Data Center Potential Flexibilities and Challenges for Demand Response to Facilitate 100% Inverter-Based Resources: A Review

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Abstract
The availability of flexibility services from demand-side management is one of the key features identifying the change from traditional distribution systems to smart distribution networks. Flexibility in demand helps maintain the balance between supply and consumption while integrating inverter-based resources. Compared to residential and commercial sectors, industrial sectors are anticipated to contribute more significantly, primarily because of the facilities' existing smart management systems, high power consumption, and scheduled operations. However, there is still a lack of knowledge regarding the industrial potential for demand-side management, particularly concerning the cutting-edge and advanced technologies connected to the smart grid. Thus, the main objective of this work is to critically explore demand side flexibilities within Internet data center industrial sectors. This study investigates scenarios in which data center industries may not be a load, but rather an asset to participate in demand response programs. This is because data centers consume a significant amount of energy and have the potential for spatial and temporal load regulations. Finally, given that data centers may engage highly correlated critical loads that must adhere to strict limitations, technical and regulatory constraints that restrict further participation in demand response programs are being critically assessed.

Keywords: data center, demand side management, power system flexibility, inverter-based resources, smart grid.

1. Introduction

The European Union (EU) aims to reduce 55% of greenhouse gas emissions by 2030 and to achieve climate neutrality by 2050 [1]. This goal lies at the core of the European Green Deal and is consistent with the Paris Agreement's commitment to the EU to take global climate action. The process of decarbonizing the energy industry is associated with many challenges. The decarbonization of the energy sector over the long term and the achievement of climate goals are both dependent on increasing the penetration of variable renewable sources and increasing the electrification of end-use sectors [2]. However, the rapid expansion of electrification along with significant amounts of variable renewable sources (i.e., wind and solar photovoltaic (PV)) could have an impact on the power system's

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reliability if not carefully planned. Wind energy and solar PV are important components of sustainable energy systems, but their variability and weather dependence result in short-term power mismatches between supply and demand [3].

In this context, more flexible resources that can react to sudden changes in supply and demand as well as to the variability in power generation are required [4]. The International Renewable Energy Agency (IRENA) defines flexibility as the capability of a power to cope with the variability and uncertainty that solar and wind energy introduces at different time scales, from short to the long term, while minimizing renewable power curtailment and reliably delivering energy demand to all customers [5]. On the supply side, conventional power plants have traditionally been used to provide system flexibility. However, with the increasing urgency to decarbonize the energy sector, there is a global need to examine demand-side flexibility more closely. Demand-side flexibility is a strategy for leveraging flexibility that includes both the supply and demand sides of the market considering both technological and behavioral changes through demand-side management (DSM). DSM aims to change a portion of electricity usage based on price or incentive signals that can be reduced, increased and shifted over different times to facilitate the integration of inverter-based resources (IBR) such as wind and solar PV, reduce peak load and seasonality and reduce electricity generation costs. Applying demand-side bidding the customers are allowed to shift low priority loads from higher price time slots to other cheaper periods [6]. Furthermore, in the DSM, customers can curtail demand while turning off low priority loads by implementing policies and methods that control electricity demand, such as demand response (DR) [7].

Electrification of end-use sectors includes buildings, transport, and industry (i.e., electric vehicles (EV) smart charging [8], heat pumps (HP), energy storage including behind-the-meter batteries, the Internet of things (IoT), and artificial intelligence and big data [9]). The electrification of end-user is anticipated to result in high penetrations of HP and EV, creating new business models for demand flexibility. According to the IEA, operational demand side flexibility of 40 GW today could rise to 200 GW by 2040 and the current average potential of 457 GW (4000 TWh), which is the sum of flexible loads at each hour over a year, is projected to increase to an average of 800 GW (7000 TWh) by 2040 [10]. This is expected to change the characteristics of the distribution network as most of these devices are interfaced with the grid via smart power electronics devices. Given the efficiency gains obtained by electrifying these sectors, electrification of end-use sectors is viewed as a potential solution to decarbonization [11], to allow the penetration of variable renewables [12] and enable effective cross-sector integration via smart energy systems [13].

The establishment of the smart grid (SG) concept is the wide adoption of advanced metering infrastructure and the enormous capabilities that result from the development of information and communication technology (ICT) solutions to monitor and control electrical energy. DSM must be fully integrated, which involves the use of automated metering, communication and sensor systems, intelligent devices, and advanced processors [14]. This implies that a new communications layer for communication channels and control will be added on top of the current power network layer. Smart metering and innovative ICT for energy management in distribution systems present a pragmatic possibility to pursue energy savings, take advantage of renewable energy, and encourage consumer participation in the energy market. Innovative ICT infrastructures enable the communication of regular price updates and support a more efficient network operation, offering new challenges for

DSM. The ICT enables more reactive, dynamic pricing mechanisms needed to account for real time variability of renewable generation while tracking the balance between supply and demand [15].

