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Review article

Data centres as a source of flexibility for power systems

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A R T I C L E I N F O

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A B S T R A C T

The increasing penetration of variable renewable energy resources and new demands have significantly heightened the need for flexibility in power systems. Data centres present a unique opportunity to enhance power system flexibility due to their substantial yet controllable energy consumption and advanced technological capabilities. This paper provides an in-depth analysis of the potential role of data centres in improving power system flexibility. Initially, the flexibility requirements of modern power systems are defined, followed by an exploration of the flexibility assets and operational flexibility capabilities of data centres. Then, the flexibility capacities of data centres are examined, and the opportunities and benefits of leveraging this flexibility are explored, supported by case studies illustrating real-world examples. This paper underscores the vital role of data centres in the evolving energy landscape. In particular, the analysis reveals that data centres have a high potential to address the increasing flexibility requirements driven by the integration of renewable energy and the transition towards net-zero emission goals. Moreover, the findings emphasise key challenges, including ensuring Quality of Service (QoS) and adherence to Service Level Agreements (SLA), the need for further legislative development to facilitate data centres' participation in energy markets and the provision of ancillary services, as regulatory frameworks differ across regions and variations exist in energy market structures. The findings provide actionable insights for policymakers, industry stakeholders and data centre operators, demonstrating how data centres enhance the stability, flexibility and efficiency of power systems.

1. Introduction

In the last decade, the world has witnessed an unprecedented acceleration in digital transformation, which has been characterised by the proliferation of Internet of Things (IoT) devices, the integration of advanced Artificial Intelligence (AI) technologies, and an exponential increase in online platforms. As a direct consequence, data centres (DCs) have been catapulted to the forefront, becoming the indispensable backbone of our digital infrastructure, as substantial amounts of generated big data need to be stored and processed in DCs to maintain services without interruption or latency. Digital data generation is expected to grow from 33 zettabytes in 2018 to 175 zettabytes by 2025, (Reinsel et al., 2018), along with a projected rise in IoT-connected devices to approximately 25.4 billion by 2030 (Holst, 2021).

Furthermore, the COVID-19 pandemic has accelerated the adoption of digital platforms and online services, transforming how individuals and businesses connect, collaborate, and conduct transactions. The shift from offline to online has also significantly changed major business activities, resulting in substantial growth in virtual platforms. These changes require a massive volume of data transfers and underscore the necessity for robust infrastructure capable of storing and processing this extensive data.

In tandem with this digital revolution and the rise in data generation, the transformative power of AI and Machine Learning (ML) has become vital. The increasingly sophisticated AI models have heightened the demand for computing power due to the nature of their ongoing learning and adaptive capabilities (CBRE Research, 2023.; Beets et al., 2023). This requires robust infrastructure to manage data processing and computational power demands effectively.

Data Centres fulfil businesses' rapidly expanding data management needs by storing or processing data appropriately for specific objectives, such as being used for data analytics, AI and ML applications, autonomous decision-making or providing online services. They also play a pivotal role in sustaining business operations by providing computational power with high-performance servers and reliable backup and disaster recovery solutions.

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The exponential increase in the demand for DCs significantly boosts their energy consumption. According to the 2022 National Grid ESO Report (NationalGridESO, 2022), the UK possesses Europe's largest data centre capacity, with approximately 600 commercial DCs consuming around 2.5 % of the nation's electricity. This rate is expected to rise to 6 % by 2050, underscoring the pivotal role that DCs may play in attaining the UK's 2050 net-zero target. In 2022 (International Energy Agency (IEA), 2023), global data centre electricity use was estimated at 240–340 TWh (1 %–1.3 % of global demand), excluding cryptocurrency mining's 110 TWh (0.4 %). By 2026, data centre energy consumption is expected to reach 620–1050 TWh, nearly double 2022 levels, driven by the growing demand for AI-based services and cryptocurrency mining (Çam et al., 2024).

This growth is attributed to the essential components of a typical data centre, including information technology (IT) equipment (high-performance servers, network equipment, etc.), large cooling units, power conditioning equipment (UPS and PDU losses, etc.) and lighting. The majority of total energy consumption in the data centre arises from the operations of IT equipment (approximately 50 %) and the cooling demand (around 40 %) (Zhao and Wang, 2021).

As the energy demands of DCs continue to rise, their relatively flexible and easier-to-manage load characteristics, compared to those of other industrial consumers position them as pivotal players in power systems. With high-capacity UPS battery systems, generators, and the integration of renewable energy sources, DCs are poised to act as prosumers, capable of contributing to power system flexibility. Despite this potential, the existing literature has not fully explored the multifaceted role of DCs in terms of their contribution to power system flexibility. The current research predominantly focuses on technical aspects, such as frequency response contributions from data centre UPS systems, optimisation algorithms to minimise energy costs, load shifting strategies and the technical analysis of data centre participation in energy markets. These technical approaches, while valuable, often fail to address the broader understanding of how specific data centre assets can practically provide flexibility and the conditions under which such flexibility can be reliably utilised. This gap leaves readers and stakeholders sceptical about the practical feasibility and the actual contribution of DCs to flexibility, particularly in terms of integrating theoretical approaches with real-world implementations. To address this gap, this paper examines not only the potential of individual DC components to provide flexibility but also how these components can collectively deliver meaningful benefits under specific regulatory, operational, and market conditions. Moreover, the study bridges theoretical insights with practical applications by providing case studies, analysing the capacity of DCs to meet flexibility requirements, and discussing barriers and regulatory challenges. This integrated prospective highlights how DCs can be critical players in future power systems.

This paper begins with an overview of the power system flexibility requirements and then delves into the potential flexibility assets within DCs and their operational flexibility. It then examines the opportunities and benefits of leveraging data centre flexibility and presents case studies to illustrate these concepts in real-world scenarios. Finally, it discusses the barriers to obtaining flexibility from DCs. Through this investigation, we aim to underscore the critical importance of DCs in the evolving energy landscape and to provide actionable insights for policymakers, industry stakeholders, and data centre operators.

2. Overview of power system flexibility requirements

Recent transformations in global power systems, fuelled by initiatives like Net Zero Targets, are driving the increased integration of renewable energy sources with inherent intermittency and stochastic nature. This transition presents a significant challenge in meeting energy requirements and maintaining power system stability. As dispatchable power plants decline, the grid must adapt to more variable and less predictable energy resources. Specifically, additional grid balancing services and enhanced flexibility within the power system will be required to regulate the voltage and frequency and to adapt to changing consumption patterns, such as steeper demand ramps and shorter but more frequent peaks (Babatunde et al., 2020).

The power system flexibility is the capacity of a power system to balance the supply and demand at all times and locations across the electricity network (Babatunde et al., 2020). To understand the significance of power system flexibility, it is crucial to analyse the level of flexibility requirements. According to the JRC report (Koolen, 2023), the EU's flexibility requirement was 11 % of the total electricity demand in 2021. The report anticipates that this need will escalate to 24 % of the EU's total electricity demand by 2030 and further increase to 30 % by 2050. Numerically, 2189 TWh of flexibility will be needed by 2050 in the EU.

