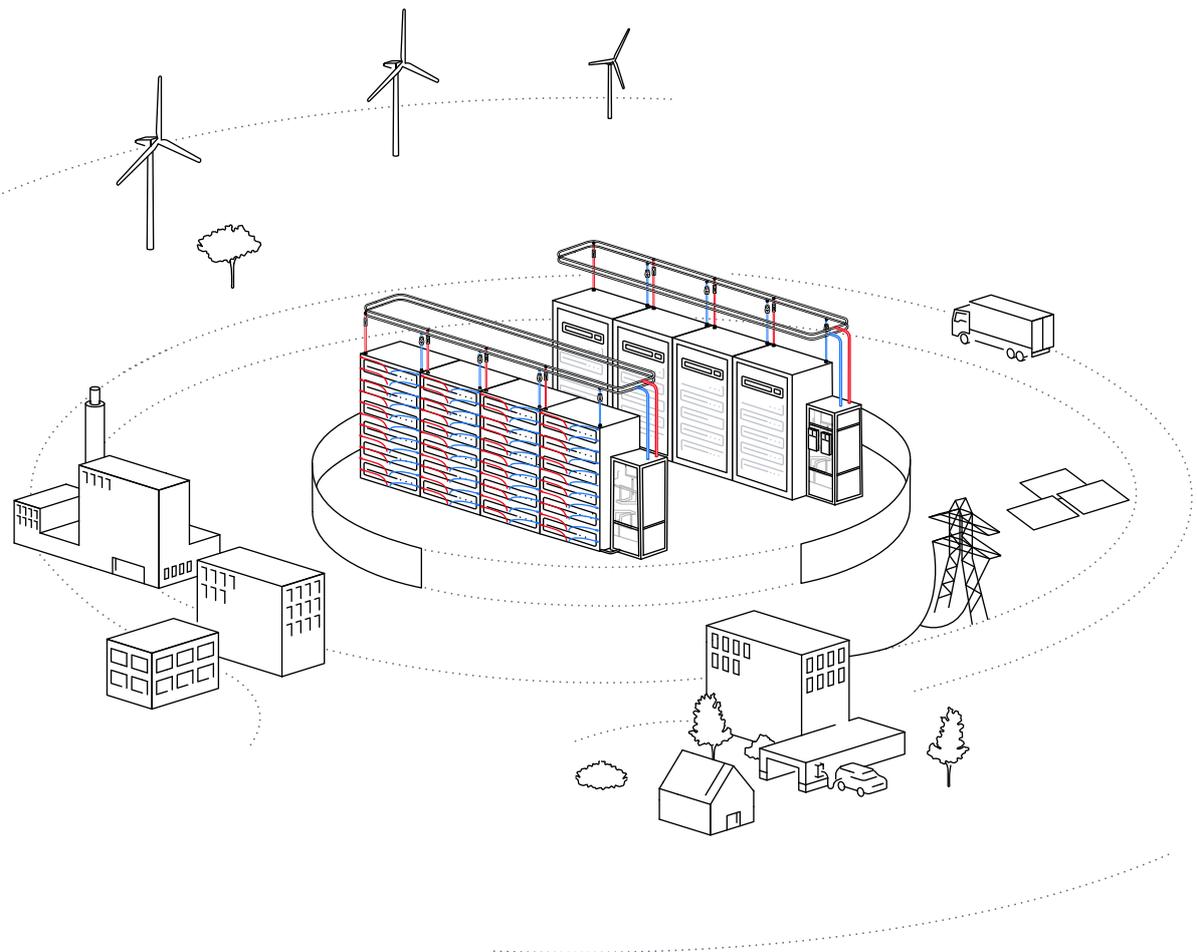




# Data centers

A new lever of flexibility,  
integration, and security



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can be assets to  
our energy system

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## Brief

Drawing on empirical evidence and data from a range of credible sources, **Danfoss Impact Issue No. 8** shows how data centers can become valuable assets to the energy system. It outlines how stronger operational efficiency, waste heat recovery and reuse, and more flexible operation can strengthen grid resilience and help lower system costs.

This paper also highlights technologies with significant energy- and emissions-reduction potential that remain underutilized today, despite being widely accessible and offering favorable payback times. In this paper, the terms “data center electricity use” and “data center consumption” refer to total facility-level electricity consumption, including IT equipment, cooling systems, power delivery infrastructure, and auxiliary loads. Where relevant, any distinction between total facility consumption and specific components (e.g., IT load) will be explicitly stated.

This Impact Paper is written primarily for policymakers and industry leaders shaping how data centers are integrated into future energy systems. It is also relevant for data center operators and other industry stakeholders seeking scalable pathways to improve efficiency, flexibility, and sustainability.

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The views expressed in this paper are those of Danfoss. Their completeness and accuracy should not be attributed to any external reviewers or entities.

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## Foreword

# Why data centers can be assets to our energy system

Digitalization is advancing at an extraordinary pace, and the rapid adoption of AI is reshaping every part of society. At the heart of this transformation are data centers, providing the digital backbone that enables modern society to progress.

Demand for data center capacity is accelerating far beyond historical rates and, in many regions, it has outpaced infrastructure developments. Careful planning and integration of data centers into our energy system is more important than ever and represents a critical opportunity to build a smarter, more resilient energy system.

Data centers are a prerequisite to future technological advancements and for developing the solutions needed to decarbonize our economies. They hold the power to significantly improve energy efficiency in virtually all sectors, from transport to heavy industry. According to the IEA, AI has the potential to deliver emission reductions equivalent to around 5% of global energy-related emissions in 2035.<sup>1</sup> As data centers become ever more embedded in our daily lives, and our future, it's clear that their expansion will play a central role in shaping the next generation energy system.

We know that data centers consume significant resources as they carry out the essential work of delivering the digitalization that we're reliant on. Data centers will consume as much as 3% of global electricity by 2030.<sup>2</sup> However, this electricity demand will be concentrated regionally, providing perfect opportunities for more

**"If done right, data centers can reduce grid investment needs, strengthen energy resilience, and protect consumers from surging electricity prices."**

targeted integration into local energy systems. For example, 80% of electricity demand growth will be in China and the US, driven largely by hyperscale data centers and clear ambitions to lead the world in AI. In the EU, demand is expected to triple as leaders aim to integrate smaller, decentralized data centers into surrounding energy infrastructure.

Meanwhile, data centers use around 560 billion liters of water per year, potentially increasing to 1,200 billion by 2030.<sup>3</sup> Their impact on the energy system is already significant and will intensify further unless we redefine the way we handle their rapid expansion.

Seeing data centers solely as resource consumers only tells part of the story. In reality, data centers represent one of the greatest untapped opportunities to strengthen global energy systems. They don't have to be the burdensome facilities they're sometimes portrayed as. Through flexible operations, integration with other industries, recovery and reuse of waste heat, and resource efficiency, we can turn these resource-hungry facilities into great assets. When managed effectively, data centers can contribute to a resilient and efficient energy system.

Targeted interventions can unlock the potential while addressing the challenges of rapid expansion. Driving efficiency across both facility design and operations can significantly lower the projected resource demand and ensure that digital growth does not outpace energy-system capacity. A cross-sector, collaborative approach

can further the development and deployment of new technologies and next-level efficiency.

Policymakers can help unlock these critical system benefits by adopting a holistic approach to data center planning that enables facilities not only as resource consumers, but potential energy providers. When properly integrated into local energy ecosystems, aligned with renewable generation, and enabled to support grid flexibility, data centers can transform from sources of strain into stabilizing assets. If done right, data centers can reduce grid investment needs, strengthen energy resilience, and protect consumers from surging electricity prices. Ultimately, they can transform and innovate our industry, thereby strengthening our combined efforts to boost competitive decarbonization.

I'm clear and resolute on the future we should pursue and build together. Digitalization is accelerating across our economy and society, and its inevitability can bring significant opportunities for innovation and efficiency. Now, we must act with both urgency and vision. We must make resource efficiency a non-negotiable foundation of data center operations and plan for data centers to become key partners in the flexible, efficient, and resilient energy system of the future.

Kim Fausing  
President & CEO, Danfoss

Data centers represent one of the greatest untapped opportunities to strengthen global energy systems.

## Only got 2 minutes?

- 1 AI can strengthen grid reliability and improve energy system resilience**

While AI consumes a lot of energy, it can also be deployed as a useful tool for making our entire energy system more resilient and efficient. According to the International Energy Agency (IEA), AI has the potential to deliver emission reductions equivalent to around 5% of global energy-related emissions in 2035 through energy efficiency gains across transport, buildings, and heavy industry.<sup>4</sup>
- 2 Energy efficiency is the fastest and cheapest way to cut the resource use of data centers**

Most of the energy used inside a data center comes from servers and cooling, making these the most important areas for reducing energy consumption. Digital tools like sensors, AI-supported controls, and variable speed drives have the potential to lower energy for cooling by 10%-20% with short payback times.<sup>5,6</sup> By deploying highly efficient liquid cooling, cooling-related energy use can be reduced by more than 15%, while dramatically reducing water consumption.<sup>7</sup>
- 3 Integrating data centers locally unlocks massive potential and saves money**

Every unit of electricity used in a data center eventually turns into heat and most of that is wasted instead of reused today. With the right location and planning, this heat can be captured and used to heat nearby homes, businesses, and industries from other important institutions. The IEA estimates that recovered heat from data centers could cover up to 10% of Europe's space-heating demand by 2030.<sup>8</sup>
- 4 Data centers have the potential to become important assets for grid-balancing**

Moving non-urgent computing tasks out of peak hours when the grid is most stressed can free up capacity across the grid. The flexible operation of data centers can cut grid costs by up to 5% while reducing emissions by as much as 40%.<sup>9</sup> If data centers operated flexibly even 1% of the time, today's long grid connection queues would shrink dramatically. In fact, the full pipeline of new data centers expected by 2035 could be connected without overwhelming the grid.<sup>10</sup>

# Breaking the energy gridlock

The world is quickly embracing new digital technologies and AI. Their use is becoming part of everyday life: industries test new products virtually, we make video calls from Amsterdam to Shanghai, and we are witnessing major breakthroughs in the treatment of serious diseases. It's already clear that intelligent computing is changing how we live and the appetite for it will only continue to grow. Now the important challenge is how to support this growth while simultaneously managing the demands data centers place on critical resources. Governments and other decision-makers are responsible for enabling this growth while also managing data centers' demand for resources such as energy and water. Fundamental to preventing energy gridlock is energy efficiency and the integration of data centers into our energy system.