Moreover, large-scale data center industrial loads are well positioned for DSM due to their significant energy consumption, which accounts for more than 20% of all global electricity usage by 2025 [16]. The challenge is also their financial resources and emissions [9], and most countries plan on moving to renewable energy technologies to mitigate and eliminate emissions from their power systems. Therefore, the sectors and industries that use ICT want to be seen as corporate and socially responsible like other large industrial and commercial loads (e.g., refining and mining, food chilling and storage, and manufacturing facilities) [17]. Indeed, green credentials play a large part in this but purchasing renewables and emission offsetting are losing credibility meaning that new factors to make significant differences will be required (i.e., DR services) [18]. Incorporating these services into SG contributes to lower greenhouse gas emissions by reducing the utility's average carbon footprint and marginal emissions, which are reflected in data center footprints.

Furthermore, these customers can use DSM programs to change their production schedule to account for changing electricity prices over time, particularly through wholesale energy and ancillary services markets [19]. There is a significant amount of flexibility in these sectors that can be utilized, benefiting both the industries and the grid operators, given the advancements being made in monitoring and controlling infrastructure and electricity market mechanisms. This requires the addition of a two-way communication link between the system operator and the industry agent participating in the DR program. The majority of data center sites already have smart sophisticated energy management systems and metering infrastructure in place to enable their participation in DR. This assists both system operators and customers in operating the electricity market more efficiently in various business models. Nevertheless, a low participation rate is seen, primarily because of a lack of knowledge, the absence of the right price signals, regulatory frameworks, technical limitations, and complexity issues [20].

Many recent studies have attempted to approach the above limitations such as authors in [21] focused on the problems of data center DR in an SG area with utility companies competing to attract more customers, a comprehensive review of data centers participation in DR studied in [22], research in [23] proposes coordinating multiple coupled regulation methods in data centers to fully utilize data center spatial and temporal load regulation for DR, a framework for the optimal operation of data centers, leveraging their delay-tolerant workloads, heating, ventilation, and air conditioning unit, and battery storage system (BESS) for participating in DR proposed in [24], the use of data center resources as static and dynamic DR for frequency response service was investigated in [7]. In [25], a tie-line power fluctuation smoothing algorithm with holistic data center DR consideration is investigated. Even though literature has examined the technical aspects of the aforementioned issues, there is still a lack of knowledge about technical flexibility and limitations within data centers that prevents them from becoming active DR participants. Nevertheless, none of the previous literature assessed flexibility resources within data centers, in the context of system operators' plans to achieve net zero targets.

The motivation for this research lies in the fact that data centers represent a particularly promising sector for the adoption of DR programs to facilitate secure power system operation with high IBR. The ICT industry is made up of a variety of technologies with controllable characteristics that have the potential to play a key role in changing the energy landscape. Thus, this paper considers the most suitable utility support service types for data centers in order to provide insights into DR opportunities in the context of the data center power system infrastructure. The remainder of the research is structured as follows. Section 2 examines DR schemes and energy efficiency. Deep analyses of data center flexibilities is given in In Section 3. Section 4 provides the main barriers and limitations that prevent data center participation in DR programs. Discussions and recommendations are provided in Section 5. Section 6 concludes the paper with some remarkable future work directions.

2. Demand response schemes

Demand response is the demand change in relation to grid generating capacity. It is intended to address the imbalance between supply and demand, high wholesale electricity prices, and improve grid reliability. Power system utilities have been utilizing DR schemes through price-based capacity bidding programs to gain economic benefits for decades [26]. A summary of DR programs is shown in Fig. 1.

