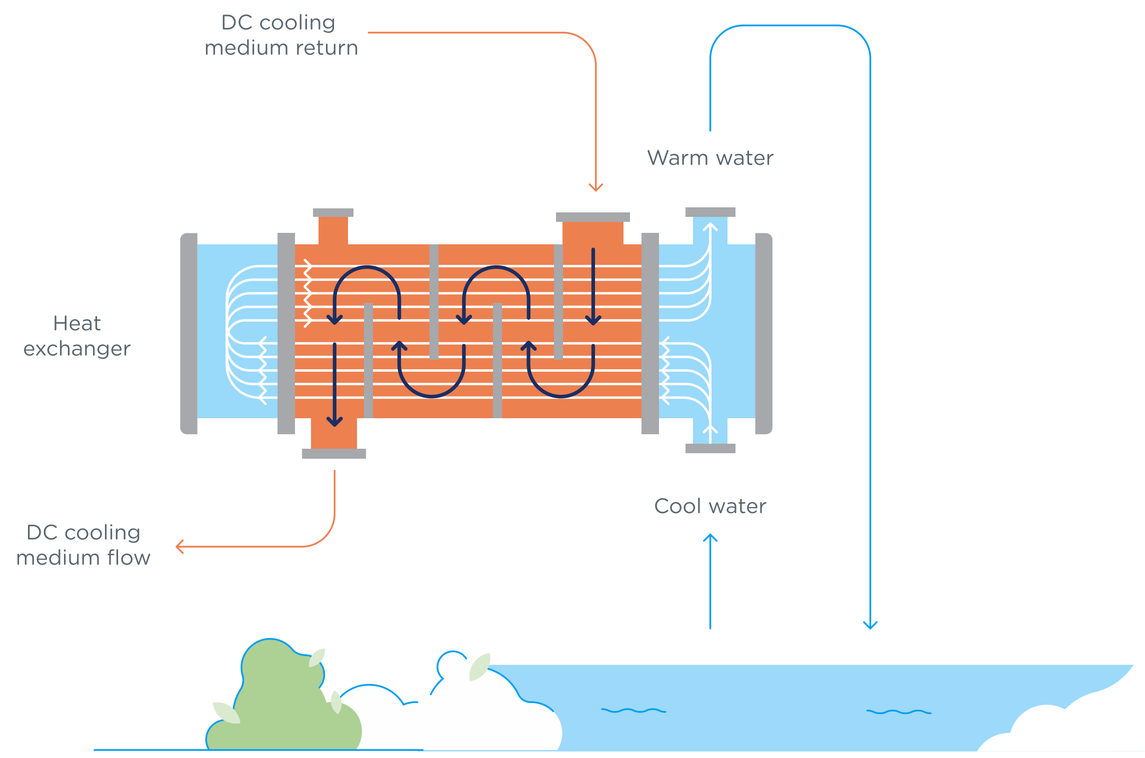
Typical examples of water bodies used in this method include rivers, canals, lakes and seawater. The systems use a relatively small amount of electricity to transfer the water flow and achieves a relatively high degree of cooling. For this reason, the cooling can be viewed as low energy or free cooling.

Whilst water is not consumed, and is entirely returned the water source, this system does have the following environmental impacts:

- Water temperature increase can be harmful to aquatic life and so the degree of temperature increase must be constrained within safe limits.
- The intake screening mechanisms for these system types, which are required to filter and prevent debris entering the system, can also be harmful to aquatic life. Modern screen design is focused on minimising this outcome.

Figure 18

Heat transfer cooling



Evaporative cooling

This process utilises direct evaporation to the atmosphere to achieve cooling effects to a water medium. Through the phase change, energy is extracted from the remaining cooling medium when a proportion of it changes from a liquid to a gas state.

The remaining water medium is then transferred directly to the data centre cooling equipment, either in an open loop system, or indirectly, in a closed loop system via a plate heat exchanger to achieve segregation (as shown in Figure 19).

The source of water required to make up the loss through evaporation may be a natural body (lake, canal, river etc), utility supplied, or locally recycled water from another process. Certain sources impose constraints depending on the water's natural characteristics (e.g. brackish water).

Whether an open or closed system, any unevaporated water can be recirculated and reused. However, each evaporation cycle leaves behind a greater concentration of any dissolved solids. This recirculation and concentration cycles, referred to as 'cycles of concentration', is a key operational and design parameter. The concentrated water must then be returned to source or discharged as waste, referred to as 'blowdown'.