## Challenges to a sustainable build-out of data centers

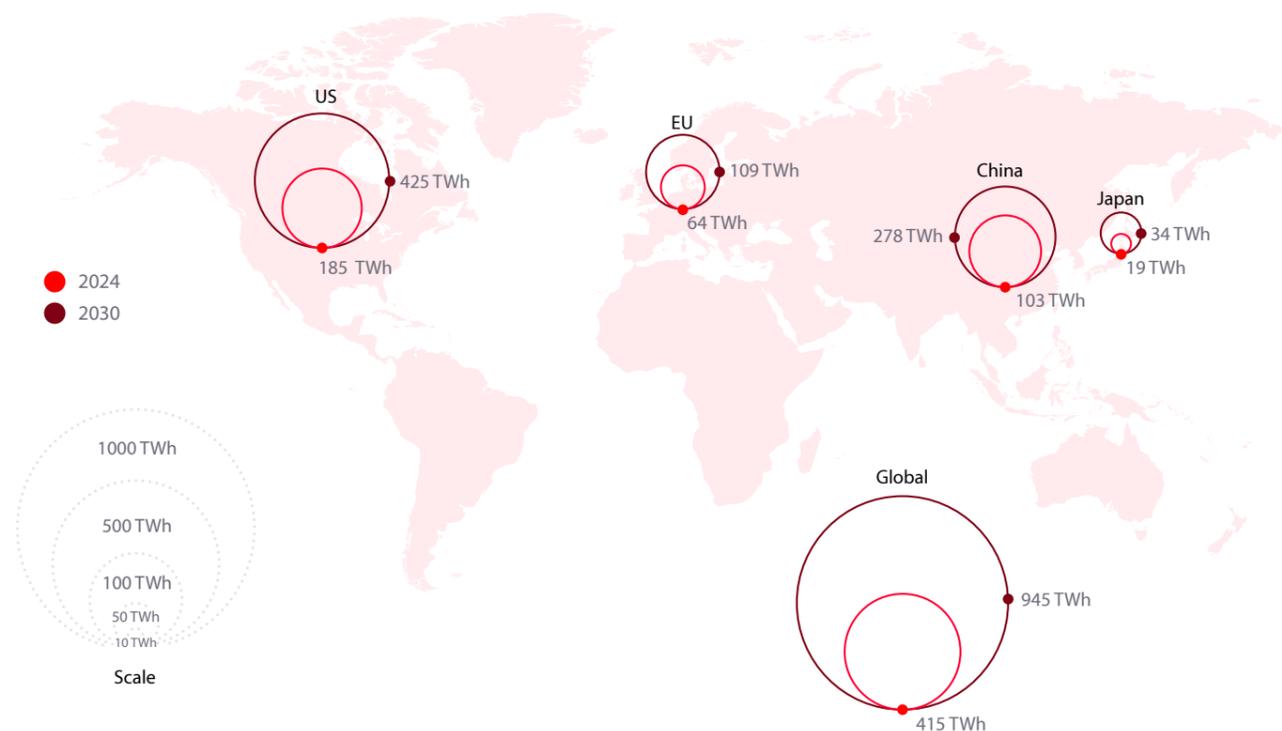
The build-out of data centers is an inevitable consequence of the technological advancements that improve our way of living, from accurate weather forecasting, predicting potential natural disasters, to improving research and innovation across all industries. However, this growing impact on our energy system also presents challenges.

- **Data center electricity consumption is outpacing existing energy supply.** Electricity consumption by data centers is outpacing existing energy supply, with demand increasing at a rate that supply simply cannot match in many areas. The US and the EU are already facing difficulties meeting demand, while China is still able to keep up, as it is rapidly increasing generation capacity to meet rising energy needs.
- **The current grid is not ready to provide the required energy supply, resulting in grid connection queues.** Queues are growing longer, and in some places the wait to connect is as long as a decade. This is partly due to a lack of generation capacity, local resource constraints, stringent bureaucracy, and uncertainty over who bears the grid upgrade costs.
- **Data centers have a local impact on resources.** If not managed properly, rising energy demand from data centers risks increasing electricity prices for consumers, putting a strain on local water availability, and driving up emissions if powered by carbon-based electricity supply.

## Key actions to overcome these barriers:

- **Efficient data centers can slow the increase in power consumption.** The adoption of energy-efficient solutions kept pace with data center growth for many years. However, with the rapid expansion of data centers, improving the efficiency within data center operations must now take priority to prevent energy waste and meet rising energy demand. Wasting energy and water in the energy sector will harm the progress of electrification in other sectors, have a negative impact on the environment, make countries more dependent on energy imports, and harm competitiveness. *Explore concrete examples in Chapter 2.*
- **A holistic approach to data center planning can make them both consumers and providers of energy, alleviating political and local concerns.** Energy efficiency is not only about data centers using less energy, but also using the available energy at the right time. By maximizing the potential of 'demand response' and strategically integrating the data center sector with other sectors, we can recover excess heat and leverage data centers' large electricity loads as a grid-balancing mechanism. *Explore concrete examples in Chapter 3.*

**Figure 1**  
Current and projected electricity consumption of data centers<sup>11</sup>



## The age of data centers

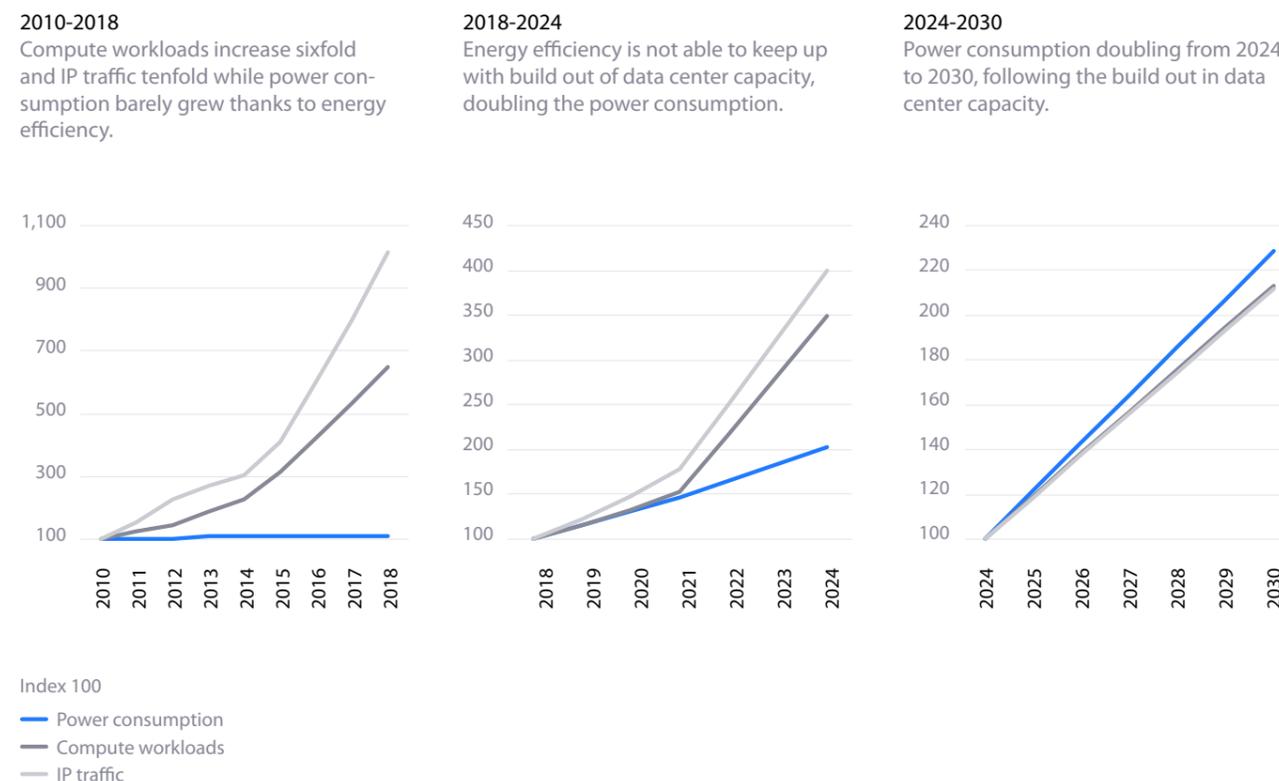
As our economy and daily lives increasingly depend on cloud services, AI, and real-time information, our reliance on data centers has become foundational. They are both a product of technological progress and a prerequisite for modern society.

For a long time, energy-efficient designs helped keep in check the impact of data centers on the energy system. But as data centers grow and become more central to our economy and daily lives, reducing their footprint has become increasingly difficult. Data centers will soon account for 3% of global final energy consumption, up from 1.5% today. The IEA projects that global data center electricity demand will double by 2030<sup>12</sup> while other studies project even higher increases.<sup>13</sup> This surge in

demand is expected to be concentrated in the US, China, and the EU (Figure 1).<sup>14</sup> For that reason, this paper aims at bringing forward scalable solutions that improves data center’s sustainability in areas experiencing high growth, especially the US, China, and the EU. However, data center growth is global, and the content of the paper is relevant in every region facing a surge in data center build-out, such as the Middle East, Africa, and Canada.<sup>15,16</sup> The rapid build-out of data centers is straining the grid, prompting cities and even entire countries to slow or halt new data center permits.<sup>17,18,19</sup>

There is nothing to suggest that the role of data centers will stagnate. Data centers serve as the backbone of our increasingly digitalized world and have become indispensable. As their role grows, so too does the conversation about their impact.

**Figure 2**  
Trends in global data center capacity and power consumption since 2010<sup>20</sup>



## Doing data centers right: where efficiency meets opportunity

Up until 2018, it was possible to expand data center capacity extensively without major grid implications. From 2010 to 2018, global data center computing capacity and IP traffic grew many times over, while energy use increased only slightly (Figure 2). Massive energy efficiency improvements in data centers managed to keep up with the expansion. However, from 2018 to 2024 energy efficiency has not been able to keep up with the surges in compute workloads and IP traffic, largely driven by an increasingly digitalized economy and AI proliferation.

To meet rising data center power demand, we need to build new and highly efficient data centers, and deeper integration of them with our energy system. With data

center growth expected to continue through 2030 and beyond, the case for a two-pronged approach to managing their energy demand is clear:

- 1 Data centers must become more operationally efficient by using state-of-the-art technology to improve energy use and boost productivity.
- 2 We must look beyond the operational efficiency of data centers and leverage AI, waste heat, and flexibility in energy systems globally.

By operating data centers as efficiently as possible and integrating them into the broader energy system, we can turn data centers from a challenge into an opportunity. If implemented well, data centers can help phase out fossil fuels, reduce grid investment needs, and shield consumers from rising electricity prices.

## Chapter 2

# Sustaining growth through efficiency

Data centers currently consume 1.5% of global electricity and are projected to nearly double their energy and water use by 2030, driven largely by the rapid rise of AI and cloud computing.<sup>21</sup> The stakes are high: poorly managed growth risks stressing our energy grids and worsening water scarcity. This makes energy efficient data centers not simply a cost issue, but a foundational requirement for grid connection, permitting, and long-term system resilience. At the same time, resource efficiency improvements inside the data center deliver important co-benefits, including improved reliability for surrounding communities and noise reduction. Against this backdrop, understanding where and how energy and water are used inside a data center becomes essential. The solutions already exist, but what's needed now is deployment at scale.

## Challenges to optimizing energy efficiency in data centers

Despite efficiency gains in recent years and the availability of technical solutions that can improve energy and water efficiency, resource transparency or enforcement of minimum performance standards is still at a minimum. Efficiency is therefore merely treated as voluntary ambition rather than a requirement, which limits progress on both energy and water performance. Cooling alone has a key role to play in efficient data centers and permitting and reporting frameworks rarely account for regional water stress or the efficiency of modern cooling system designs.