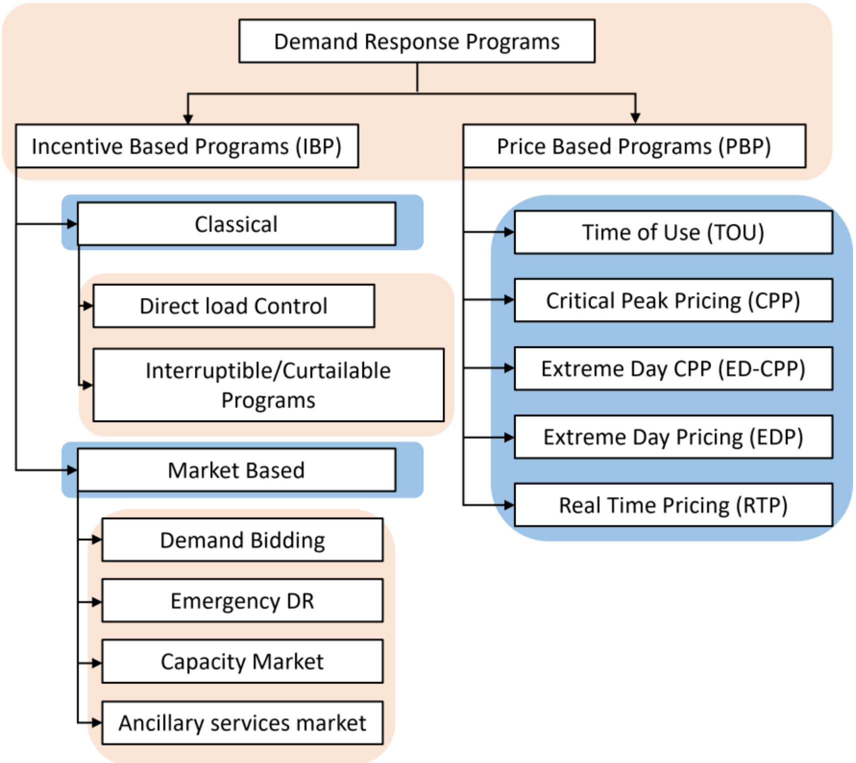

Fig. 1. General classification of DR programs in the market.

2.1 Price based demand response

Capacity bidding is a manageable power that is ready for use when power system operational constraints are at risk of being violated [27]. After a participant confirms to provide this service, a prepayment is settled typically in the day ahead through market predictions. Participants in the day-ahead market agree to buy or sell energy one day before the operating day in order to reduce price volatility and balance forecasted demand and generation. The participant is penalized if the contracted amount of demand change (reduced or incremented) from the base profile is not achieved during an event [28]. While most price-based demand response schemes are limited to infrequent peak shaving and load shifting applications, demand flexibility is acknowledged as having the potential to offer more lucrative ancillary services like voltage and frequency regulations, and even black start through incentive-based programs.

Fig. 1 depicts two examples of price-based DR programs: real time pricing (RTP) and direct load control (DLC). In residential DSM, DLC programs [15] are based on a contract between the power system operator and the users, during which a third party aggregator remotely controls the operations and energy consumption of specific appliances (i.e., thermal loads, refrigerator thermostats, and HPs). Smart pricing is an alternative to DLC where users are incentivized to manage their loads independently and voluntarily, for example, by lowering their consumption during peak hours [29] [30] using real-time pricing (RTP), time-of-use pricing (ToUP), and critical-peak pricing (CPP). As per RTP programs, the cost of electricity varies depending on the time of day, and each user is anticipated to respond to the time-differentiated prices on their own by shifting low priority loads from the high price times to the low price time slots. This is intended to encourage lower electricity consumption during periods of high wholesale market prices or when power system reliability is jeopardized.

2.2 Incentive based demand response

It is worth noting that for the incentive-based program, effective DR behavior on shorter time scales requires additional investment to execute real-time or fast DR options (i.e., ancillary services or spinning reserves) [31]. Two main differences between DR for ancillary services compared to typical DR applications are the reduced notification time and more advanced technical requirements related to measurements (speed and accuracy). Ancillary services are required to support the delivery of energy to the distribution system while ensuring the stability and security of the transmission system. Ancillary services bidding is provided upon the confirmation to provide a certain amount of reserve to provide frequency response in wholesale markets. However, this service requires frequent dispatch of fast responding devices for short periods while providing higher incentives than other programs [32]. Besides, this service is more lucrative than day ahead market. For power quality services related to transients and harmonics, inverter interfaced flexible loads can change their consumption. Instead of requesting generators to swiftly raise power during under frequency disturbances, a faster action could be elicited by asking a load to reduce power. In ERCOT, for example, industrial loads and smart appliances participate in the ancillary services market while contributing to the interconnected power system frequency reserves which assist in maintaining power system security in the event of a sudden loss of generation [11]. Other advances have also been made in the breadth and scope of DR programs, with new programs designed to enhance transient stability during fault events by providing fast frequency response (FFR) service from DR (e.g., EirGrid/SONI) [33], [34]. It is worth noting that data center onsite resources are well suited to participate in both incentive-based and price-based market programs.