According to different 2050 scenarios for the UK, around 57 GW of flexible capacity is projected to be needed (Brearley, 2021). This capacity consisted of 30 GW from short-term storage and demand-side response (DSR) and 27 GW from interconnection. According to

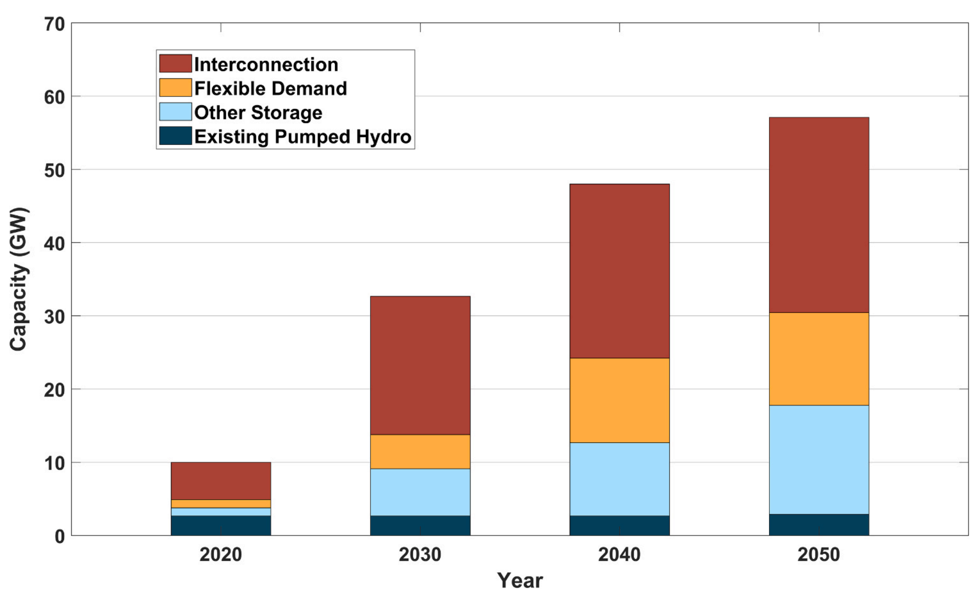

Fig. 1. Projected Deployment of Flexible Technologies (Brearley, 2021).

analyses of the Ofgem Report (Brearley, 2021), the breakdown of flexibility requirement capacities by year and flexible technologies is illustrated in Fig. 1.

Currently, flexibility requirements are met mainly by fossil fuel sources. However, a significant challenge emerges as the world transitions to low-carbon energy sources that support decarbonisation goals. Consequently, power systems actively seek alternative sources to enhance flexibility and explore new options. At this point, DCs are stepping onto the stage with their ability to promptly respond to power grid needs through capabilities such as UPS systems, thermal energy storage, and the load-shifting paradigm. In this paper, we define IT workload shifting as the rescheduling of computational tasks to different time periods, whereas IT workload migration refers to the spatial relocation of these tasks to different data centres. Shifting IT workloads inherently affects the power demand required for processing tasks, which influences the overall electricity consumption. On the other hand, load shifting refers to adjusting power demand over time and is a broader concept that encompasses power demand shifts caused by IT workload shifting, cooling demand shifting, and leveraging the thermal mass of data centres.

Another notable feature of modern DCs is their bidirectional power flow capability. This enhances the flexibility of the power grid by allowing DCs to draw power and supply surplus power back to the grid.

3. Flexibility from data centres

A conventional data centre hosts IT servers responsible for data processing and job execution, as well as data storage equipment such as hard disk drives and solid-state drives. Network equipment, including routers and switches, facilitates communication between the data centre and external networks. Robust power infrastructure, such as uninterruptible power supplies (UPSs) and backup generators, guarantees uninterrupted operation during power outages. Advanced cooling systems, including air conditioners, chillers, and CRACs (computer room air conditioning), are used to maintain ideal temperature and humidity levels within the facility to prevent overheating, increase the reliability of the hardware and optimise energy efficiency. Immersion cooling is also used in high-performance computing servers to prevent overheating and equipment failure (Taddeo et al., 2023).

The power and chilled water flows of a typical data centre are illustrated in Fig. 2 (Dayarathna et al., 2016). DCs typically meet their energy needs from the power grid. However, other on-site energy sources, such as diesel or renewable energy, can be utilised in addition to the grid, providing energy to the data centre through the primary switchgear. The energy requirements of primary priority equipment, including servers, data storage units, network equipment, and lighting, are supplied through a UPS in case of grid power outages. Additionally, cooling towers, pumps, chillers and economisers are powered by a primary switchgear.

Data centres can provide flexibility to power systems through their various assets or smart operational strategies, which are detailed below.

3.1. *Potential flexibility assets*

In this section, the various components of DCs from which flexibility can be achieved are explained. One of the essential data centre assets is **UPS**, which stores energy and maintains the electricity supply with its battery capacity during power outages. The UPS also works as a device that mitigates and purifies power supply fluctuations. This guarantees the secure and uninterrupted functioning of delicate electronic devices and, therefore the uninterrupted operation of the company by securing IT equipment and other essential systems. Their fast response characteristics make them useful in demand response systems, which help the electrical grid handle sudden energy needs. Proper sizing aligned with the data centre rack capacity provides energy capacity for the desired period.

Omdia, a global analyst and advisory company, recently conducted a comprehensive survey involving 380 participants, including data centre operators and utility companies. According to 80 % of the respondents, a substantial portion of the UPS capacity deployed within DCs, ranging from 10 % to 50 %, was considered surplus capacity, i.e. idle energy that the data centre would not need even in the event of a power outage (Robinson, 2022). This seemingly idle energy can proactively contribute to the flexibility of power systems. The surplus capacity of UPS systems can be defined according to the particular UPS topology used in DCs, including N, N + 1, 2 N, and 2(N + 1), as illustrated in Fig. 3 (Alaperä et al., 2018). The N topology lacks minimal redundancy or surplus capacity, making the system vulnerable to significant interruptions during UPS breakdowns. For example, in a data centre using a N-type UPS topology, a 3 MW IT load can be powered by three UPS units with a