- **Lack of standardized efficiency reporting.** Most jurisdictions rely on voluntary reporting rather than mandatory disclosure of metrics such as Power Usage Effectiveness (PUE), Water Usage Effectiveness (WUE), or Energy Reuse Factor (ERF), hindering comparability and continuous improvement. Current reporting also varies due to differing interpretations and approaches.
- **No common sustainability rating system.** The absence of an internationally recognized framework prevents benchmarking and discourages investment in best-in-class solutions.
- **Water-responsible policy lags behind innovation.** Water-responsible policy does not get the required attention. Regulatory frameworks do not consider the important link between water usage and cooling technology. In the absence of standards that recognize or reward closed-loop and direct-to-chip systems, operators lack clear incentives to adopt them.

## Key actions to overcome these barriers:

- **Introduce mandatory reporting.** Require transparent reporting of at least PUE, WUE, and ERF for both new and existing data centers, regardless of capacity or type, and use the data to establish binding minimum performance thresholds. Use international standards such as ISO to ensure cross-regional comparability.
- **Promote water-responsible cooling.** Prioritize closed-loop cooling and direct-to-chip technologies, particularly in high-stress regions, and integrate water use into environmental impact assessments to prevent local depletion.
- **Establish a sustainability rating scheme.** Develop a standardized sustainability certification system for data centers to benchmark performance and guide procurement, financing, and permitting.

## Key terms: Data center efficiency

There are several important metrics for policymakers to understand when evaluating the performance of data centers:

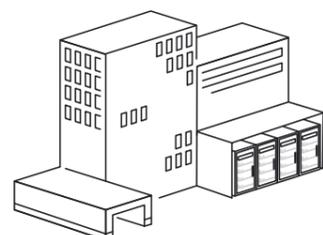
- **Power Usage Effectiveness (PUE)** is a ratio that describes how efficiently a data center uses energy — specifically, how much energy is used by the computing equipment. PUE is the ratio of the total amount of energy used by a computer data center facility to the energy delivered to computing equipment. The lower a data center's PUE is, the more energy-efficient the facility is.
- **Energy Reuse Factor (ERF)** is the ratio of energy being reused (e.g., as captured waste heat) divided by the sum of all energy consumed in a data center. The higher a data center's ERF is, the more of its energy use is beneficially reused.
- **Water Usage Effectiveness (WUE)** is the ratio between the use of water in data centers and the energy consumption of the IT equipment. The lower a data center's WUE ratio is, the more efficient its use of water resources is.
- **Energy Reuse Effectiveness (ERE)** measures the extent to which a data center reuses the heat it generates. Unlike ERF, which quantifies how much

energy is reused, ERE shows how energy reuse changes the data center's effective efficiency. The lower a data center's ERE is, the greater the positive impact of energy reuse on overall efficiency.

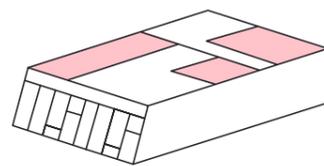
- **Carbon Usage Effectiveness (CUE)** is a metric developed by The Green Grid to measure data center sustainability in terms of carbon emissions. CUE is the ratio of the total CO<sub>2</sub> emissions caused by total data center energy consumption to the energy consumption of IT equipment. The lower a data center's CUE is, the lower its carbon emissions per unit of IT energy.
- **Renewable Energy Factor (REF)** represents the ratio of total renewable energy consumption to total energy consumption. Similar to CUE, this metric helps to understand the carbon intensity of energy input into a data center. The higher a data center's REF is, the greater the share of its energy that comes from renewable sources.

Each of these metrics can be assessed in the performance evaluation of a data center, through modeling or real-time performance evaluation, to help determine both financial costs and ESG impacts (and impact improvements) of a data center.

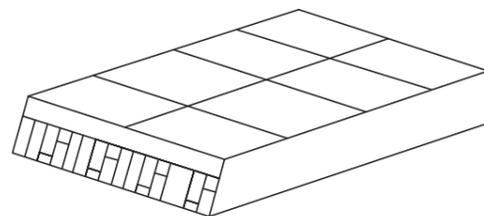
Figure 3  
Types of data centers<sup>22</sup>



**Enterprise**  
Typically owned and operated by a single entity for its own use.

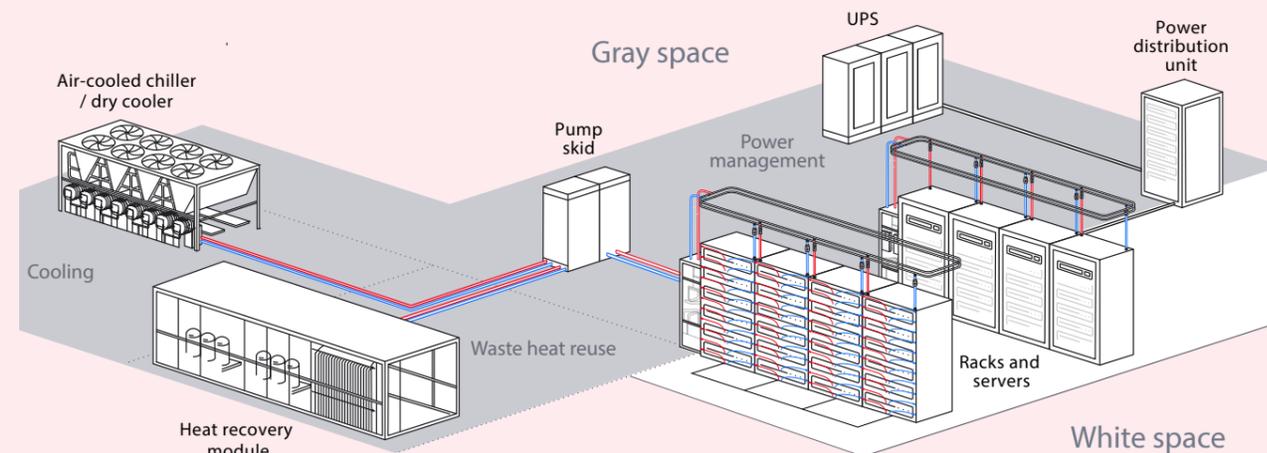


**Colocation**  
Typically owned and developed by a third party, and leased to one or more businesses.



**Hyperscale**  
Typically owned and operated by global cloud provider.

Figure 4  
The gray and white space within a data center



Explainer

## White space and gray space in a data center

A data center is generally organized into two main zones: the white space and the gray space. The white space is the heart of the facility, where computing takes place. This includes the servers and storage systems that carry out the data processing and communication tasks — the core function of data centers. As these components operate, they generate significant heat as an unavoidable byproduct of continuous computing. The same type of heat you feel from having your laptop on your knees.

Surrounding and supporting the white space is the gray space, which houses the infrastructure needed to power and cool the IT equipment. The gray space includes uninterruptible power supply (UPS), chillers, fans, pumps,

compressors, transformers, and backup generators. Some cooling systems span both the white space and the gray space. While part of the cooling happens in centralized systems in the gray space, other cooling occurs close to the servers, or even directly at the server racks, to remove heat where it is generated.

The white space relies on the gray space for stable power and effective cooling, without which the IT equipment will overheat and not operate reliably or break down. Cooling is critical for data centers, since even short periods of inadequate temperature control can lead to performance slowdowns or complete hardware failures, which can cause significant financial damages.

“Energy efficiency solutions, including advanced cooling, retrofits, and AI-optimized operations, can dramatically reduce data centre energy use, but remain underused due to regulatory, financial, and technical barriers.”

United Nations Environment Programme Copenhagen Climate Centre<sup>23</sup>

## Digital solutions across the data center

Digital solutions are becoming essential for achieving high levels of efficiency in data centers. As AI adoption accelerates and the demand for data centers expands, governments face the challenge of enabling this growth while ensuring that local communities still have access to a reliable and affordable grid. Without highly efficient, digitally-optimized operations, the rapid build-out of data centers risks intensifying local pressures, including rising electricity costs, grid instability, and increased noise pollution. Achieving a high level of operational efficiency requires greater usage of digital solutions such as sensors and data-driven transparency.

Sensors allow operators to access and analyze key data across the data center. They provide visibility into temperatures, airflow, and pressure differences that were previously managed through estimates rather than real-time insights. This shift enables more accurate, data-driven operations.

Without this level of insight, operators must optimize based on incomplete information, increasing the risk of inefficient and unstable operations, including over-cooling and overheating of servers. These conditions increase electricity use, place strain on cooling and IT equipment, and raise the risk of outages and downtime.<sup>24</sup>

At Three UK’s data centers, handling around 28% of the UK’s mobile data traffic, high data-processing demand creates substantial cooling needs and electricity costs. **After deploying sensors and real-time optimization tools, Three UK reduced cooling energy use by 12.5% across four sites in less than ten weeks.**<sup>25</sup> As cooling

typically accounts for 30–40% of a data center’s energy use, improvements in this area can generate significant cost savings.<sup>26</sup>

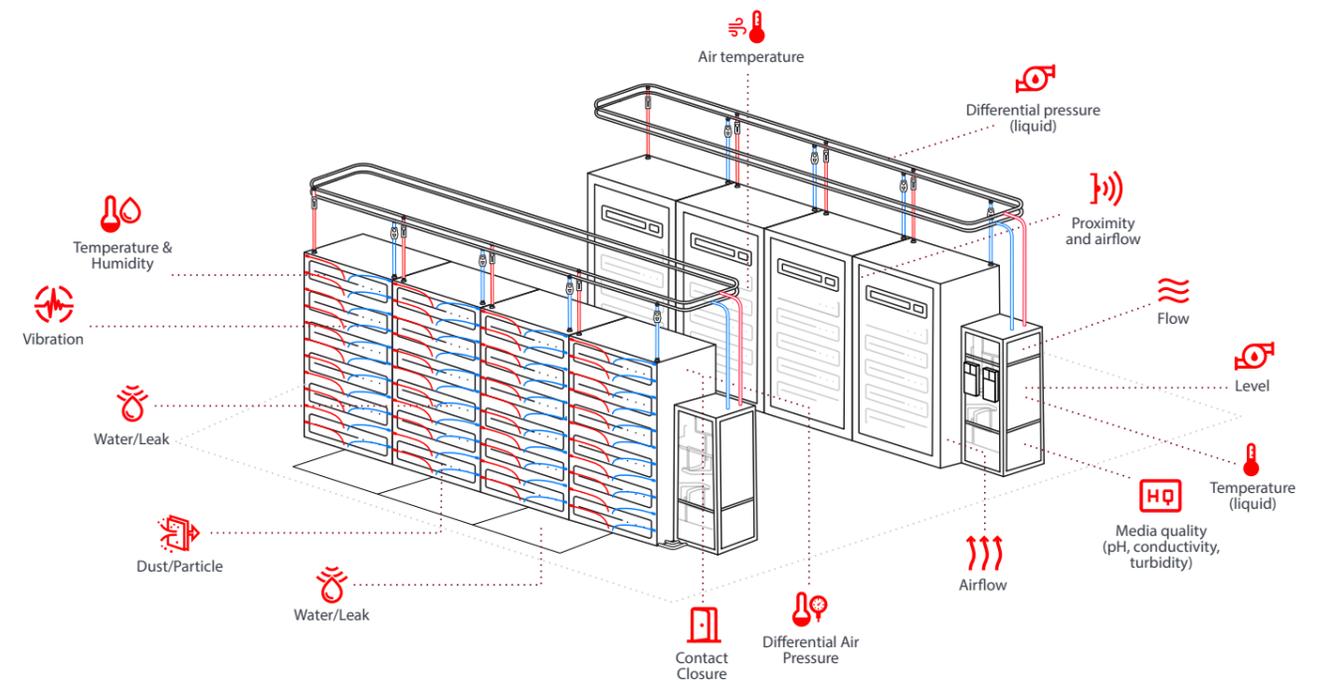
For Three UK, the lower cooling demand translated into annual operating-cost savings of approximately GBP 233,000, a figure expected to grow as electricity prices rise.<sup>27</sup> Put another way: these cost savings give Three UK a competitive edge over companies that have not invested in such digital upgrades.