2.3 Power system needs

Maintaining a power system's operation requires a continuous balancing of the generation and demand at any time. Any imbalance causes the system frequency to deviate from its nominal value [35]. Frequency deviations are frequently caused by disturbances, which must be addressed by several ancillary system services at the transmission level such as synchronous inertia, FFR, primary operating reserve (POR), secondary operating reserve (SOR), and tertiary operating reserves [33]. The operational needs for power systems under high penetration of IBR can be classified into: i) Power system stability and power quality (i.e., the ability to regain an equilibrium state after being subjected to a disturbance without violating grid codes) [35], ii) Capacity adequacy and security of supply (i.e., the sufficient spinning reserve should be available to cover peak demand) [36], iii) Power system resilience and system restoration (i.e., grid capability to respond to extreme catastrophic disturbances) [8]. Historically, synchronous power plants were the primary source of these system needs via grid codes, wholesale electricity markets, and ancillary services markets. However, to ensure the future power system needs can be met, the source of system services to meet these needs will change from synchronous plants to other sources (i.e., DR, uninterruptable power supply (UPS), batteries, and variable renewable sources).

A summary of system services that DR can provide is shown in Fig. 2. Small scale data centers can be integrated into a virtual power plant (VPP) at the system generation level. The VPP is a concept for combining various devices into a single flexible entity that is big enough to take part in energy trading and/or offer real time grid services [37]. The VPP makes use of renewable forecasting data to allow for real-time corrections within intermittent renewable power sources as well as changing consumer needs.

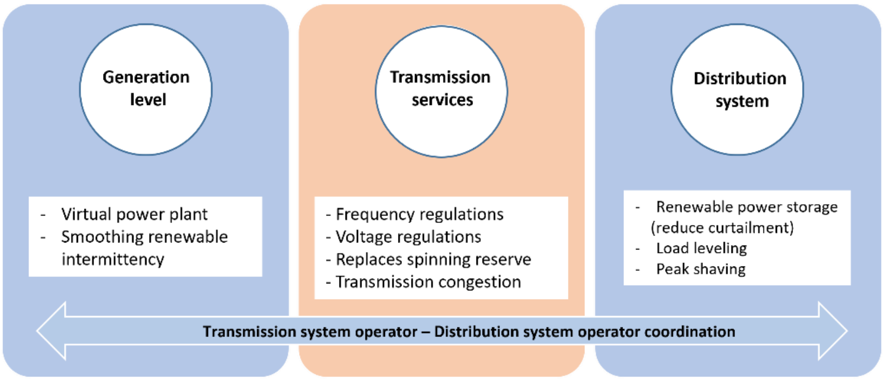

Fig. 2. Services that demand response can provide at different levels in a power system.

Demand response to frequency excursions represents a novel technique to reduce the need for spinning reserves of conventional generators [38]. Such services could help to reduce system demand at times of typically high prices, potentially reducing output from expensive peaking plants (i.e., gas power plants) and thereby lowering system expenses. Furthermore, displacement of conventional generation at high IBR can result in a significant shortage of steady state reactive power capability, particularly in weaker parts of the system with high IBR far from synchronous generation [36]. As a result, voltage deviations that violate the relevant planning and operation standards may become more severe and frequent, as well as propagate throughout the system. In literature, demand scheduling in low voltage distribution networks to maintain voltage violation issues was proposed [39]. This technique proved to have the ability to improve the maximum active power injection from variable renewable generation rather than leaving a portion of the capability curve open for reactive power movements. In [40], the DR program was used to shift some of the loads from peak hours to times when additional power consumption is anticipated to lower over-voltage conditions.

In summary, the main objective of demand shifting, reduction, or demand increase is to do the followings:

1) Reshape load profiles to accommodate intermittent renewable generation and assist the integration of large-scale renewables.
2) Voltage and frequency regulation, peak shaving, and even sending power back to the grid for profit, as in data centers.
3) Reduce power generation expenses by moving load from times of high supply price to low prices periods.
4) Investments in transmission and distribution system upgrades that are required to meet anticipated load growth in specific grid regions are delayed, reduced, or totally eliminated.

2.4 Energy efficiency

An important aim of energy management is energy efficiency, particularly in environments where lowering energy costs is necessary and plays a significant role. Recent developments in the Internet of things (IoT) (such as low-cost wireless sensors, interconnected networks, and asset management software) have made it possible to apply control actions and use smart systems for energy conservation [14]. Facility managers can evaluate the operational flexibility of the demand units using dashboards provided by modern automation systems. These devices offer facility managers complete information on the status of the participant in the DR program to respond to signals from the system operator during contingencies [41]. The possible effects of efficiency and DR measures on the quality of customer service are shown in Fig. 3 [15]. As demonstrated, the customer's existing infrastructure of buildings and equipment determines the prospects and potential for both energy efficiency and DR service. Short-term mitigation measures and long-term investments in energy efficiency are both included in the daily energy efficiency segment of actions. End-use customers can take part in various DR operations (i.e., signing up for a ToU rate and scheduling loads like air conditioners and pool pumps for off-peak hours) or they can invest in energy efficiency to manage their electric service needs and costs.