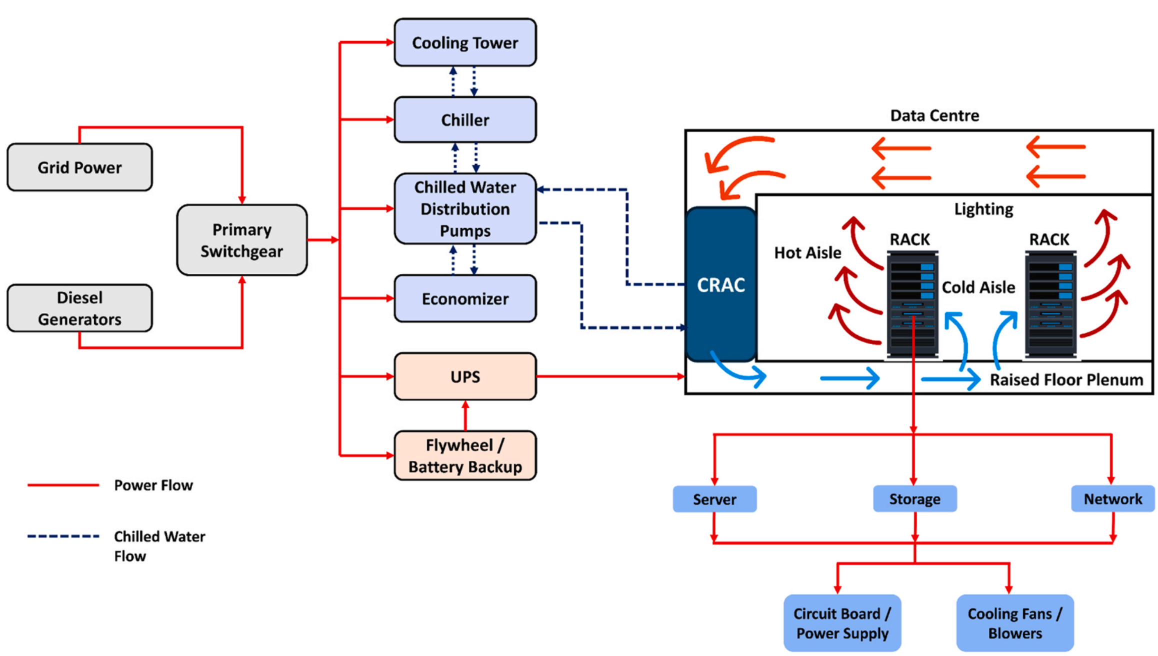

Fig. 2. Data Centre Power Flow and Chilled Water Flow (Dayarathna et al., 2016).

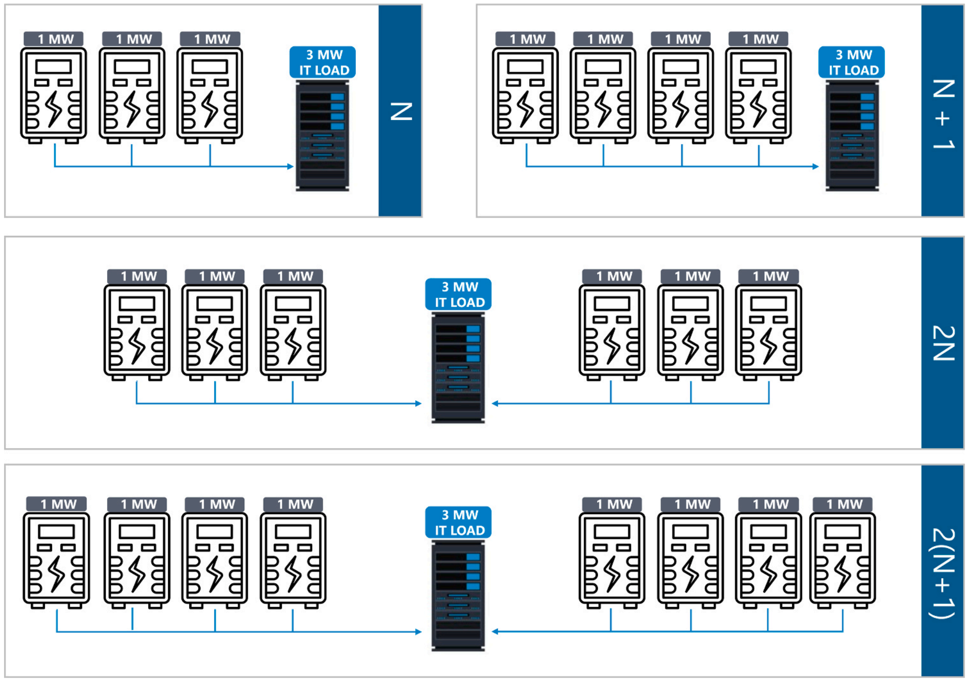

Fig. 3. UPS topologies deployed in DCs (Alaperä et al., 2018).

capacity of 1 MW each, as illustrated in Fig. 3. The 2 N topology incorporates redundancy by including two separate power delivery systems, each consisting of three UPSs with a capacity of 1 MW in the data centre.

This enables the simultaneous supply of the 3 MW IT load by two power delivery systems with a combined capacity of 6 MW. The 2 (N + 1) topology exhibits the highest UPS capability redundancy. The IT load in this setup is supplied by two separate power delivery systems, each capable of housing four UPS units, each having a capacity of 1 MW. The entire capacity of the UPS system is 8 MW, and the IT load is 3 MW. Many leading data centre firms adhere to 2(N + 1) structural standards, especially those with high IT capacity. Since the capacities of UPS units and their batteries are high enough, this capacity can also be considered an energy source, reducing reliance on the grid—especially during peak times—or supporting ancillary services through an efficient energy management algorithm within operational flexibility strategies.

Backup generators are essential components of DCs, providing energy to maintain operations during long-term power outages. Although not environmentally friendly, diesel generators provide a reliable backup power supply for DCs. However, technological advancements have led to more efficient and cleaner diesel generator options, minimising their environmental impact and aligning with the overarching goal of sustainable energy practices. Although using them directly as a source of flexibility may not be the best option due to the current focus on shifting from diesel-based systems to zero-carbon alternatives (Kenefick et al., 2021), strategically integrating them with the power grid could greatly enhance power system flexibility. These generators can reduce the peak demands of energy system and local networks, optimise energy usage, and minimise peak energy costs.

Thermal Energy Storage Tanks have been adopted as significant components in the cooling system of DCs in the case of emergencies to meet the cooling demand of DCs. If there is a power outage, thermal storage can be used to expand the capacity to cool IT equipment in a data centre. The thermal energy storage capability can serve as a flexible resource by discharging energy during peak periods and recharging during off-peak periods or in response to other grid demands, thereby reducing grid stress as needed. Another method for thermal energy storage involves using the data centre's thermal mass to store energy through controlled overheating or overcooling, which is based on adjusting the indoor temperature within the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) defined limits throughout the day (ASHRAE TC 9.9, 2016) By overcooling during off-peak hours or when renewable energy is abundant and releasing it during peak demand periods, the data centre supports load shifting, participates in the demand response and enhances the overall power system flexibility.

IT Servers are the fundamental infrastructure of DCs since they perform *"useful work"* such as storing and processing data, executing programs, and hosting websites. Servers are essential assets due to their share of the total data centre energy consumption and their energy consumption characteristics, which are highly dependent on the server utilisation rates. Therefore, IT server technology is evolving rapidly to improve energy and computational efficiency. The technology utilised varies widely from one data centre to another. In addition to this variation, several factors, including the sensitivity of different risk assessments, the performance of virtual machine management tools, and fluctuating workload types and demands, lead to differing server utilisation rates across DCs. Due to the nonlinear relationship between server utilisation and power consumption, managing server utilisation rates effectively is crucial to optimise energy use.

Moreover, many DCs host several idle servers that are kept ready for immediate deployment even though they do not perform any computational work. According to Chris Zaloumis from IBM (Zaloumis, 2022), the average server utilisation rate changes between 12 % and 18 % of the total capacity, whereas it is 30 % according to (Suthar, 2025). However, McKinsey states that the average server utilisation can range from 20 % to 30 % per day, with best practices achieving 70-80 % utilisation (Ghia, 2011). Therefore, these variable utilisation rates indicate that servers possess unused or standby capacity that can be manipulated through various IT workload shifting or migration methods or by creating synthetic workloads.