Other operators are also using AI tools to improve their cooling and airflow. For example, Meta has applied AI-based airflow optimization since 2021, reducing cooling-fan energy use by around 20% and water consumption by 4%.<sup>28</sup> As far back as 2016, Google famously applied DeepMind’s machine learning to its data center HVAC, cutting cooling energy use by up to 40%, and improving PUE by 15%.<sup>29</sup>

Beyond direct energy savings, digital solutions improve operational reliability through predictive maintenance. Sensors and data-driven controls allow operators to identify equipment issues early. Reducing unnecessary equipment use and limiting wear and tear means extending component lifetimes. Not only does the predictive maintenance reduce downtime but also resource waste, e.g., delivering more precise and efficient cooling exactly when and where it is needed.<sup>30</sup>

Cybersecurity is becoming increasingly critical as data centers rely more heavily on connected monitoring, automation, and digital control. Protecting data flows and control systems helps ensure that digital tools across the data center run safely and without disruption. This can create a secure foundation for more advanced, AI-driven optimization.

Figure 5  
Sensors in a data center



### Case story

## Increasing efficiency with sensors in an old data center

A federally operated data center serving the US Department of Agriculture in St. Louis demonstrated the potential of installing a network of wireless sensors to optimize their cooling needs. Instead of replacing equipment or redesigning the cooling system, the team focused on improving visibility by placing sensors across the data center to capture real-time temperature, humidity patterns, and pressure. Alongside the sensors, the operators installed an integrated software platform to help analyze the data.

With improved visibility, the data center was able to cut its cooling load by 48% and reduce total facility power use

by 17%. These changes saved roughly 657 MWh annually, improved the site’s PUE from 1.83 to 1.51, and lowered operating costs by nearly USD 30,000 per year, despite being in a region with very low electricity prices. The whole project had a payback time of 3.4 years and was estimated to cause an annual reduction of 542 metric tons of CO<sub>2</sub>.<sup>31</sup>

The project demonstrates the importance of visibility for upgrading cooling performance in legacy data centers. For facilities facing rising energy demands, this kind of digital upgrade offers a practical and cost-effective way to achieve meaningful savings without major infrastructure changes.

## Technology potential: Digital twin

Another powerful solution that AI can help scale is the use of digital twins: virtual replicas of machines, processes, or even entire factories. By mirroring real world operations in a dynamic digital environment, digital twins make it possible to test scenarios, optimize performance, and predict failures long before they occur.

In energy-intensive sectors such as HVAC and cooling, the impact is already clear. End-to-end digital twin-enabled data center projects have shown up to 20% energy savings,

25% lower development costs, and 30–50% reductions in unplanned downtime, thanks to fewer breakdowns. This not only minimizes operational disruptions but also reduces maintenance expenses and extends equipment lifetime.<sup>32</sup>

With continuous AI-driven monitoring, digital twins can optimize energy flows in real time, detect anomalies, provide early warnings, and generate actionable insights. The result is a smarter, more resilient, and more sustainable operation — one that learns, adapts, and improves every day.

## Advanced cooling for an efficient data center

Delivering on data centers' potential to revolutionize clean technologies requires massively increased computing power. As chips become more powerful, they generate far more heat within the same physical space. This rising heat density is now outpacing what traditional cooling systems can manage.

To meet rising computing demands, an increasing number of operators are turning to direct-to-chip liquid cooling, a closed-loop system that brings the cooling liquid (i.e. 'coolant') directly to the processor. Compared to traditional methods of cooling, closed-loop direct-to-chip liquid cooling is far more effective at removing heat, consumes far less water, and typically delivers at least 15% energy savings.<sup>33</sup> These efficiency gains are increasingly important in regions where grid capacity and water supply are limited, helping data centers reduce their local footprint and operate more responsibly as demand grows.

Liquid cooling also brings important benefits to the communities around data centers. It generates significantly less noise than traditional air-based cooling, reducing local disturbances. In addition, it also enables easier recovery and reuse of waste heat — a benefit which is largely untapped today.<sup>34</sup>

Beyond cooling processors, liquid cooling can also enhance power electronics in data centers. Power electronics make up the systems that manage and deliver electricity inside the data center, such as uninterruptible power supply (UPS) systems. These systems are presently air-cooled, which

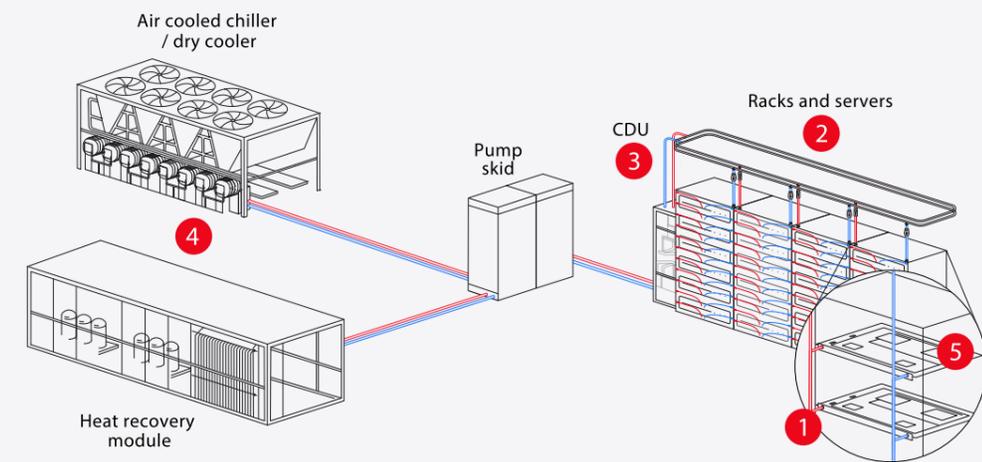
limits their power density. By removing heat more effectively than air cooling, liquid cooling can enable power electronics to operate at higher power levels in a smaller physical footprint, reducing both space requirements and material use. Importantly, liquid cooling also prevents humid or dirty cooling air from entering the system, which can compromise the reliability of electronics. And because cooling fans are no longer needed, audible noise is reduced.

Other prominent forms of liquid cooling known as 'single-phase' and 'dual-phase' immersion cooling also exist — though they are still in development and are rarely deployed in a commercial setting. These processes involve entirely submerging server racks in non-conductive cooling fluids to maintain safe operating temperatures. While these offer strong potential for energy and water savings, they also come with drawbacks — including high fluid viscosity that can create pumping difficulties, and the use of tightly regulated coolants.

In practice, many data center operators deploy a mix of cooling approaches, combining advanced air cooling with different forms of liquid cooling depending on workload requirements and the operational context of the facility.

While energy efficiency often dominates the conversation, the water footprint of data centers can also be critical, as many facilities rely heavily on water for cooling. Globally, data centers consume 560 billion liters per year, and this could rise to 1,200 billion in 2030.<sup>35</sup> That's six times the EU's total freshwater abstraction in 2022.<sup>36</sup> Shifting to more water-efficient cooling technologies such as closed-loop direct-to-chip liquid cooling is therefore essential not only for reducing energy demand but also for dramatically lowering water consumption.

Figure 6  
Direct-to-chip liquid cooling system structure



## How direct-to-chip liquid cooling works

In a direct-to-chip system, coolant continuously circulates in both directions, carrying heat away from the chip and returning cooled liquid back to the chip. The steps below describe the process starting from the moment the coolant absorbs heat at the chip.

- 1 Heat is absorbed at the chips through a cold plate**  
A cold metal plate sits directly on top of the chips, such as CPUs or GPUs. Coolant flows through tiny channels inside the plate and picks up heat right at the chip.
- 2 Coolant moves through hoses, valves, and couplings in the rack**  
The now warmed coolant then travels through a network of hoses, valves, and couplings. These small components appear throughout both the white and gray space, and because there are hundreds of them in a single rack, their efficiency matters. For example, more efficient couplings can reduce unnecessary flow resistance, meaning pumps use less electricity to move the same amount of coolant. Coupling designs on the market today can save 246 kWh/ server rack compared to the standard solutions, simply because there is less friction in the system (read more about this in case *Chasing the margins in liquid cooling holds tremendous savings potentials*).<sup>37</sup>
- 3 The Coolant Distribution Unit (CDU) manages the cooling loop**  
All coolant from the rack flows into a Coolant Distribution Unit (CDU), which separates the server cooling loop (secondary loop) from the facility water system (primary

loop). The secondary loop circulates coolant within the IT equipment, while the primary loop carries heat away via the facility water system. Inside the CDU, a heat exchanger transfers heat from one loop to the other while maintaining stable temperatures.

The CDU also contributes to energy efficiency by managing pressure and flow across the cooling loop. By ensuring that coolant is circulated at the required levels, without excessive pumping, it helps limit unnecessary energy use. Sensors are increasingly used to monitor temperature, pressure, and flow, supporting stable and efficient operations.

- 4 Heat is removed by chillers powered by compressors, or recovered to be reused**  
The heat carried by the coolant is transferred to the primary loop where it is either reused or removed by compressor-driven chillers and released outdoors. The choice of compressor technology can influence both efficiency and operational impacts. Oil-free compressors, for instance, avoid oil-related losses and experience less mechanical wear, which can contribute to longer equipment life and more stable performance. They also typically generate less noise than conventional designs, helping to reduce local noise impacts.

- 5 The cooled liquid returns to the chips**  
After cooling, the liquid returns through the secondary loop to the cold plates on the chips. Because liquid transfers heat far better than air, this closed-loop system remains efficient even at very high rack densities.