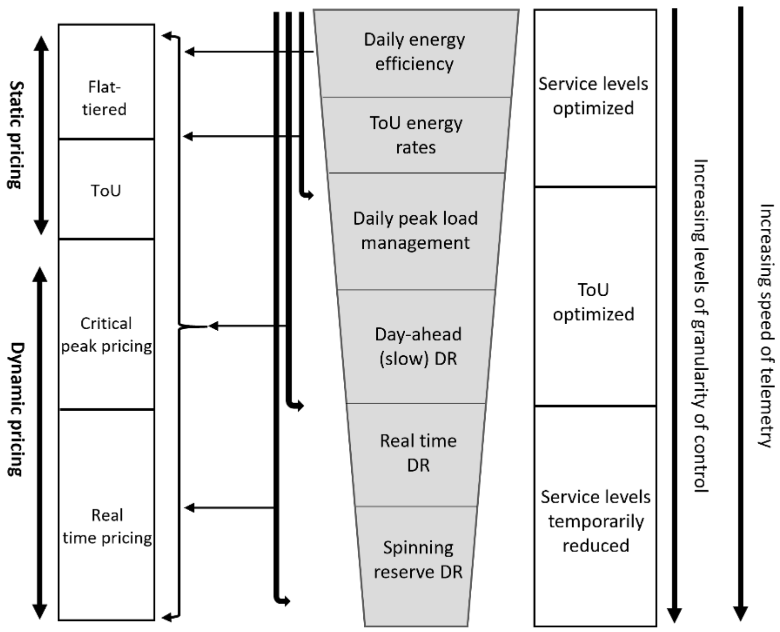

Fig. 3. Energy efficiency and DR conceptual perspective.

As shown in Fig. 3, DR services have become more sophisticated due to modern telecommunications and ICT infrastructure such as smart meters. Although rapid communication to a growing number of widely dispersed load nodes appears to be becoming more feasible [42], DR utilization as a supplement source to rebalance emergency power mismatch presents new challenges. The issue is associated with manipulating and estimating the power flexibility of a large number of participants, including their visibility to the system operator as well as communication and actuation delays associated with activating various small-scale DR units [26]. To cope with the aforementioned issues, there have been a variety of potential efforts to standardize demand response and demand flexibility programs such as the IEEE standard 2030.6-2016 [43], and the National Institute of Standards and Technology (NIST) Smart Grid Interoperability Standards [44].

3. Internet data centres

Internet data centers are a key element of the digital economy in the twenty-first century, providing the critical computing and storage infrastructure that will be required to unlock economic development over the coming years. Currently, information factories are considered one of the fastest-growing electricity consumers and a more significant source of power demand [45]. According to the international energy agency (IEA), they consume around 205 TWh accounting for 1% of global electric power generation and their power consumption is anticipated to rise as data generation, processing, and storage requirements grow [46]. In the EU data center, dominant countries (i.e., Germany, Ireland, Netherlands, Norway, and the United Kingdom), hyperscale and colocation data centers are projected to have a total installed capacity of 6.9 GW and actual power consumption of 3 GW by the end of 2021, as illustrated in Fig. 4 [47]. This means that about 50% of the installed data center capacities will be actively live, consuming total energy of nearly 26 TWh, accounting for 2.3% of these countries' total annual electricity usage. The installed capacity is projected to increase by 83% between 2020 and 2030, while energy consumption will grow by approximately 50% to 47.6 TWh. This figure shows that data center energy usage in Ireland will nearly double from about 5 TWh in 2021 to above 10 TWh in 2030.