Additional water is consumed and blown down in further flushing processes which are required to mitigate issues such as accumulated solids, water quality generally, scale formation, corrosion, and microbiological growth. This process type can be used in a range of different formats including water cooling towers, adiabatic dry coolers, hybrid dry coolers, adiabatic chillers, and direct and indirect evaporative coolers using forced outside air.

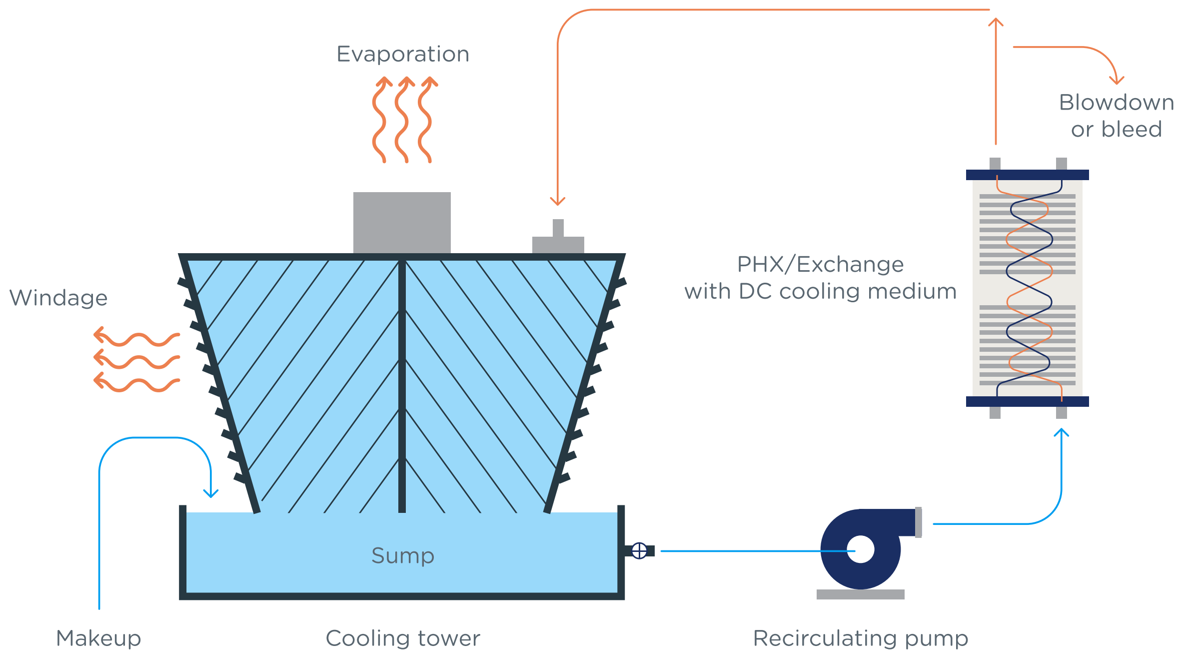
Returning water to a natural or manmade body following a high number of cycles of concentration does minimise water consumption but has other – sometimes adverse - environmental impacts. The high concentration of other water constituents may have adverse characteristics impacting the environment of the water source. Thus, it may be necessary to treat the discharge water requiring additional electrical energy thereby diminishing the carbon saving benefits.

The evaporation process, which typically entails water spray devices, allows a certain amount of liquid water to drift into the atmosphere in the form of droplets.

Equipment type and efficient drift eliminators can minimise but not eliminate this effect entirely. Thus siting the system at a suitable distance from sensitive environmental receptors to minimise impacts is also an typical mitigation strategy.

Figure 19

Evaporating cooling ▼



Water reuse and conservation strategies

Avoid using water-based cooling

One way to minimise water consumption is to avoid this method of cooling entirely. However, this requires additional electrically derived cooling capacity. In areas of high GEF, this is generally unfavourable due to the associated increase in operational carbon. To avoid water-based cooling in these locations without increasing carbon emissions, it is necessary to derive a source of renewable electricity capacity for the non-water-based cooling energy.

Another measure suited to locations with water scarcity and high GEF, which are often dry, arid, desert biomes, is night-time heat rejection and storage. The climate in these locations often fluctuates throughout the day, with significantly lower nighttime temperatures. The use of phase change coolth storage (e.g. ice storage) can be adopted to undertake cooling at night with lower ambient and lower PUE. The cooling is then discharged during the day-time peak temperatures.

Maximise cycles of concentration

The acceptable number of cycles of concentration depends on the quality of supply water and the limitations to discharge water concentration for safe environmental operation, often defined by the local authority. This is specific to the location and water source selected, the choice of which can be made to optimise these limits. Water treatment of the source or discharge water would also allow increased cycles of concentration while also meeting local discharge limits.