## Technology potential: Chasing the margins in liquid cooling holds tremendous savings potential

As data centers grow, even small efficiency gains can have an outsized impact. Within liquid cooling, there are meaningful choices to be made, and opting for state-of-the-art solutions will drive big savings. Choosing the most efficient solutions can save 246 kWh/server rack compared to the standard solutions, simply because there is less friction in the system.<sup>38</sup> A large 1 GW hyperscale data center can hold as many as 8,700 server racks. Selecting the efficient liquid cooling solution can save 1.9 million kWh/year,

equivalent to 175 US households. With electricity rates in Northern Virginia, one of the world's largest data center hubs, this could save USD 188,000 every year, savings that will only grow as electricity prices rise.<sup>39</sup>

As data centers become even bigger and more power hungry, so do the benefits of choosing the energy efficient options — both for the energy bill and the local grid.

## Variable speed drives for optimized control

There are electric motors all over a data center's cooling system, controlling key components such as compressors, pumps, and fans, all of which play a central role in maintaining stable temperatures. By adjusting the speed of these motors to match actual need, rather than running continuously at full power, a variable speed drive (VSD) can reduce cooling-related energy use by 15-40% while maintaining required temperatures. In addition to lowering energy consumption and improving Power Usage Effectiveness (PUE), VSDs reduce mechanical stress

on equipment, helping extend component lifetimes, lower maintenance needs, and improve overall system reliability.

Beyond basic motor regulation, modern VSDs increasingly operate as core components within data centers' broader digital infrastructure. Using input from sensors and other monitoring systems, VSDs can respond to real-time operating conditions and allow for greater predictive maintenance of the facility. With predictive maintenance, emerging cooling issues can be identified early, thereby supporting the uptime and reliability of a data center. Even short downtimes for data centers can disrupt services, cause data loss, and have significant economic and operational consequences.

### Case story

## How Tencent in China uses liquid cooling to support high-density data centers

As Tencent's cloud and AI services have expanded, its data centers have had to handle far more powerful servers that generate much more heat. In response, Tencent introduced direct-to-chip liquid cooling. In this setup, around 75% of the server's heat is removed by liquids, greatly reducing the need for fans and air conditioning. The cooling system can operate with an inlet water of up to 37°C, which allows it to rely on natural cooling using outdoor conditions rather than chillers. As a result, much of the cooling process requires less mechanical equipment and electricity, lowering overall operating costs.

In parallel, Tencent shifted to a more modular way of building data centers, making it easier to add new computing capacity as demand grows. The liquid-cooling system was adapted to support this approach, ensuring reliable operation and effective control as the data center expands.

By combining liquid cooling with modular deployment, Tencent reduced cooling-related electricity use, improved overall efficiency, and enabled rapid expansion of high-density data centers under tight power constraints.<sup>40</sup>

### Case story

## Retrofitting data centers with variable speed drives to reduce energy use in Colorado

Across the United States, data centers are facing rising electricity prices and mounting pressure to reduce their energy footprint. In Colorado, Enabled Energy showed how a simple retrofit to existing cooling equipment could deliver large, immediate energy savings by installing variable speed drives in six different data centers. The project demonstrated the untapped potential for efficiency upgrades in legacy facilities.<sup>41</sup>

The six data centers in the project relied on air-handling units, specifically computer room air condition units (CRAC), that operated at a constant fan speed. This approach consumed far more energy than necessary, particularly during periods of lower cooling demand. This resulted in avoidable electricity use, higher operating costs, and faster wear on equipment.

When VSDs were installed onto the air-handling units, fan output could be adjusted to match real-time cooling needs. While each data center only installed between 3–6 VSDs per site, each of the six data centers saw significant efficiency gains and cost savings. **Through optimizing the energy use of cooling with VSDs, it resulted in annual energy savings of over USD 157,000 across the data centers, with an average estimated project payback time of 1.41 years.** Better airflow management additionally strengthened operational resilience, cut emissions, and improved the lifetime of existing data center equipment.

This project shows how many existing data centers can significantly reduce energy consumption without waiting for new innovative cooling technologies or major capital investments.<sup>42</sup>

# Data centers as energy assets

Transforming data centers from a burden into an environmental and economic opportunity means seeing them as a key part of our energy system. If placed in optimal locations with the right connections to both energy producers and consumers, they can become major sources of flexibility and low-emissions heat, lowering costs, increasing competitiveness, and strengthening energy security.

## Challenges to data centers' role as a key part in the energy system

Current policy and planning frameworks treat data centers as isolated electricity users rather than active participants in the wider energy system. The technical potential for waste heat reuse and energy-system integration is well established but remains untapped. This disconnect limits the contribution data centers can make to decarbonization, resource recovery, and grid stability.

- **Waste heat remains largely untapped.** Permitting and planning often focuses on grid access rather than closeness to industrial users or heat networks, leaving most waste heat unused.
- **Flexibility potential is underutilized.** Regulatory and market rules rarely let data centers take part in demand-response or flexibility markets, limiting their role in supporting grid stability and renewable energy integration.
- **Planning is fragmented.** Local and regional authorities often lack mandates or coordination mechanisms to integrate data centers into energy and infrastructure planning, leading to missed synergies.
- **Local community opposition can be severe.** Adding large electricity users to the grid can drive up bills and stress the local network if not managed carefully. Likewise, the water needed for cooling can create local impacts.

## Key actions to overcome these barriers:

- **Incentivize waste heat recovery and reuse.** Require new data centers to assess heat-recovery potential as part of their permitting process and encourage placement near industrial off-takers or district heating. Where possible, facilities should be "heat-reuse-ready" through standardized pre-piping, cabling, and dedicated space for a heat pump. Benefits realized by heat recovery hardware and heat pumps should positively contribute to the data center's performance indicators. Encouraged use of closed-loop direct-to-chip liquid cooling helps to mitigate local water impacts.
- **Enable flexibility and system integration.** Adapt market rules and tariff structures to reward data centers for enabling demand response and grid services. Promote local microgrids linking data centers with renewable generation, heating networks, and energy storage.

## Strategic planning unleashes data center potential

The accelerating growth of data centers represents a challenge, but also an opportunity to make them assets to our energy system. How societies manage to plan data centers into the wider energy system will have a tremendous impact on the grid, the environment, and the economy. The solutions exist, but without a change in approach, data centers could become a major burden for societies.

We have previously explored how to design the future energy system in *Danfoss Impact No. 4 — Energy efficiency 2.0: Engineering the future energy system*.

Located just outside Washington DC, US, one of the world's largest data center hubs consumes as much power as the entire city of Boston. In Data Center Alley, home to 200 data centers, 60 of them suddenly dropped off the grid and switched to back-up power without warning in the summer of 2024. This disruption was caused by a standard safety mechanism across the data center industry, and it led to a massive drop in energy demand, pushing the grid into crisis. Only a last-ditch intervention by grid operators prevented a cascading regional power outage.<sup>43</sup> By carefully integrating data centers into the energy system, events like these can be avoided, and, in fact, the opposite can be achieved: securing greater grid stability.

Electricity prices can also skyrocket because of data center demand. In the US, the demand expected from data center and crypto mining growth by 2030 means that electricity costs could increase by 8% nationally. Alongside such cost increases, an additional 275 million tons of CO<sub>2</sub> could be emitted, equivalent to the annual emissions from the energy sector in France.<sup>44</sup> Consumers have already started to foot the bill for the surge in electricity demand. Electricity prices are now as much as 267% higher than five years ago in areas where many data centers have been constructed.<sup>45</sup> These cost increases are being passed on to everyone, from households, to industries, and even to data center operators.

Another challenge is that large grid connection queues will slow down the roll-out of data centers. Some 20% of the planned data center connections will be delayed until 2030, simply because the grid cannot keep up. Already now, connection queues for new data centers are year-long. In the US, the average wait time is one to three years, and can even reach seven years in some states. In the Netherlands, the wait time is up to 10 years, while in Kanto, Japan, it is more than five years.<sup>46</sup> Cities, and even whole

countries, have put the brakes on issuing data centers permits because the grid cannot keep up.<sup>47,48,49</sup>

This is why it is crucial that we begin to see data centers differently. By positioning data centers as integral elements of our energy systems rather than just users, it transforms them from a challenge to an opportunity. Data center owners as well as politicians need to ask themselves how synergies across energy producers and consumers can be taken advantage of.

The following section will explore how data centers present major opportunities for societies. Leveraging AI can optimize all corners of societies in unprecedented ways. Tapping into waste heat can warm up entire cities with the right planning. And because they use so much electricity, data centers can help balance the grid by shifting some of their energy use to off-peak times.

## AI can save energy across all of society

AI alone could become a cornerstone of building a more resilient energy system. AI could save around 2,200 TWh of energy by 2035 in industry alone. That is roughly equal to the EU's industrial energy demand and far more than the projected total data center energy demand.<sup>50</sup> For example, gathering high-resolution data with sensors and applying AI-driven analytics and controls, it is possible to unlock hidden efficiencies and reduce downtime significantly in industrial motor systems (see case *Optimizing industrial motor systems through AI*). Another solution that can be proliferated through AI is digital twins, virtual replicas of processes or factories. They can accelerate optimal energy efficiency implementation and process optimization.

On top of savings in industry, AI could enable 278 TWh of electricity savings in the heavy-duty trucks sector and 833 TWh in the road freight sector — the latter is equivalent to the total energy demand of Argentina. In the buildings sector, AI could lead to 300 TWh of electricity savings globally in digitalized, electrical HVAC systems. Additionally, AI can also serve a grid-balancing function. For example, it has the potential to cut localized outage durations by 30-50% through early fault detection.<sup>51</sup>

Additionally, AI can boost energy resilience through operational improvements within the energy sector. For example, grid-balancing AI can cut localized outage durations by 30-50% through early fault detection.<sup>52</sup>

**AI could save around 2,200 TWh of energy by 2035, in industry alone.** That is roughly equal to the EU's industrial energy demand and far more than the projected total data center energy demand.

### Case story

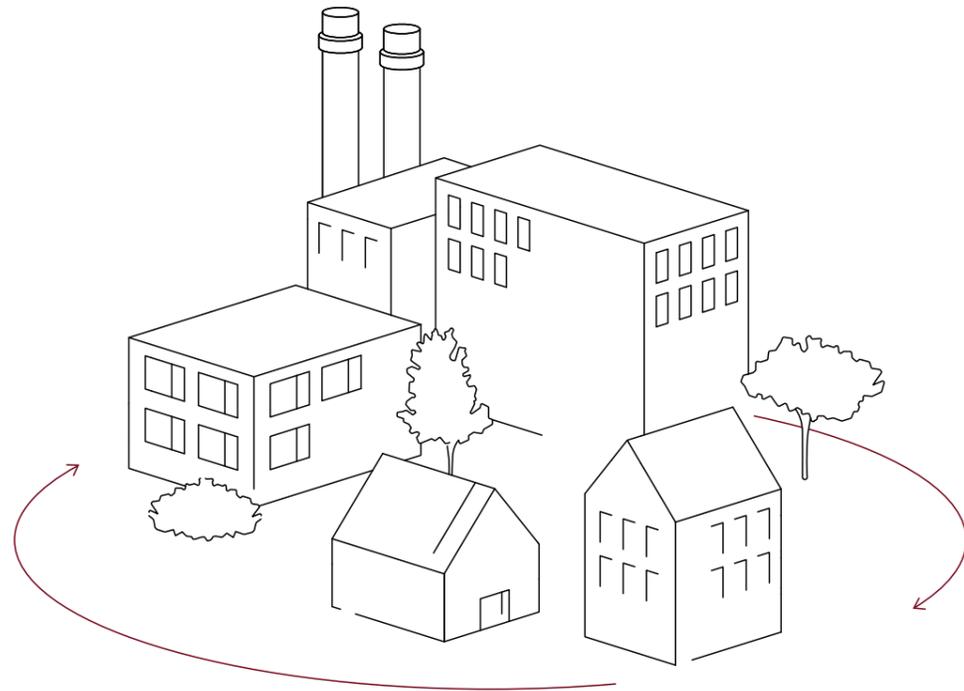
## Optimizing industrial motor systems through AI

It is now possible to connect legacy and analog motor systems to the cloud to gain insight about both component efficiency and overall system efficiency. Many modern variable speed drives (VSDs) are equipped with on-board microprocessors. This means that they can be used as sensor hubs to collect and process data about the motor system. In short, by gathering information on vibrations, pressure, and temperature and processing them in an AI-based cloud, VSDs can digitize an entire facility's systems and give companies deep insight into how to optimize operations.