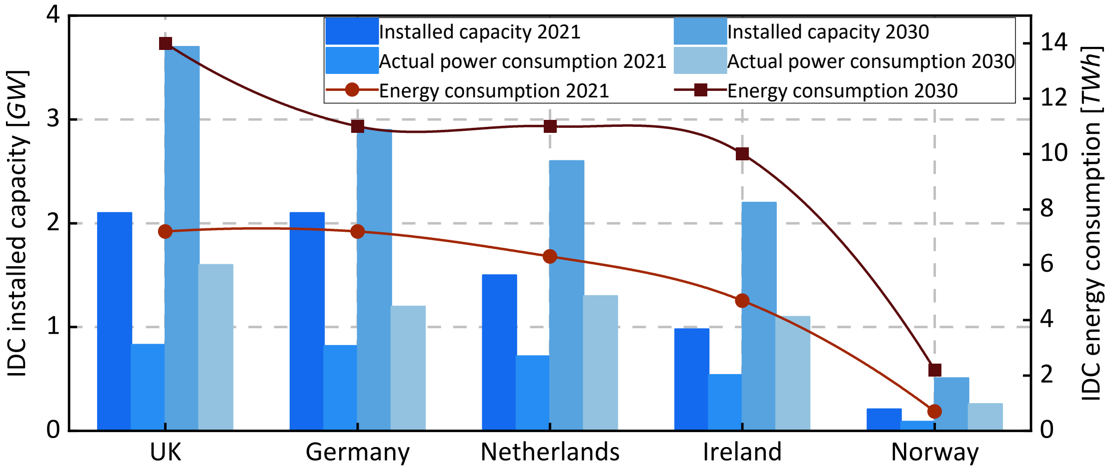

Fig. 4. Data center installed capacity, the actual power consumption that will actively be alive, and energy usage in five EU dominant countries. *IDC: refers to internet data centers.

Fig. 5 compares the actual power consumption of data centers in the aforementioned EU nations as a proportion of the maximum demand forecast in 2030. As shown, the UK and Germany have the highest data center energy consumption, accounting for 3% and 1% of total national demand, respectively [47]. The percentage of data centers will remain nearly the same compared to the peak demand in these countries. In Ireland, however, when compared to actual demand on the island, data centers accounted for 15% of the overall demand in 2021, the highest percentage among the priority countries [47]. By 2030, this is likely to rise to 24% and more than 31% under the medium and high-demand scenarios, respectively [48], whereas only 17% and 23% of the maximum demand is projected to be actively alive [47], as depicted in Fig. 4. Ireland is often regarded as having the greatest hyperscale data center capacity in the EU, and the most big-tech firm data center capacities (i.e., amazon web service (AWS), Google, Microsoft, Apple, and Facebook). Between the end of 2019 and to end of 2021, an additional 124 MW of design capacity is expected to be deployed, with a total of 524 MW by 2024 [49]. Accordingly, this raises concerns about the impact of data center power consumption on the grid's future resiliency [48].

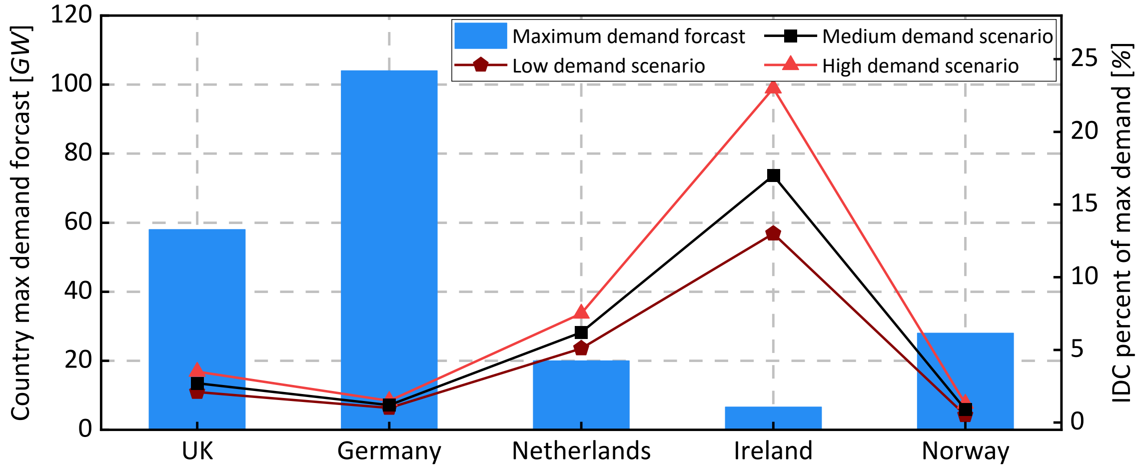

Fig. 5. Live data center demands in the percentage of the country's maximum demand forecast in 2030.