In conclusion, these assets within DCs can be crucial in providing flexibility to power systems. By repurposing UPS batteries, utilising thermal energy storage, and employing backup diesel generators wisely, DCs can actively contribute to the stability and sustainability of a more flexible power grid. Moreover, the IT server capacity can provide operational flexibility to power systems.

3.2. Operational flexibility

DCs can enhance power system flexibility through smart operational management strategies using hosted assets. This operational flexibility is analysed in two subsections.

3.2.1. Load shifting

DCs can support power grid operations by reducing or increasing the power demand because of their flexible load characteristics, which makes it easier to shift in time compared to other industries. The increasing use of AI in every aspect of daily life requires high computational power in data centres. Therefore, AI workloads may enhance the flexibility characteristics of data centres due to their predictability, modularity and time flexibility. Predictability allows for anticipating resource requirements because AI operations often rely on structured and schedulable processes (e.g., model training). Modularity enables the decomposition of AI workloads into independent components, thereby allowing each module to be optimised with distinct resources. Temporal flexibility enhances IT workload shifting capacity.

IT workload shifting can be implemented for various objectives. These include avoiding IT load congestion, reducing energy costs, achieving high sustainability metrics for DCs (e.g., Carbon Usage Effectiveness - CUE), preparing for potential future carbon generation limits set by the EU, enhancing DCs' reputation, and aiding power grid reliability.

One approach is to shift the IT load from peak to off-peak times or migrate it between geographically distributed DCs. To achieve this, it is important to classify the workload into two categories: delay-sensitive and delay-tolerant, based on performance and timing requirements (Liu et al., 2024). Delay-sensitive workloads, also referred to as non-flexible workloads, require real-time or near-real-time responses to function effectively (Liu et al., 2024; Radovanovic et al., 2023). These time-critical tasks include various user-facing services, such as web search, mapping applications, and video platforms like YouTube, alongside cloud workloads operating in dedicated Virtual Machines. Moreover, delay-sensitive workloads extend to online gaming, video conferencing, and VoIP, real-time financial transactions, autonomous vehicles, IoT applications, and healthcare systems (e.g., telemedicine, emergency response services), where any delay can significantly degrade performance and impact user experience.

In contrast, "Delay-tolerant workloads," also known as "flexible workloads," are tasks that can withstand significant latencies without affecting the overall system performance or user experience. Unlike delay-sensitive tasks, these workloads do not require immediate processing and can be queued or scheduled for later execution. Examples include big data analytics, data compaction, machine learning, backup and data archiving, batch processing jobs, video processing pipelines, software updates, scientific simulations, rendering, email or file transfer services, and various asynchronous or background tasks (Liu et al., 2024; Radovanovic et al., 2023).

In October 2023, Google announced that a novel approach based on shifting "delay-tolerant" workloads in time and space was implemented to support the grid when the local grid requires more flexibility (Mehra and Hasegawa, 2023). Furthermore, numerous researchers have suggested evaluating and implementing load-shifting methods from different perspectives (Radovanovic et al., 2023; Cioara et al., 2019; Zheng et al., 2020; Klingert and Szilvas, 2020; Basmadjian, 2019). One such study is carbon-aware IT workload shifting (Wiesner et al., 2021). This approach aims to reduce carbon emissions by rescheduling computational workloads from periods in which electricity from the grid has a high carbon intensity to periods in which the energy supply is likely to have a lower carbon intensity. Furthermore, DCs can reduce electricity costs by strategically scheduling computational tasks during periods of low electricity demand while providing flexibility to the power grid.

Shifting the cooling load could be another innovative strategy applicable to DCs. Because the heat generated by IT computational workloads is the primary reason for cooling demand, shifting IT loads directly influences the cooling requirements within the corresponding timeframe. Moreover, the cooling demand can be individually shifted over time by overcooling or overheating the data centre by leveraging the thermal mass. For example, by adhering to ASHRAE-recommended safe temperature thresholds, the data centre can be intentionally overcooled during off-peak hours while allowing controlled overheating during peak hours. To ensure optimal data centre performance, the ASHRAE recommends maintaining an indoor temperature of 18°C to 27 °C (ASHRAE TC 9.9, 2016). These temperature levels are the common limits for DCs classified under categories A1, A2, A3, and A4, each of which exhibits distinct characteristics. Specific temperature ranges are determined for each category. For instance, A1, which encompasses corporate servers and storage units, suggests a temperature range of 15°C to 32°C. Therefore, the indoor temperature can be adjusted to within these specified limits (ASHRAE TC 9.9, 2016; ASHRAE TC 9.9, 2015).

DCs can contribute to achieving a more reliable and flexible power system using the load-shifting method through various demand response services and obtaining financial benefits from these services.

3.2.2. Utilisation of data centres as virtual energy storage systems

Increasing emphasis on reducing carbon footprints through the Net Zero Strategy in the UK (Committee on Climate Change, 2019) and the EU's aims to be climate-neutral by 2050 (The European Parliament and The Council of The European Union, 2021) encourage industries to adopt sustainable energy practices and carbon-neutral management programs, even if they procure energy from green energy suppliers. However, the need to derive energy from renewable energy resources, which are characterised by intermittent nature, to achieve carbon-free energy introduces various challenges and requires enhanced flexibility in the power grid. To overcome such problems and provide more flexibility to the grid, virtual energy storage systems (VESS) have been used as innovative solutions adopted in recent years (Sami et al., 2022). VESS can be identified as a combination of controllable Distributed Energy Resources, such as flexible demand and small-capacity energy storage units (Sami et al., 2022). The proposed concept enables the provision of efficient power services, effectively emulating the functionality of an extensive conventional energy storage system. From this perspective, DCs equipped with renewable energy sources, energy storage units (such as UPS batteries and thermal energy storage), and the ability to leverage the cooling inertia and flexible load characteristics can be considered VESSs. With this capability, DCs have significant potential to enhance power system flexibility and contribute to decarbonisation efforts by participating in demand response schemes and integrating with smart grid applications through smart energy management algorithms. This leads to several additional advantages, such as providing flexibility to the power grid, reducing peak points in the power load curve, mitigating transmission losses, alleviating congestion in the energy network, and generating financial savings for both utility and data centre operators (Takcı et al., 2021).

3.3. Flexibility capacity of data centres

A data centre's flexibility capacity comprises shares from various components, such as thermal storage capacity, UPS energy storage capacity and load shifting capacity. In this section, we focus on scaling the flexibility capacity of data centres by considering UPS systems and load shifting.

UPS systems with high energy storage capacity batteries in DCs are suitable sources of flexibility in terms of participation in energy markets and ancillary services, especially primary frequency response. Ancillary services, which differ in name and requirements between countries, are typically defined as services that require immediate activation of the energy source and supply of energy for up to 15 minutes to the power grid. Therefore, instead of participating in ancillary services by investing in the construction of individual battery energy storage systems, it will be more economically and environmentally efficient if DCs can participate in these services with their grid-interactive UPS systems. As part of this process, the data centre operator ensures that the minimum state of charge of the UPS is sufficient to maintain the primary function of the DCs.