A case catalogue from EMSA — an IEA-affiliated motor efficiency research organization — presents various cases on how digital technologies such as VSDs can boost industrial motor system efficiency.<sup>53</sup> For example, Hamilton Bonaduz — a large Swiss medical equipment manufacturer — implemented VSDs and sensors throughout an air compression system, providing insights into how to further optimize the system. By doing this, the company was able to reduce the system's electricity consumption by 16% while producing the same amount of air volume.

In addition to digital VSD capabilities, the EMSA catalogue also highlights other digital tools such as software and digital controls, which can further optimize a motor system. For example, at IKEA in Sweden, advanced controls combined with online performance monitoring optimized compressors and load shifting in chillers, resulting in 20% electricity savings. In Austria, BMW established a comprehensive data collection system to monitor electricity and compressed air consumption, which included visualizations of electricity consumption on production lines. Additionally, base load targets were set per line for non-production times in 2016 and 2019, leading to respective savings of 52% of the original electrical base load and 14% of the compressed air base load.

Across the cases presented in the EMSA review, digital solutions were applied to motors for pump systems, ventilation systems, air compressors, chillers, and production lines, providing significant savings in all applications. This evidence strongly supports the effectiveness of digital solutions in further increasing the energy efficiency of industrial motor systems.



The IEA estimates that 10% of the EU's space heating demand can be recovered from data centers near district heating grids by 2030 — and at a much more attractive price than natural gas.

## From energy consumer to heat provider

A majority of the energy used in a data center ends up as heat, and that heat can be captured and reused. A Microsoft data center in Finland is a great example of this potential, demonstrating that it is possible to recover 75% of its waste heat.<sup>56</sup> With the global power consumption for data centers set to double by 2030,<sup>57</sup> the waste heat potential from data centers is significant. This heat is currently wasted by simply being released into the atmosphere. Tapping into this free source of energy provides a great opportunity for providing affordable, low-emission heating.

As data centers run 24/7/365 and are 'critical facilities' with backup power systems to ensure they do not go down, they can provide a stable and resilient source of heat for off-takers, and this heat can be used at different scales. Already, there are multiple examples of data centers using waste heat to warm smaller facilities like greenhouses,<sup>58,59,60</sup> fish farms,<sup>61</sup> and pools.<sup>62,63</sup> It can also be reused to grow algae,<sup>64,65</sup> produce insects for food,<sup>66</sup> supply industrial process heat,<sup>67</sup> and supply space heating for nearby users in microgrids.<sup>68</sup> At a larger scale, the waste heat can be repurposed in the district heating network to heat cities. Already today, 35-85 TWh can effectively be recovered globally from data centers near district heating grids.<sup>69</sup> The IEA also estimates that 10% of Europe's space heating demand can be recovered from data centers near district heating grids by 2030 — and at a much more attractive price than natural gas.<sup>70</sup>

Let's walk through the process of waste heat recovery and reuse in data centers. As explained in Chapter 2 (p.19), the servers are cooled through air or liquid cooling. Air cooling cools the air around the chips, which in turn removes heat from the chips, while liquid cooling removes heat directly from the chip without relying on the surrounding air.

All this heat from the chips ends up in the cooling medium (air or liquid) and needs to be removed from the data center. In a conventional setup, this heat is simply released to the atmosphere, for example through a cooling tower, wasting energy that has already been paid for and has not served its full potential. Instead, the medium can be sent to a heat exchanger, where the heat is transferred to a second cycle, which is connected to an off-taker, for example an industrial microgrid or a district heating grid. Here, the heat is boosted with a heat pump to match the temperature needs of the grid. This process is especially efficient with liquid cooling, as it is already captured in liquid at a higher temperature than when rejected to the air, meaning less additional heat pump work is required to upgrade it to the required reuse temperature.

One of the key challenges is that waste heat from data centers can only be utilized if a suitable off-taker is available. The location of data centers is primarily determined by electricity grid access,<sup>71</sup> whereas other factors, such as access to renewable electricity and to waste heat off-takers, are less determining. This is not because data center operators are not interested in giving away their heat, but because doing so involves a complex landscape of stakeholders and legislation. Data center operators are in fact interested in repurposing the waste

### Case story

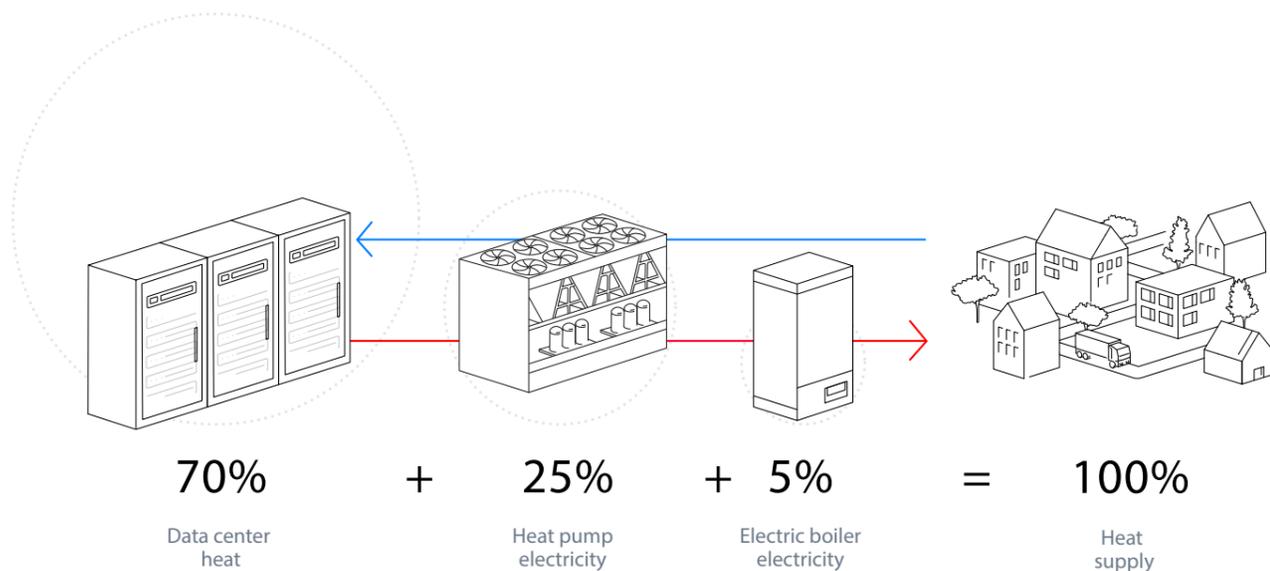
## Automating heating with AI

Both load-shifting and peak-shaving processes can be automated with digital technologies that control how or when equipment or machinery uses energy. This is achieved primarily through implementing digital tools known as model predictive controls. In buildings, for example, these **AI-driven technologies can save up to 20% of a building's energy costs by combining building, weather, and user data to predict heating and ventilation demand.** By utilizing such controls, buildings can pre-heat ahead of peak hours, or lower heating when the sun is about to shine on the building facades, thus saving energy. Observations on 100,000 apartments equipped with this technology, based mainly in Finland, show that

the maximum power usage was reduced by 10-30%.<sup>54</sup> Meanwhile, by shifting the consumption to the most economical period, the system ensures up to 20% savings in a building's energy costs without impairing the comfort of residents.<sup>55</sup>

While these technologies are currently aimed primarily at the residential building sector, their application is rapidly expanding in the industrial sector as well. **Early estimates from a Danfoss pilot show a potential to save 5% of energy used for heating in factories.** These savings are only expected to grow as the effectiveness of the technology in an industrial setting continues to develop.

Figure 7  
Principle of recycling waste heat<sup>72</sup>



heat as it is a burden for them. It is in the interest of all stakeholders, including off-takers, to make it easier and more attractive to reuse the waste heat.

The waste heat captured can be used in a wide variety of constellations in industrial clusters, microgrids, and district heating. Even in areas where there is no district heating infrastructure, it can still be profitable to set up a microgrid and utilize cross-sector synergies. For instance, you can see how a data center in Seattle, US, provides heating for a nearby building, projected to save 80 GWh over the course of 25 years (see case on p. 29).

Heat recovery can increase district energy resilience by adding multiple distributed heat sources and reducing reliance on a few large plants. To recover excess heat, sensors and control software regulate pumps, valves, and heat pumps to transfer heat from the data center to off-takers. Heat recovery can also require new digital connections with utilities or district-heating operators, increasing the number of interfaces that must be secured. While decentralization can create more potential entry points, it can also reduce single points of failure and make it harder for one incident to disrupt the entire heat supply. This is in addition to the resilience which a critical facility energy source itself, with its

associated uptime requirements, adds for waste heat users.

A frequently missed benefit of data center heat recovery is the elimination of heat rejection water use. The primary purpose of ongoing water use in data centers is to efficiently reject heat. Heat recovery 'closes the loop', eliminating this heat rejection water use requirement (read more in *Danfoss Impact Paper no. 7: The potential of the water-energy nexus*).

The opportunity to tap into waste heat immediately seems clear, and it can prove to be an important pillar in the energy system. Operators can earn money on a waste product, and cities and countries can tap into this source to phase out fossil fuels from their energy mix. The recovered waste heat can even help meet renewable energy targets.<sup>73</sup>

While the administrative burden is a very real concern for utilizing waste heat, the city of Stockholm is a notable example of a city that overcame these challenges through formalized partnerships and has managed to attract data centers and utilize their waste heat (see case *How waste heat is being recovered all over the world*).

### Case story

## How waste heat is being recovered all over the world

Data centers waste vast amounts of heat, but it does not have to be this way. Instead of simply releasing this heat into the atmosphere, it can be repurposed to warm residential and commercial buildings. Waste heat can be used in smaller microgrids — something Amazon has demonstrated at their Seattle, US, headquarters — or to supply heat to entire urban areas, as seen in Finland and Sweden.