Stringent, continuous monitoring and controls of flushing and blowdown concentration levels will maximise water conservation. For example, concentration and discharge controls using conductivity sensors, to accurately measure salts concentration levels at the required criteria before discharging blowdown, can maximise the level of water reuse up to the required limits. Similarly, corrosion sensors and flow meters can monitor, and control water use accurately for maximum reuse and affect. Good maintenance and cleaning of equipment and other operational behavioural patterns will also maximise this parameter.

Access additional water resources

In areas of moderate and/or variable water availability, the use of large quantities of water for cooling systems may still present a challenge to this environmental resource, placing a burden on local water utility storage and distribution infrastructure. Therefore, accessing additional water resources reduces this burden and the use of natural and manmade bodies of water such as those discussed above should be considered.

Available resources may be expanded by considering lower quality sources that are otherwise of low value and use. Recycled wastewater effluent or low grade water course water (e.g. canals) may be utilised by incorporation of water treatment to upgrade the water.

Rainwater harvesting is another potential option. This requires tank storage and careful calculation, modelling, and prediction of fluctuating and seasonal rainwater, and water consumption levels to correctly size.

In areas of scarce drinking water, additional freshwater resources are typically unavailable. However, saltwater may be accessible. Desalination plants can be used to reduce the salinity level to make the water suitable for evaporative cooling. However, desalination is an energy intensive process and compounds the operational carbon challenge in these locations.

Other water uses and reduction measures

Data centres also use water for humidification processes within their ventilation systems. This is necessary to maintain minimum relative humidity of the internal data centre environment as required by IT server equipment. Low levels of relative humidity can affect IT equipment by causing static electricity. Humidification is particularly necessary in cold environments when external air is heated to reach minimum levels and further heated by the IT equipment. While efficient humidification equipment can be selected, using recirculation air handling units to prevent the loss of moist air should be considered.

Water reuse and conservation measures applicable to conventional building types can also be applied to the more domestic water uses in the ancillary and occupied spaces in a data centre facility.

Reduced irrigation and water feature use, and reducing domestic and sanitary water use, are all necessary considerations, while water reuse strategies such as grey water recycling are also an option

Reduction of potable water consumption by conventional strategies such as absence detection and low flush and low flow sanitary devices are all also applicable.

How to achieve water neutrality in data centres

- Avoid water-based cooling where possible
- Balance water usage against operational carbon – both PUE and WUE metrics are important and trade off against each other
- Consider other environmental impacts of these systems; - to air, water and ecology
- Maximise cycles of concentration in evaporative systems:
    - Within water environmental limits for discharge water
    - Consider water treatment to maximise water conservation through each cycle of concentration
    - Good operational and maintenance practices
- Assess potential additional water resources:
    - Rainwater harvesting
    - Unused/low value water resources
    - Recycled waste water effluent
    - Lower quality source water combined with water treatment
- Water saving measures applicable to occupant and landscape use in data centre support spaces is also applicable
- Overall water neutrality is achievable with the appropriate water reduction and re-use strategy across all water consuming systems