According to the report (Kenefick et al., 2021), the total design capacity of DCs in five countries (Germany, Ireland, the Netherlands, Norway, and the UK) reached approximately 6.9 GW by the end of 2021, with an associated IT power demand of around 3 GW. The IT power demand is also anticipated to reach 5.4 GW, with a design capacity of 11.9 GW by 2030. In the same report, the total flexibility capacity (obtained through UPS, backup generation, and load shifting in time or space) is estimated to be around 16.9 GW. Furthermore, the proportion of renewable energy generation in Europe is projected to reach 56 % by 2030 (Kenefick et al., 2021). This underscores the need to expand reserves for ancillary services.

Although auction periods and reserve amounts vary by country, Fig. 4 provides a high-level comparison of Fast Frequency Response (FFR) and Dynamic Containment Low (DCL) requirements across different markets and UPS capacities for the dates 1 April and 1 October 2022 (Kenefick et al., 2021; Paananen, 2023). The data belonging to the "Nordic" are comprised of Finland, Sweden, Norway, and East Denmark. *"Designed-based UPS capacity"* denotes the UPS capacity designed to supply energy to the maximum IT load capacity of the data centre, while *"demand-based capacity"* refers to the capacity reserved for the data centre's actual IT utilisation rate. As shown in Fig. 4, DCs have a significant potential to fulfil the reserve capacity needs of ancillary services by adopting an efficient energy management algorithm.

As mentioned in the previous sections, IT workload shifting is another method for obtaining flexibility from DCs. To calculate the flexibility capacity of IT workload shifting, determining the ratio of delay-tolerant to delay-sensitive workloads is essential. A study (Rasheduzzaman et al., 2014) analysing Google workloads classified them into four levels of delay sensitivity, ranging from least to most sensitive: "0", "1", "2", and "3". According to this classification, 38.28 % of the total workload falls into the category "0". In contrast, only 0.77 % of the workload is in the category "3". Categories "1" and "2" account for 32.01 % and 28.94 % of the workload, respectively. If categories "0" and "1" are considered flexible loads that can be shifted in time, they account for approximately 70 % of the total workload. Another study (Zhao and Wang, 2021), using the Alibaba Data Centre's 2018 workload dataset, revealed that an average of 10 % of the workload is delay-sensitive and needs to be completed immediately upon request. The remaining 90 % is delay-tolerant and can be shifted in time. According to (Zhao and Wang, 2021), the distributions of delay-sensitive and delay-tolerant workload rates over 24 h is obtained and shown in Fig. 5. The highest proportion of shiftable workloads occurred between 13:00 and 18:00.

The delay-tolerant workload ratio varies according to the type of data centre and its workload diversity. The capacity of a data centre's load-shifting flexibility can be determined by the power demand of the servers required to complete these tasks.

4. Exploring potential opportunities and benefits of leveraging data centre flexibility

By providing flexibility, DCs can unlock numerous benefits, thereby establishing a symbiotic relationship between their technological capabilities and the grid's requirements. The advantages of providing flexibility can be examined in three main categories: benefits to the power grid, environmental benefits, and financial benefits.

4.1. Benefits to the power grid

The flexibility offered by geographically distributed DCs, as opposed to power plants located in one location with very high reserve capacity, yields benefits in terms of mitigating the risk of failure and alleviating transmission network congestion. A previous study (Takcı et al., 2021) investigated the impact of DC participation in the DSM on the peak load reduction of the world load duration curve for 2018. The study revealed that a 0.77 % decrease in peak load could be attained, which accounts for a 30.8 GW reduction. Consequently, with the improvement in the loss factor, transmission losses could be reduced by 1.5 %, equivalent to 11,865 GWh for 2018. The decrease in peak load and transmission losses not only contributes to reducing network congestion and achieving a more reliable power grid but also leads to benefits such as deferring new power plant establishments, reducing carbon emissions, and monetary savings (Takcı et al., 2021). Furthermore, several flexibility providers in the system enhance market competitiveness and lead to more efficient and consistent market administration.

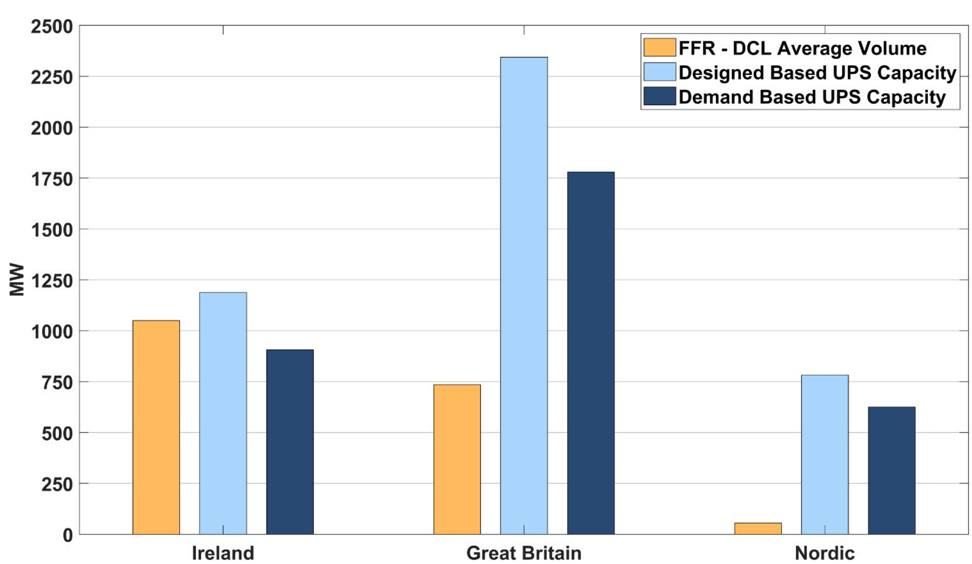

Fig. 4. Comparison of FFR Volumes and UPS Capacity by Country (Kenefick et al., 2021; Paananen, 2023).

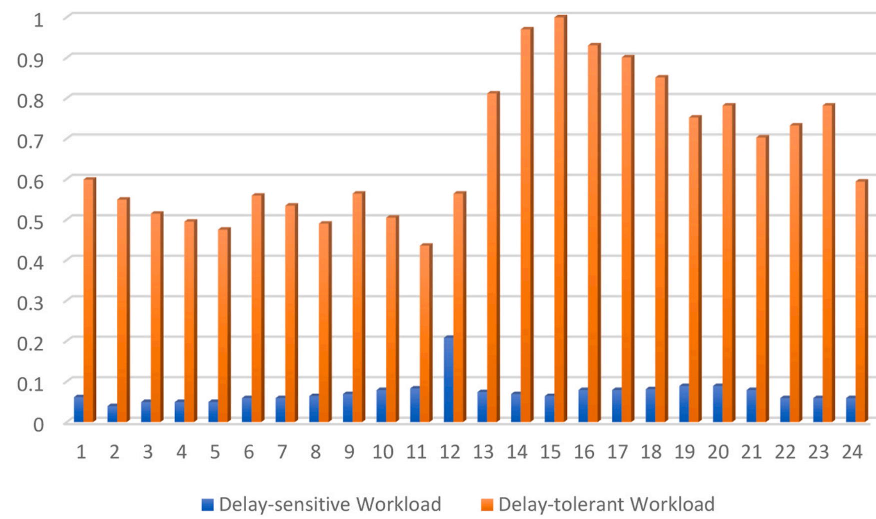

Fig. 5. Workload characteristics of data centre (Zhao and Wang, 2021).