### Amazon headquarters, Seattle, US, heated from neighboring data center

Amazon's Seattle headquarters shows how waste heat from data centers can be reused through local networks. Instead of relying on conventional boilers, the Amazon campus taps into waste heat through a microgrid from the neighboring Westin Building Exchange — a 34-story colocation data center. The result is comfortable offices warmed almost solely by energy that would otherwise be wasted. Two pipes move low-temperature water (18°C) from the data center to Amazon, where the heat is boosted to 54°C and distributed in the building. A 1.5-million-liter tank adds backup thermal storage to add heat on the very coldest days. This tank simultaneously works as a backup water supply for the Westin. The system is designed to heat almost half a million square meters and is projected to save 80 GWh of electricity over 25 years. The project offers a hedge against rising energy prices while also supporting Seattle's goal of becoming carbon-neutral by 2050.<sup>74</sup>

### Waste heat reuse at Wuqing Qingshu Science Park, Tianjin, China

The Wuqing Qingshu Science & Technology Park in Tianjin is a 103,450 m<sup>2</sup> mixed-use complex located around 400 meters from a cluster of data center facilities. The area is planned to host nine data centers, with more than 100,000 operational server racks.

The complex recovers heat from the data centers' cooling loops and uses it locally. In winter, the recovered heat supplies space heating and domestic hot water. In summer, the system switches mode and provides cooling for the park using rooftop cooling towers.

Even during its first winter of operation, when the occupancy in the complex was below its full capacity, the average heat cost fell by about 60% compared with local commercial district-heating rates.

At the complex's target occupancy level, the project is expected to reduce annual energy use by 1.1 million kWh for the adjacent data centers, while cutting emissions by an estimated 1,659 tons of CO<sub>2</sub> per year. The additional upfront investment required has an overall payback time of less than 3 years.<sup>75</sup>

### The world's largest data center heat recovery project in Finland

Just outside Helsinki, the world's largest data center waste heat project is underway. The utility company Fortum will recover the waste heat from Microsoft's two data centers in Hepokorpi in Espoo and Kolabacken in Kirkkonummi. When putting this heat to use, the data centers will provide 40% of the space heating in Espoo, Kirkkonummi, and Kauniainen, and can deliver 2-3% towards Finland's new emissions reduction targets. The heat recovery plants are expected to be active during the 2025-2026 heating season, where they will deliver 350 MW of heat.<sup>76</sup>

### Stockholm has included waste heat from 20 data centers in district heating

Stockholm is heated by one of the world's largest district heating networks and the ambition is to supply all the network's heat through renewables and recovered waste heat. Recovering heat from data centers is an integral part of this plan, and already in 2022, more than 100 GWh of energy was recovered to the district heating grid — about as much as the heating demand for 30,000 apartments.<sup>77</sup>

The Stockholm Datapark initiative has been instrumental in making this happen. Key stakeholders, such as the municipality and the fiber optic cable company, established a system that allowed data centers to navigate the complexities of sharing waste heat, easing the process of establishing themselves in Sweden and connecting to the district heating networks.<sup>78</sup>

It is a collaborative setup in which Stockholm Exergy, the city's energy utility, provides the infrastructure, while the data centers invest in heat pumps that enable heat recovery. The business model allows the data centers to sell their excess heat to Stockholm Exergi. Stockholm Exergi pays about EUR 190,000 per MW of heat supplied, compared to EUR 730,000 per MW of heat from unabated natural gas.<sup>79,80</sup>

## Policy potential: Data center waste heat can meet 18% of the EU's renewable energy target

The increasing excess heat generated by the powerful processing units in modern data centers not only requires operators to adopt innovative cooling methods, but it can also be reused to meet heat demand elsewhere. According to the IEA, waste heat from data centers can meet 10% of Europe's space heating demand by 2030.<sup>81</sup>

While the largest data centers will be placed too far from urban areas to make meaningful use of their waste heat, facilities situated within a few kilometers of heat off-takers could meet 300 TWh of heat demand.<sup>82</sup> The waste heat captured from data centers must be boosted with a heat pump to be usable in district heating, something that is especially efficient with waste heat recovered from liquid cooling.

Waste heat reuse is not only efficient, but also economically sensible. The IEA has reported that

waste heat from data centers can supply district heating networks at a cost of EUR 190,000-250,000 per megawatt of heat, compared to more than EUR 730,000 per megawatt of heat from an unabated natural gas combined heat and power plant.<sup>83</sup>

The EU must build out renewable energy capacity by 1,214 TWh by 2030 to reach their binding renewable energy targets.<sup>84</sup> As waste heat can be accounted as renewable energy,<sup>85</sup> tapping into data center waste heat can contribute significantly to reaching the binding target. Because waste heat recovered from air-cooled data centers must be boosted with heat pumps, data centers could still contribute 18% of the binding target,<sup>86</sup> turning data centers into a crucial lever for achieving affordable energy security and meeting climate ambitions.

# 18%

Potential contribution to the EU's 2030 renewable energy target.

# 10%

Waste heat from data centers could meet up to 10% of Europe's space-heating demand by 2030.

# €190-250k

per MW  
Cost to supply district heating with recovered data center heat, compared to >€730k per MW from unabated natural gas.

"Saving a unit of electricity during peak hours on a day with little renewable generation delivers significantly more carbon savings and environmental benefit than saving the same unit during hours of excess renewable generation."

Prof. Nick Eyre<sup>89</sup>

## Leveraging flexibility for grid resilience

The way data centers use electricity over the course of a day is not aligned with when that electricity is produced. Data centers run continuously, using huge amounts of electricity around the clock, while renewable energy is generated only when the sun shines or the wind blows. As a result, data center demand often fails to match renewable energy production. This misalignment between energy consumption and production is not just about data centers, it is one of the central challenges facing modern electricity systems.

When renewable electricity production is not enough to meet demand, fossil fuels are used to fill the production gap. This increases CO<sub>2</sub> emissions and electricity prices because fossil fuels are more expensive. On the other hand, when renewable electricity production exceeds demand, producers are sometimes paid to shut down excess energy. This is called curtailment and is ultimately paid for by consumers.

As data centers are adding stress to the grid, regions in the US are setting records for curtailment — some even having seen a six-fold increase since 2020.<sup>87</sup> China, on the other hand, has managed to keep curtailment at bay in an increasingly renewably powered grid by strengthening

local networks and incentivizing demand response.<sup>88</sup> In a world where we can no longer fire up natural gas power plants to meet peaks in demand, we must find new ways to manage energy more flexibly. This section presents pathways for enabling a more flexible electricity system, as well as new data on the possible energy and cost savings of implementing demand response solutions at scale.

### What is demand response?

Demand response is about using the renewable electricity when it is plentiful and lowering demand during peak hours. It is about leveling out energy consumption, so we do not experience periods of simultaneous high demand and low supply.

The primary way to achieve this is either by shifting energy use away from the busiest times when the grid is under pressure, or by avoiding such peaks altogether by reducing energy usage for one function to serve another, also known as load-shifting or peak-shaving. In one way or another, both of these methods are about reducing peak energy demand. While the process can actually lead to higher energy use in some instances, it is less problematic, and sometimes even cheaper and greener, especially if the energy being used is renewable, as opposed to fossil-fuel based electricity generation. Minimizing electricity use in

## Technology potential: Energy management control

Every data center cooling system needs intelligent control, and the right controllers can unlock substantial energy savings. Modern smart controllers, paired with advanced software and powerful AI, can manage cooling systems dynamically and continuously optimize energy use down to the lowest possible level.

But efficiency is only the beginning. With intelligent control, data centers can also become active participants in the energy ecosystem. By communicating directly with power utilities, controllers can automatically reduce consumption during peak demand periods and shift

loads to times when renewable energy is abundant. This transforms cooling systems from passive energy consumers into flexible assets that support grid stability.

Cloud connectivity takes this even further. Entire fleets of cooling systems can be monitored, optimized, and updated remotely, ensuring consistent performance across multiple sites. And by adhering to high cybersecurity standards, these cloud enabled solutions protect critical infrastructure from digital threats while still delivering the benefits of real-time optimization.

peak hours reduces strain on the grid and saves money. Demand response solutions become even more effective when coupled with efficient energy storage mechanisms, like batteries. The process of energy storage can be automated so that the energy is acquired during low-demand periods and deployed when demand is higher. This enables consumers to use cheap, renewable energy during times when energy is otherwise expensive and carbon intensive.

### Data centers, a key player in a flexible electricity system

Data centers offer significant opportunities to make the electricity system flexible. Depending on how data centers are integrated in the system, they can either become a huge burden or an opportunity to reduce costs and emissions.

As data centers use such a large amount of electricity, any sudden changes in their demand can take the grid offline. However, the opposite is true too. If data centers are enabled to shift their load, they have the potential to balance the electricity grid and provide great system benefits.

A prerequisite for enabling data center flexibility is that they are well integrated into the grid, and that they are

always sufficiently supplied with power to carry out their tasks. Precise power conversion is a necessity to integrate hyperscale data centers into the grid. This way, on-site power supply and backup, such as batteries, can limit the data center's impact on the grid. Once this is in place, data centers can actually become a lever for building a resilient and decarbonized grid while also alleviating local supply issues through their own battery and generation capacity.

Most of the time though, data centers do not utilize all their computing power, operating only at an 80% load.<sup>90</sup> A lot of their tasks do not need to be performed immediately which makes them ideally suited for flexibility. Tasks like AI model training and machine learning can be carried out in non-peak hours.<sup>91</sup> Only a small part of the tasks, like streaming content, have a 'here-and-now' pull on the data centers. This provides a substantial opportunity to shift tasks when the pressure on the grid is lower. In practice it means that when renewable electricity production is lower than demand, tasks can be postponed to a period where the abundance of renewable energy exceeds demand.

This so-called 'demand-side flexibility' can be a driver for making sure we get the maximum utilization of renewable energy and none of it goes to waste. In many regions, wind and solar supplies are so plentiful at certain times of day that not all of the electricity produced can be used.

Cooling data centers with direct liquid cooling is not only more efficient than conventional technologies — **it also adds substantial opportunities for flexibility.**

But if it can be used, it is a cost-competitive alternative to conventional fossil fuel-based energy sources. In these cases, data center flexibility can lead to better usage of these renewable energy sources and drive down grid costs and emissions.

A Massachusetts Institute of Technology review of data center flexibility in Texas has shown it can be possible through flexibility to reduce emissions by up to 40%, accelerate fossil source phase-out, and reduce total system costs by 5%. Even in cases where flexibility does not lead to decarbonization, it still lowers total system costs because it makes it possible to tap into the cheapest possible energy sources and reduce the needed grid build-out.<sup>92</sup> This ultimately reduces the energy bills for all consumers. This is not only relevant in the United States. A case study in Japan found that implementing data center flexibility could reduce the total energy system costs by 18% and significantly reduce the needed build-out of renewable energy.<sup>93</sup> It is worth noting that these estimates are conservative, as they do not include the flexibility potential in liquid cooling.