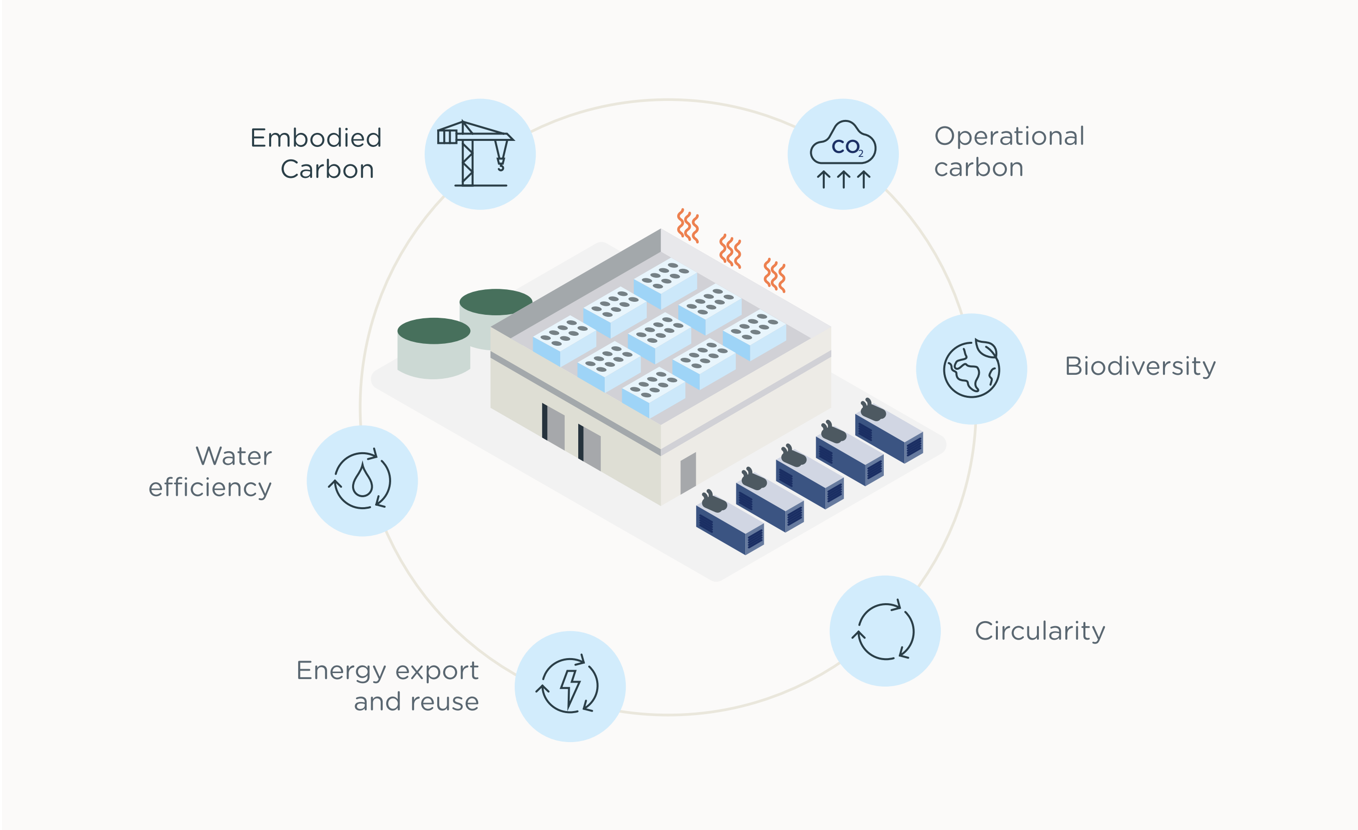
Photo: Damien de Gouveia

How to assess the environmental performance of a data centre

To drive improved sustainability outcomes and reduce negative environmental impact, data centre developers must take a holistic approach to optimise design and operational performance. All of these factors are important and sometimes need to be balanced; it is critical to consider them early in the planning stage, and as an integrated part of the design solutions and operating strategies.

Proposed key benchmarks:

- Power and cooling efficiency (PUE)
- Embodied energy
- Operational energy
- Energy export and reuse
- Water use
- Embodied ecological impact
- Circularity of base materials and REE
- Reuse and recycling
- Biodiversity net gain or loss



Power and cooling efficiency

For air cooled systems, annualised PUE benchmark set at 1.2 from July 2026 based on the German Energy Efficiency Act, normalised for regional climatic conditions.

Embodied carbon

An initial upfront carbon (A1-A5) benchmark of 1,500kgCO_2e/m^2 is suggested based on literature review and project comparison. Additional data review of this proposed benchmark is necessary to ensure the benchmark remains current.

Operational energy

- Proportion of reused/exported energy 10% from July 2026 increasing to 20% from July 2028 - German Energy Efficiency Act.
- Operational energy net zero achieved by carbon offsetting after deducting waste heat energy reuse/export and emission reductions achieved by demand response.

Water use

Proposed benchmark is water neutrality.

Embodied ecological impact

Proposed benchmark for all high-impact commodities in the product supply chain is no net loss of biodiversity, using a recognised biodiversity accounting framework (e.g., IUCN, BBOP, TNFD, SBTN, IFC, Natural Capital Protocol).

Circularity

Proposed benchmark all materials reusable or recyclable with zero materials to landfill or incineration.

Biodiversity

Proposed benchmark biodiversity net gain 10% - UK Environment Act 2021.