4.2. Environmental benefits

By providing flexibility services, DCs can indirectly contribute to reducing carbon emissions by promoting the widespread use of renewable energy sources, ensuring their efficient utilisation, minimising transmission losses, and implementing peak shaving strategies. Furthermore, actively contributing to reducing fossil fuel production enhances environmental sustainability. In (Takcı et al., 2021), it was demonstrated that reducing transmission losses through the flexibility provided by DCs participating in the DSM for a short period can lead to a CO_2 reduction of 10.78 million metric tons. This figure can be increased even further by utilising various flexibility services from DCs.

Moreover, implementing carbon-aware IT workload shifting, which means relocating workloads to times when less carbon-intensive energy sources meet data centres' energy demands, enhances power system flexibility while decreasing carbon emissions. Wiesner et al. (2021) analysed the impact of carbon-aware IT workload shifting on carbon reduction using two scenarios: short-running, periodically scheduled jobs, and long-running machine learning training. They obtained the carbon density graph of energy production for Germany, Great Britain, France, and California in 2020 on a 24-hour basis. The analysis assessed the potential reduction in carbon emissions achieved through IT workload shifting compared with the baseline workload schedule. The study found that the extent of carbon reduction is contingent on the carbon intensities of energy production in various regions and the duration of IT workload shifting. The study concluded that shifting IT workload could result in carbon reductions ranging from 5 % to 20 % across different regions.

Another study (Zheng et al., 2020) examined the impact of shifting workloads among geographically dispersed DCs on the reduction of greenhouse gas (GHG) emissions. This study focuses on the migration of data centre IT workloads from the Pennsylvania-New Jersey-Maryland interconnection (PJM) region, which heavily relies on fossil fuel energy resources, to the California Independent System Operators (CAISO) region, which heavily relies on renewable energy resources. DC capacity was calculated based on the profiles of listed DCs in California, with an average annual total power consumption per colocation site of 9.92 MW. As a result, the study estimates that IT workload migration could have led to a total net reduction in GHG emissions of 113–239 KtCO2e in 2019.

Consequently, it's apparent that data centres' contribution to providing the fast and reliable flexibility required by the grid can also reduce GHG emissions.

4.3. Financial benefits

By implementing innovative strategies such as load shifting and using UPS batteries, DCs can significantly reduce overall energy expenses and concurrently obtain revenue from the energy market, and participate in ancillary services. For the power grid, these actions help stabilise the balance between supply and demand, reduce operational costs, and postpone the need for new infrastructure investment. Furthermore, decreasing peak demand and enhancing grid efficiency reduce reliance on fossil fuel power plants, thereby leading to lower emissions and potential cost savings from the harmful effects of emissions.

The study (Takcı et al., 2021), which includes a quantitative analysis of the DCs' participation in DSM, emphasises that reducing the peak point of the world load duration curve will prevent the construction of power plants planned to meet peak energy demand. In return, financial savings ranging from \$11.83 to \$71.72 billion could be achieved.

Another economic benefit could be achieved by reducing carbon emissions. According to (Center for Global Development, 2007), each ton of CO_2 can result in an economic loss of up to \$100. Therefore, preventing a maximum of 10.78 million tons of CO_2 in response to the reduction in transmission losses through the flexibility provided by DCs participating in the DSM (Takcı et al., 2021), could save 1.078 billion dollars.

Furthermore, DCs could obtain substantial financial revenue by providing flexibility to the power system. In (Alaperä et al., 2019a), a study conducted for Finnish ancillary services analysed the economic feasibility of DCs participating in primary frequency response using UPS Li-Ion batteries. Within the scope of the evaluation, the cost of the Li-Ion battery was assumed to be 450 €/kWh, with a lifespan of 12 years. Additionally, the market revenue price for FCR-N (Frequency Containment Reserve for Normal Operation) participation was assumed to be 23.1 €/h/MW. After the net present value (NPV) analysis, the break-even point for the 1 MW/1MWh system was calculated as the 8th year. Consequently, it was calculated that revenue of €59k was attained by the end of the 8th year, increasing to €264k by the end of the 12th year. This revenue can only be obtained by participating in frequency response. By participating in other marketplaces, this revenue may be further increased.

Furthermore, the price of Li-Ion batteries is steadily declining annually, and this downward trend is expected to persist in the future. For example, the McKinsey report (McKinsey and Company, 2017) predicts that battery costs will fall below \$100/kWh by 2030, reducing the battery capex. Therefore, Li-Ion battery-based energy storage is expected to become more common.

The grid can also benefit from increased power system flexibility, allowing for better integration of green energy production. This adaptation helps to accommodate the intermitted nature of renewable energy resources. Thus, energy costs can be reduced by more effectively managing renewable energy resources. Furthermore, increasing the flexibility in the power grid, which is obtained by effectively using technologies such as smart grid operations, energy storage systems, and demand response using DCs, helps network operators optimise their investment and operating costs. Additionally, a flexible power grid ensures a reliable energy supply, which helps reduce power outages, congestion, and losses in energy networks, leading to cost savings. It also makes a financial contribution to market operators due to increasing energy trade with the help of energy markets or ancillary services.

5. Case studies

This section summarises real-world examples demonstrating how DCs serve as flexibility resources. These examples are categorised into two main groups. The first category includes cases in which DCs provide frequency response services. The second category examines cases in which DCs participate in energy markets by adjusting their workload according to low-carbon-intensive resources or grid operator signals.

5.1. Frequency response services

Efforts to meet electricity demand with renewables, particularly in Europe, are increasing in line with Net Zero targets. The growing emphasis on sustainability drives an ongoing investigation into novel approaches for protecting the delicate balance between energy demand and generation in the power system. In this context, the emergence of frequency response applications related to DCs has become apparent in recent years. This is particularly highlighted with the introduction of bidirectional grid-interactive UPS technologies, enabling DCs to both draw power from and supply power to the power grid. One of the field experiments on data centre integration with power grids was carried out in Norway (Alaperä et al., 2019b). Statnett, the transmission system operator in Norway, initiated a pilot program to evaluate the efficacy of FFR as a potential solution for increasing frequency stability in 2018. The pilot program involved upgrading a data centre's UPS equipment to offer FFR services. Statnett determined the frequency threshold value for activating the FFR service in the Pilot region to be 49.60 Hz. In the Nordic frequency system, between 2012 and 2017, the average number and duration of frequency drops below 49.60HZ were recorded at five times and 4.2 seconds per year, respectively. Given these low figures, participating in FFR with the UPS system will not incur additional costs for the data centre, such as impacting battery life. Moreover, it will not jeopardise the disruption of its services. During the 4-week test period between July and August 2018, a failure was detected in the Finnish nuclear power plant on 18 July 2018. Operating as a unified synchronous area, the Northern European power system experienced a sudden drop in generation capacity, with the lowest frequency measured at 49.57 Hz. Remarkably, the UPSs of the DCs in the pilot region responded successfully to this frequency drop. According to the measurement results, the UPS system became active when the grid frequency dropped to 49.65 Hz and provided a full response at 49.60 Hz. The battery response time was measured at 30–40 ms. Additionally, the UPS system responded by reducing its power consumption from 377 kW to −572 kW, thereby contributing 949 kW support to the grid. The pilot study conclusively demonstrated that DCs with suitable UPS technology successfully participated in frequency response, meeting the FFR requirements.