As the EU electricity system is currently decarbonizing, data center expansion is taking place against a backdrop of increased variable renewable power. While data centers are considered loads for the power grid, each MW of data center capacity combines an MW of power generation from the utility, an MW of backup power generation, and energy storage in the UPS [50]. This opens up possibilities for data centers to both run on more clean electricity and contribute to and support the secure transition to scale-up renewable power generation through demand response services. The concept of utilizing data centers for demand response services stems from the increasing need to quickly maintain a balance between generation and demand, partly attributed to the increased power consumption due to the deployment of large-scale data centers and the rapid adoption of inertia less variable renewable power generation. Data centers are sophisticated energy systems and well suited to address these challenges and be part of this narrative of a more open, interactive, and flexible power grid for two main reasons:

1) Data centers are large-scale concentrated loads at a single site that can be shifted in response to grid requirements [51], making it much easier to access than a vast number of small-scale fragmented and dispersed loads (i.e., residentials, HPs, and EVs).

2) Data centers host various potential resources in a single site, including UPS, batteries, cooling systems, load shifting, and backup generators. All these DG assets are already aggregated, centralized, and equipped with a sophisticated and automated energy management system (EMS) that monitors and controls cooling and electrical networks [52]. This greater centralization means that the load can easily be monitored and estimated compared to the aggregation of thousands or even millions of EVs when participating in ancillary services.

The followings are the main source of flexibility within a typical data center that can be deployed to provide ancillary system services:

3.1 Uninterruptible power supply

A UPS is a short-term energy storage unit utilized to maintain data centers' seamless operation. The UPS enhances the grid power quality supplied to critical information technology (IT) loads during regular normal operations. In the event of grid failure, the UPS uses batteries to offer instantaneous power to IT devices up to an emergency backup power is operated. The BESS is traditionally a valve-regulated lead-acid battery (VRLA). However, lithium-ion battery (LIB) has been displacing VRLA batteries recently due to lower costs, improved performance [53], longer lifespan, and eight times better life cycle rate than VRLA [54]. Because of the short charge and discharge times, and the ability to be monitored and regulated by a battery monitoring system through data exchange with the UPS, LIB is currently a preferable solution for grid applications [55].

Conventionally, UPS systems are only meant to supply backup power for a few minutes or until alternative backup power, such as a diesel generator, comes online. Thus, the UPS and batteries are sized based on data center IT load capacity and for up to 5 to 30 minutes of energy duration [56]. This is untapped energy that is mostly idle in developed countries where the utility grid is stable. It was previously thought to be the inevitable cost of having to use them occasionally to support the critical load. However, utility incentive-based DR service is expected to open up opportunities for data centers to use their UPS energy storage systems to support grid security. They can be called upon for quick bursts of power when the grid requires to accommodate short-term spikes in demand. After they have served their purpose, the UPS can be charged back up to the levels required to ensure the data center's security.

Several data center operators are already utilizing their UPS to offer flexibility. In the PJM area of the US, Microsoft is looking into using its UPS for frequency reserves [54]. From a practical viewpoint, in 2019, Basefarm actively participated in a trial with the Norwegian system operator Statnett to provide FFR reserves [57]. A field study by a Swedish system operator illustrated that a 0.1 MW Fortum UPS was able to act fast enough to fulfill technical requirements for frequency containment disturbance reserve without affecting operational limits [58]. DigiPlex data center operator, another colocation partner, has entered into a contract to use their UPS to participate in Statnett's FFR services [59]. In 2019, Eaton launched a trial project called Energy Aware with EirGrid, a transmission system operator in Ireland, and energy services provider Enel X in which its UPS systems provide electricity back to the Irish grid [60]. More recently, Noriker Power engaged Vertiv to offer a 20 MW UPS solution with modern technology and the required technical speed of response to provide FFR services directly to the National Grid of Great Britain [61]. The Liebert® EXL S1 UPS, for example, enables both dynamic and static frequency regulation by modifying its response in accordance with the predefined frequency or voltage threshold limits. The dynamic grid support functionality enables energy-intensive enterprises to proactively use UPS systems that are compatible with VRLA and LIB technologies. This is schematically illustrated in Fig. 6.