List of abbreviations

AI	Artificial intelligence
BaU	Business as usual
BBOP	Business and Biodiversity Offsets Programme
BESS	Battery energy storage
BNG	Biodiversity net gain
BREEAM	Building Research Establishment Environmental Assessment
CCUS	Carbon capture, utilisation, and storage
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
CPD	Construction Products Regulation
CSRD	Corporate Sustainability Reporting Directive
DR	Demand response
DX	Direct expansion
EEI	Embodied Ecological Impact
EPDs	Environmental Product Declarations
FCR	Frequency Containment Reserve
FFR	Fast frequency response
FFR	Firm frequency response
GEF	Grid emission factor
GHG	Greenhouse gas
GWP	Global warming potential
IEA	International Energy Agency
IFC	International Finance Corporation
IUCN	International Union for Conservation of Nature
LCA	Life cycle analysis
LEED	Leadership in Energy and Environmental Design
MEP	Mechanical, electrical and plumbing
NG	Natural gas
NOx	Nitrous oxides
PEMFC	Proton exchange membrane fuel cell
PPA	Power Purchase Agreement
PUE	Power usage effectiveness
SBTN	Science-Based Targets for Nature
SMR	Small Modular Reactor
SOFC	Solid oxide fuel cell
SOx	Sulphur oxides
STOR	Short term operating reserve
TNFD	Taskforce on Nature-related Financial Disclosures
UHI	Urban heat island
UPS	Uninterruptible power supply
WUE	Water usage effectiveness
WWF	World Wide Fund for Nature

References

1. Boston Consulting
www.bcg.com/publications/2025/breaking-barriers-data-center-growth#:~:text=Global%20power%20demand%20by%20data,the%20years%202020%20through%202023

2. IEA Energy Demand from AI
www.iea.org/reports/energy-and-ai/energy-demand-from-ai

3. United Kingdom Environment Act 2021
www.legislation.gov.uk/ukpga/2021/30/contents

4. EU Energy Efficiency Directive (2023/1791)
energy.ec.europa.eu/topics/energy-efficiency/energy-efficiency-targets-directive-and-rules/energy-efficiency-directive_en

5. IEA
www.iea.org/commentaries/what-the-data-centre-and-ai-boom-could-mean-for-the-energy-sector

6. IEA - Emissions Factors 2021
www.iea.org/data-andstatistics/data-product/emissions-factors-2021

7. Institute for Global Environmental Strategies (2021). List of Grid Emission Factors, version 10.10.
pub.iges.or.jp/pub/iges-list-grid-emission-factor

8. The Convention on Biological Diversity
www.cbd.int/convention/articles?a=cbd-02

9. Global Risks Report 2025 | World Economic Forum
www.weforum.org/publications/global-risks-report-2025

10. Hyperscale Data Centers Hit the Thousand Mark; Total Capacity is Doubling Every Four Years | Synergy Research Group
www.srgresearch.com/articles/hyperscale-data-centers-hit-the-thousand-mark-total-capacity-is-doubling-every-four-years

11. How nature can help cities fend off record-smashing heat
www.unep.org/news-and-stories/story/how-nature-can-help-cities-fend-record-smashing-heat

12. Embodied Ecological Impacts | UKGBC

13. Global Biodiversity Framework
www.cbd.int/gbf

14. The Taskforce on Nature-related Financial Disclosures
tnfd.global

15. Science-Based Targets for Nature
sciencebasedtargetsnetwork.org

16. Measuring biodiversity - Ramboll Group
www.ramboll.com/measuring-biodiversity

17. Qualis Flow research
qualisflow.com/uk-construction-waste-report-2023

18. Circular Economy Action Plan ref
environment.ec.europa.eu/strategy/circular-economy-action-plan_en

19. UK Greater London Authority Circular Economy Statements
www.london.gov.uk/sites/default/files/circular_economy_statements_lpg_0.pdf

20. Google's Saint-Ghislain data centre
www.datacenterdynamics.com/en/news/google-picks-fluence-for-275mw-grid-supporting-battery-system-in-belgium/#:~:text=The%20batteries%20can%20store%205,to%20the%20grid%20as%20needed

21. Microsoft Dublin
www.datacenterdynamics.com/en/news/microsoft-to-roll-out-data-center-battery-sharing-worldwide/#:~:text=In%20Dublin%2C%20Microsoft%20replaced%20the,term%20need

22. Conapto Stockholm
www.datacenterdynamics.com/en/opinions/grid-balancing-yet-another-great-contribution-from-a-data-center/#:~:text=Dynamic%20grid%20support%20offers%20data,would%20otherwise%20be%20left%20idle

23. Battery storage revenues in Great Britain
www.solarpowerportal.co.uk/battery-storage-revenues-in-great-britain-up-says-modo-energy/#:~:text=Energy%20www,2024%2C%20when%20revenues%20averaged%20%C2%A336k%2FMW%2Fyear

24. Stacking Battery Storage
www.ey.com/en_us/insights/energy-resources/four-factors-to-guide-investment-in-battery-storage#:~:text=In%20many%20markets%2C%20ancillary%20markets%2C,it%20is%20a%20similar%20picture