Another field trial of actively participating in frequency response has been conducted by Bahnhof AB in Stockholm (Eaton, 2021). Bahnhof AB used an Eaton Power Xpert 9395 P UPS, which is a reliable grid-interactive UPS for DCs and provides fast frequency response functionality. The primary operational principle involves prioritising the critical load within the data centre while simultaneously and efficiently using the available surplus capacity within the UPS battery system.

Moreover, Microsoft is currently investigating the utilisation of its UPS to contribute to frequency reserves within the PJM region of the United States. In the preceding year, Microsoft, in partnership with Eaton's EnergyAware UPS, effectively applied this technology at a data centre campus in Dublin. This strategic step aligns with the objectives of EirGrid, the electrical distribution operator in Ireland, that presently emphasises using non-carbon energy sources. With the help of Enel X, a company providing energy services and solutions while grouping industrial and business energy users into virtual power plants, Microsoft Data Centres are actively engaged in this effort (Roach, 2022). Telia, which owns a data centre with a 24 MW capacity in Helsinki, is also actively integrating its UPS systems into the local grid (Anghel, 2023).

An application that distinguishes itself from other examples of frequency response participation in terms of utilising flexible resources was implemented by the Bikupa Data Centre in Sweden (Vattenfall AB, 2023). Using its computational power, it collaborates with Vattenfall and Sympower to provide FCR-D (Frequency Containment Reserve for Disturbances). Bikupa's framework involves shutting down its servers, which account for approximately 10 MW of consumption in one second when the frequency drops below 49.90 Hz. This flexibility can be sustained for a maximum of 15 min.

5.2. Participating in energy markets

The other group of field experiments on data centre integration with power grids is based on carbon-aware IT workload shifting and load adjustment according to a power grid operator signal.

Since 2020, Google's carbon-intelligent computing platform has been a novel approach to improving sustainability. Google strategically plans the timing of computing workloads based on the availability of carbon-free energy. This approach is illustrated in Fig. 6 (Radovanovic, 2020). The workload demand before the adoption of the is represented by a yellow dashed line, whereas the carbon-aware workload demand is represented by a straight green line. The grey zone represents periods during which carbon-intensive resources primarily meet energy needs. As shown in Fig. 6, the workload is shifted to less carbon-intensive times of the day.

Google is now employing not only IT workload shifting in time but also extending the method to shift loads between geographically distributed DCs, aligning with its 24/7 carbon-free energy target

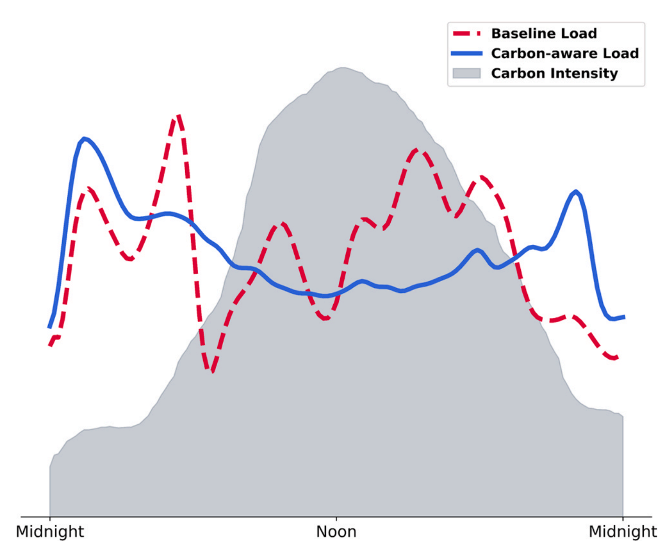

Fig. 6. Carbon-Aware IT Workload Shifting (Radovanovic, 2020).

(Koningstein, 2021).

In addition, Google employs another proactive approach to address potential disruptions to local power grids. This involves using a global computing scheduling system and sophisticated algorithms. The process starts with receiving an alert/signal from a grid operator predicting a local grid event. In response, non-urgent computing tasks are either postponed until after the grid event or, if possible and feasible, shifted to DCs located on a different power grid. It is crucial to note that this is done smoothly without the use of additional hardware or impacting the performance of essential Google services. In response to energy challenges in different regions:

Europe (Winter 2022-23): Google has taken steps to tackle the lack of natural gas by implementing measures such as reducing power usage on a daily basis during high-demand hours at DCs located in the Netherlands, Belgium, Ireland, Finland, and Denmark. This aligns with the European Union's efforts to decrease electricity consumption and provide energy stability during periods of energy scarcity.

Asia (Taiwan, Summers 2022–23): During the summer months, grid dependability might be compromised due to the geographical limitations of an islanded grid. Reducing daily power use at peak hours, Google supported a grid stability program in Taiwan and helped sustain grid reliability during supply shortages.

US (Oregon, Nebraska, Southeast): Google has partnered with local utility providers to reduce power consumption in DCs during extreme weather conditions, such as heatwaves and winter storms. This collaborative effort guarantees the stable operation of local power grids while simultaneously meeting the energy requirements of the surrounding community.

6. Barriers and challenges in obtaining flexibility from data centres

Data centre operators might face various barriers and challenges that need to be addressed to provide flexibility to the power system. The Quality of Service (QoS) and Service Level Agreement (SLA) constitute crucial challenges to maintaining the fundamental operations of DCs. Therefore, it is essential to update the agreements between DCs and their clients to gain more operational flexibility from DCs. To achieve this, additional government incentives and regulations are needed on both the customer and data centre sides to contribute effectively to the Net Zero Targets (Kenefick et al., 2021).

Because of the QoS and SLA, data centre companies are sceptical of any additional applications that may disrupt their core tasks or compromise the quality of services they provide, even though they can obtain definite economic, regulatory and climate benefits. A well-developed energy management and optimisation tool is required for DCs to provide flexibility to the electrical grid by participating in the energy market or providing ancillary services through novel demand response approaches. Otherwise, there may be a violation of SLA and QoS, leading to disruptions in the DC services. AI-based energy estimation algorithms, energy management systems, and optimisation methods might significantly improve the planning and management of workload distribution in data centres. These developments might enable a more efficient workload distribution while enhancing the ability of the systems to dynamically adapt to energy system needs, such as load shifting and peak shaving. As a result, AI can increase the flexibility of data centres. On the other hand, implementing AI-based energy management systems may increase data centres' costs.

Furthermore, a holistic perspective is required to coordinate with existing management algorithms, aiming to sustain data centre operations with maximum efficiency and low latency. Extensive R&D efforts are necessary to achieve this goal, which can be challenging due to the time and budget constraints. As a result, DCs face a substantial barrier to delivering energy flexibility, which can be overcome by strengthening government incentives.