Cooling data centers with direct liquid cooling is not only more efficient than conventional technologies — it also adds substantial opportunities for flexibility. Direct liquid cooling uses cooled liquid to remove heat from chips in the data center, which in turn heats up the

water. The water must be cooled again before it can be recirculated for another round of cooling, which requires energy. It is easy and cheap to store cold water, this can even sometimes be done over seasons,<sup>94</sup> which means that the water can be cooled when there is plenty of renewable electricity available and stored for later usage. The response rate is very fast, which means that data centers can quickly meet dips in energy production. Modern hyperscale data centers use only 7% of their energy for cooling, a significant efficiency improvement made possible in large part by advances in liquid cooling technology.<sup>95</sup> However, because such big data centers have a massive energy consumption, even making their cooling systems partially flexible can meaningfully reduce strain on the energy grid and save money on energy bills.

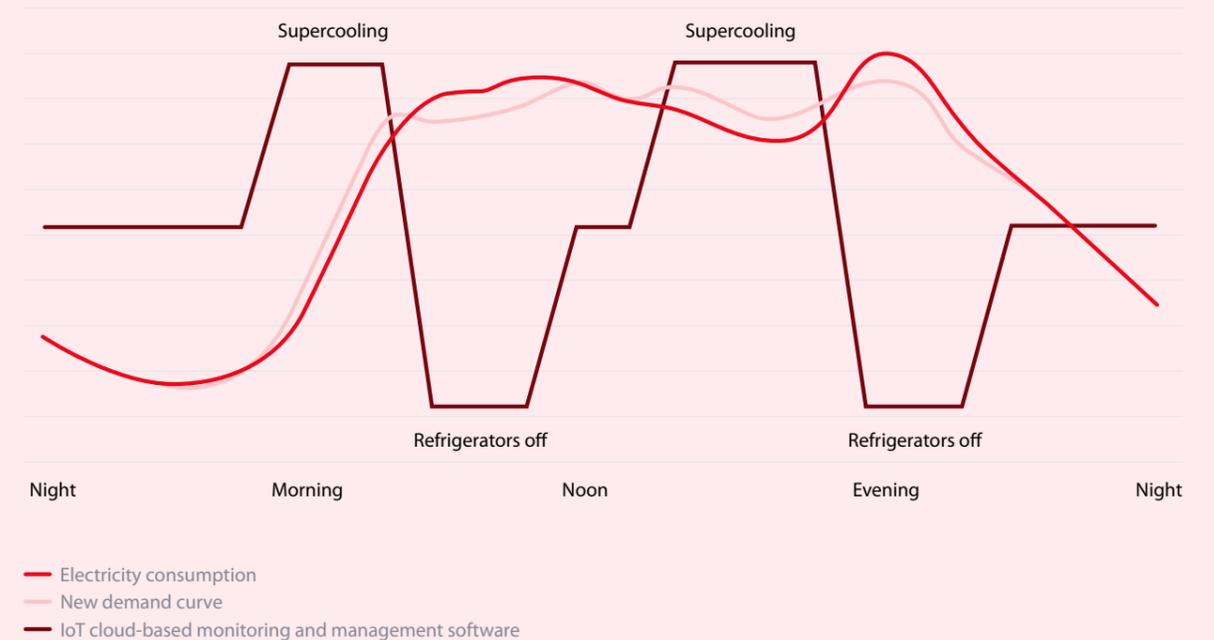
The IEA suggests that all data center additions up to 2035 can be integrated in the grid if data centers are flexible up to 1% of the time. In China, the new data centers would only need to be flexible for 0.2% of the time, or 20 hours per year.<sup>96</sup> In the US, they would need to be flexible 1% of the time,<sup>97</sup> and with only modest flexibility, the demand for all expected data centers in the US could be met without adding a single new power plant.<sup>98</sup> These periods of grid stress would only last three to five hours per event, and in most cases, more than half of the grid supply would still be available for the data centers.<sup>99</sup>

## How data centers can provide grid flexibility

- **Shift tasks in space** from a data center in a region with strain on the grid to one in a region where renewable electricity is plentiful.
- **Shift tasks in time** to periods with lower demand or higher production. Most of the time, data centers operate at 80% load,<sup>100</sup> and many of their tasks do not need to be performed immediately. This gives a substantial headroom to shift tasks in time.
- **Liquid cooling** uses cool water to chill equipment. This heats the water, which in turn must be cooled again. The water can be cooled when electricity is cheap, and stored in thermal tanks or underground reservoirs. This can add very responsive flexibility that can be stored - sometimes for seasons.
- **Battery energy storage systems (BESS)** are a necessity to manage the demand changes from the large data centers without destabilizing the grid. The batteries can store electricity from either on-site or grid-connected renewables during periods with surplus renewable generation. This way, data centers can use renewable electricity during periods with low and expensive supply.
- **On-site power generation** can serve as back-up or baseload supply to data centers. This power generation can be increased and decreased as a response to grid supply needs, making data centers less vulnerable to fluctuations in electricity production. Through hydrogen fuel cells, green hydrogen can serve as backup generation with zero noise and high uptime. Likewise, highly efficient off-grid gas generators can prove a viable transition pathway away from oil and coal power plants.
- **Solid-State Transformers (SSTs)** are a potential solution for implementing DC distribution as they convert directly from medium voltage AC to a lower DC voltage, simplifying conversion stages and reducing energy losses. These power converters also use less copper and eliminate the need for certain materials such as transformer insulation oil. The additional control afforded by an SST helps to fulfill the need for future data centers to interact harmoniously with the grid. Bidirectional operation of the SST could even leverage on-site energy resources to push power back out to the grid when available. Overall, solid state transformers have the potential to improve efficiency, reduce critical material usage, improve grid stability, and simplify integration with batteries and renewable energy.
- **DC distribution** is a future trend for hyperscale data centers where the low-voltage AC electrical supply is replaced with a higher DC voltage. This means electricity is delivered in a more direct form to computing equipment, with fewer conversion steps. As a result, efficiency is improved, copper usage is reduced, and batteries and renewable energy sources that are already DC-native can be more easily integrated.

Figure 8

Making supermarket freezers flexible through AI



### Case story

## Making supermarket freezers flexible through AI

While data centers themselves must be flexible to ensure a resilient and affordable grid, the very nature of data centers and the artificial intelligence capacity they provide can also enable flexibility in other consumers. One such example is supermarkets, which account for 3% of the total electricity used in industrialized countries.<sup>101</sup> Within supermarkets, refrigeration systems represent by far the highest share of the total energy consumed. However, it is possible to lower supermarkets' energy demand during peak hours by optimizing or shifting loads during a demand-response event.

With digital technologies, load-shifting can for example be automated to cool supermarket freezers down to a

much lower temperature than required — also called supercooling — outside the peak demand hours with the freezers effectively operating like a battery storing energy. By doing so, **the refrigerators can be switched off during the peak hours of energy demand, both lowering stress on the grid and saving money for the supermarket.** And though the system uses more electricity than conventional refrigerator systems, by using energy when it is renewable and plentiful, supermarkets can help reduce the need to resort to carbon-intensive energy sources by lowering demand peaks. Learn more in the Danfoss case study *Building better supermarkets for the world.*<sup>102</sup>

## Chapter 4

# What's next for data centers

## Recommendations to turn data centers into assets

Data centers represent an unstoppable wave of innovation and ingenuity, now colliding with the hard limits of resource availability, power generation, and grid accessibility. The benefits of the exceptional growth of AI and the digitalization of our economy are numerous and game-changing, driving efficiency, innovation, and sustainability.

Still, progress is restricted by structural limits that demand long-term solutions. Data center electricity consumption is growing at a pace that existing energy supply cannot match. In many regions, demand is outpacing supply, with the US and EU already facing significant challenges. China is still able to keep up, but only by vastly expanding generation capacity to meet rising demand. Moreover, hardware and component supply shortages, such as chips and transformers, extend lead times significantly, making an even stronger case for efficient solutions that alleviate pressure on already stressed value chains.

At the same time, the current grid infrastructure is ill-equipped to deliver required energy, leading to increasingly long grid connection queues that can stretch up to a decade in some cases as a result of limited

generation capacity, local resource constraints, and complex bureaucracy. Beyond these systemic issues, data centers also exert local pressure. If not carefully managed, they risk raising electricity prices for ratepayers, straining water availability, and increasing emissions when powered by carbon-based energy sources.

As this paper has shown, these constraints demand proactive action from decision-makers to shape the future of data centers in a way that strengthens, rather than stresses, our energy systems. This means moving beyond simply accommodating growth and instead leveraging the unique potential of data centers to create synergies across sectors.

Two priorities stand out: first, driving efficiency within data center operations to minimize unnecessary energy and water waste, which is critical for electrifying other sectors, protecting the environment, reducing reliance on imports, and safeguarding competitiveness. Second, adopting a holistic approach to planning that positions data centers as active participants in the energy ecosystem, not just consumers. By embracing demand response and integrating with other sectors to reuse excess heat, data centers can evolve into energy hubs that alleviate political and local concerns while reinforcing grid resilience.

Prioritize efficiency in data center operations to eliminate unnecessary energy and water waste, safeguard competitiveness, and accelerate economy-wide electrification.

- **Standardize reporting requirements and introduce minimum performance standards.** Require transparent reporting of at least PUE, WUE, and ERF for both new and existing data centers, regardless of capacity or type, and use the data to establish binding minimum performance thresholds.
- **Promote water-responsible cooling.** Prioritize closed-loop cooling and direct-to-chip technologies, particularly in high-stress regions, and integrate water use into environmental impact assessments to prevent local depletion.
- **Introduce a global sustainability rating which links to permitting.** Clear performance metrics, transparency, and visibility will incite innovation and competition. Fast-track permitting for sustainable data centers can create a race to adopt the best available technologies and install heat recovery systems to support local heating needs. Harmonize reporting and link permitting to minimum sustainability standards, using frameworks like ISO while allowing regional thresholds based on grid carbon intensity and water stress.

Adopt a holistic planning approach that transforms data centers into flexible energy hubs, optimizing demand, reusing excess heat, and integrating with other sectors to strengthen the grid.

- **Incentivize waste heat recovery and reuse.** Require new data centers to assess heat-recovery potential as part of their permitting process and encourage placement near district heating or industrial off-takers. Where possible, facilities should be "heat-reuse-ready" through standardized pre-piping, cabling, and dedicated space for a heat pump. Benefits realized by heat recovery hardware and heat pumps should positively contribute to the data center's performance indicators.
- **Enable flexibility and system integration.** Adapt market rules and tariff structures to reward data centers for enabling demand response and grid services. Promote local microgrids linking data centers with renewable generation, heating networks, and energy storage. This includes a recognition of behind-the-meter low-emission power generation and on-site storage that enhance grid stability.

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## What is Danfoss Impact?

Danfoss Impact is written to share our view on the potential of energy efficiency and electrification to transform our energy system. In the dialogue about the green transition, energy efficiency is often overlooked. One main reason for this is that experts and industrial leaders have inadequately explained its role in accelerating electrification to enable a future powered by renewables.

Drawing on evidence from credible sources, Danfoss Impact presents cases from a broad range of industries, highlighting solutions with great potential to save energy and reduce emissions in a cost-efficient and scalable manner. With this series, we also aim to demonstrate that the technologies we need for a rapid and sustainable green transition already exist today.

The greenest energy is the energy we don't use.