The challenges that may be experienced regarding the participation of DCs in ancillary services or energy markets can be summarised as follows:

- To participate in energy markets, system operators may require the provision of information that could be sensitive to the data centre due to transparency requirements. This may lead to data privacy and security problems for DCs and their customers.
- In some countries, there may be a lack of legislation that allows DCs to participate in the energy market or ancillary services. Therefore, there may be a need to determine legal regulations and operational prerequisites for DCs to provide flexibility. In addition, rules set by regulatory authorities for other operators to participate in the power system can be complicated for the data centre to comply with.
- The existing technological infrastructure of DCs, such as UPS technologies, may not be sufficient for integration into energy markets. Since these infrastructures generally aim to provide maximum operational efficiency by focusing on internal energy management systems, integrating bidirectional power flow with the grid may be challenging.
- Data centre managers may not have sufficient awareness of the opportunities offered by participating in energy markets and the contribution they can make to sustainability. This may prevent DCs from conducting research in this area. Additionally, a lack of a full understanding of the technical requirements related to participation in energy markets or ancillary services may hinder the willingness of DCs to participate in this system.

Regional variations in energy markets, infrastructure and climatic conditions can influence the flexibility potential of data centres, leading to distinct challenges across different geographies, summarised as follows:

- In regions with advanced energy infrastructure and smart grid systems, data centres can optimise energy usage patterns and actively contribute to grid stability. However, in areas with outdated or inadequate infrastructure, this potential becomes even more limited. For instance, in regions prone to frequent power outages and transients, the reliance on UPS system is increasing. As a result, UPS batteries are primarily reserved for emergency power needs, reducing their ability to contribute to flexibility efforts.

- Additionally, regulatory conditions and energy market structures vary by region, which shape the flexibility requirements for data centres. These differences include variations in the flexibility durations, response times, capacities, and entry thresholds. In deregulated markets, such as in certain regions of the United States, broader opportunities for energy trading and cost optimisation exist. Conversely, stricter regulations in other areas impose significant constraints on market participation.
- Climatic conditions further impact data centres' energy consumption and flexibility potential. For example, in warmer regions, cooling systems account for a significantly higher share of energy consumption. In contrast, colder regions can leverage free cooling to substantially reduce the energy demand. These climatic dynamics, particularly the role of cooling systems and thermal inertia, strongly affect the flexibility of data centres.
- The requirements and opportunities for energy flexibility vary between urban and rural regions. In rural areas, the limited number of flexibility providers and constrained distribution capacity reduce the demand for flexibility, thereby limiting the potential contributions of data centres.

In summary, it is essential to develop solution proposals that consider various operational, regional, economic, and regulatory obstacles for DCs to successfully participate in the electricity grid and contribute to increasing flexibility in the power grid.

7. Final remarks

Ultimately, it is evident that the demand for DCs, and consequently their power consumption, will continue to increase in the coming years. DCs hold significant potential to provide flexibility to the power grid with relatively little effort compared to other flexibility resources, as they already house a variety of flexibility assets. Although the endeavours to provide flexibility might initially appear to only offer financial benefits to DCs and be more beneficial for the power grid, it is also likely to help them adapt to potential future regulatory restrictions.

To address concerns about energy efficiency and sustainability, legislative and regulatory initiatives, such as the Corporate Sustainability Reporting Directive (CSRD) (The European Parliament and The Council of The European Union, 2022), the Climate Neutral Data Centre Pact (CNDCP) (Climate Neutral Data Centre Pact, 2023), and the recast Energy Efficiency Directive (EU) (The European Parliament and The Council of The European Union, 2023), are actively establishing standards, recommendations, and targets to enhance the environmental impact of large energy consumers.

From this perspective, DCs should work to increase the level of energy efficiency and sustainability not only to reduce their costs but also to comply with such regulations and frameworks. Especially since the recast Energy Efficiency Directive published in September 2023 (The European Parliament and The Council of The European Union, 2023) sets many targets and necessities to be achieved, such as *"energy efficiency first"* as an essential tenet, there will be a driving force for the development of new, innovative, sustainable, and efficient energy management solutions for DCs.

The EU promotes enhanced transparency and sustainability in DCs by encouraging member states to require the gathering and public disclosure of data related to a data centre's energy efficiency, use of renewable energy, water footprint, effectiveness of cooling and contributions to decarbonisation levels with existing or new installations, such as the reuse of waste heat in nearby facilities or heat networks. Therefore, the EU can establish new sustainability and energy efficiency indicators using the aforementioned data, assess the actual levels of progress in enhancing sustainability inside DCs and increase transparency.

In the future, there will likely be an increased emphasis on sustainability and energy efficiency, complementing the existing metrics implemented in DCs. The outlined requirements signify a shift towards redefining sustainability and efficiency, expanding beyond energy to include the water footprint, freshwater usage, carbon usage effectiveness, and waste heat recovery ratios. Relying solely on the procurement of electricity from energy companies that rely on renewable energy may not suffice for goals such as energy efficiency and zero carbon targets. These trends present both challenges and opportunities for DCs in terms of proactive preparation for the future. Overall, embracing the aforementioned developments by leveraging innovative energy management systems will be highly beneficial. These systems can also provide flexibility to the power grid, helping to minimise costs, contributing to future zero carbon targets, improving power system stability, and enhancing the sustainability of data centres.

8. Conclusion

Recent efforts to achieve net-zero targets have accelerated the integration of renewable energy sources and the adoption of low-carbon technologies such as electric vehicles, heat pumps, and smart home energy systems. As these technologies become more prevalent, the need for flexibility in power systems increases to effectively manage renewable variability, fluctuating demand, and the integration of distributed energy resources. This flexibility is essential for ensuring stable and reliable power system performance in a dynamic energy landscape.

In this context, data centres have emerged as significant flexibility resources. By leveraging their existing infrastructure—including UPS systems, generators, servers, and inherent thermal inertia—and their ability to shift IT workloads in time and space, data centres provide flexibility to power systems. Unlike traditional flexibility solutions, which often require substantial investments in dedicated infrastructure, data centres offer inherent assets that position them as a cost-effective alternative to support power system flexibility.

This paper presents a conceptual framework for understanding the flexibility potential of data centres, focusing on the strategic value they bring to power systems rather than delving into technical details. It outlines how data centres can enhance power system flexibility by leveraging their assets and operational strategies, thereby detailing the environmental, financial and grid-level benefits. Furthermore, this study presents real-world case studies to demonstrate how data centres can apply theoretical approaches in practice.

In conclusion, data centres hold significant potential to offer scalable and adaptable flexibility to power systems by utilising their existing assets and operational capabilities. They can play a critical role in supporting the integration of renewable energy and the transition towards net-zero emissions. According to our analyses, the effectiveness of data centres in providing flexibility can reach its maximum level when all flexibility assets and strategies are combined and leveraged in an integrated manner rather than being applied individually. Among the strategies, IT workload shifting in time and space stands out for its high potential; however, identifying a single optimal approach remains challenging, as it depends on regional conditions, market regulations, and the type of flexibility needed. For instance, integrating UPS systems for frequency response could provide a fast and efficient solution in regions with such requirements, while acting as VESS may yield better results for predefined grid events or participation in flexibility markets.

Future research and policy efforts will focus on enabling mechanisms and frameworks that facilitate data centre participation in flexibility markets, further enhancing the resilience and sustainability of energy systems.

CRediT authorship contribution statement

Mehmet Türker TAKCI: Writing – original draft, Investigation, Methodology, Conceptualization. **Meysam Qadrdan:** Writing – review & editing, Supervision, Conceptualization. **Jonas Gustafsson:** Supervision. **Jon Summers:** Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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