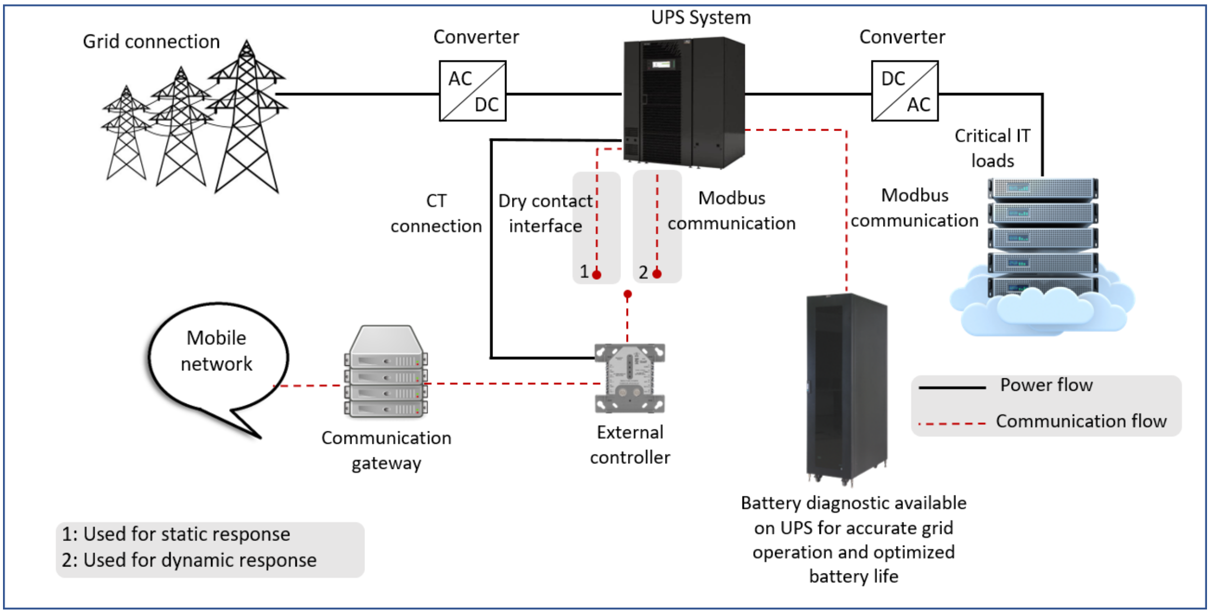

Fig. 6. Static and dynamic demand response with Vertiv™ data center UPS systems.

The UPS supports demand management to adjust the input power using both static and dynamic regulations.

1) Dry contact is used for static frequency regulation, and a predetermined fixed power response is engaged at a specific frequency variation.
2) Three operational modes are supported via dynamic regulation via Modbus signals, which is dependent on frequency deviations: i) Increase input power and battery charging when over-frequency is detected, ii) Decrease input power and increase battery discharge when an under-frequency condition is detected, iii) Continuous ramping power up and down for frequency regulations.

Furthermore, the converter side of the UPS could be equipped with grid forming (GFM) technology rather than grid following (GFL). The UPS in such cases can contribute to the power system strength due to the intrinsic characteristics of the voltage source behind the impedance of the GFM converter [62]. It is worth noting that IBR (i.e., solar PV and wind) with GFL converter contribute less to fault current than synchronous generators, reducing system strength considerably. Future power systems with a predominance of IBR connected to fragile grid areas and fewer synchronous generators online may have significant effects on distribution voltage management, protection performance, and the stability of IBR [63]. As an example, Australian Electricity Market Operator (AEMO) predicts a considerable decrease in South Australian network strength as a result of the displacement of large synchronous machines during periods of high IBR levels [64]. In such cases, data center locations with GFM converter UPS systems can be excellent segments for power system stability, allowing for secure operation with high IBR. The UPS systems can also support grid recovery from blackouts because the power system only requires the UPS for short periods to recover grid voltage and frequency.

Finally, similar to the ON/OFF state of synchronous generators, energy storage has a charging/discharging state that is usually modeled using a binary variable. It is important to ensure the state of charge (SoC) of the UPS remains within the upper and lower bands to prolong the battery life and guarantee the operational safety of data center critical loads. The industrial recommended settings for the battery SoC is above the minimum (SoC_{min}) and below the maximum (SoC_{max}) which is constrained to 40% and 80% of the UPS storage capacity, respectively [55], [62]. The SoC ranges can be further adjusted using a machine interface to accommodate grid over/under-frequency events, as shown in Fig. 7. Thus, each energy storage unit must meet the charge/discharge power and SoC restrictions during every dispatch interval.

Energy saved for IT loads (DR service is disabled)	Energy stored for FFR service (under and over frequency)	Additional energy capacity to protect against over frequency
0 - 40%	40 - 80%	80 - 100%
SoC_{min}	SoC	SoC_{max}

Fig. 7. Battery energy storage state of charge recommended settings.

3.2 Backup battery

This is an external power storage capacity co-located with the data center to provide backup power in the event of a power outage as an alternative to backup generators. Traditionally, this is not designed to function as bi-directional microgrids, but rather as unidirectional microgrids during utility outages. Only a few data centers are currently dedicating backup batteries (e.g., Google 2.7 MW/5.4 MWh battery at one of their sites in Belgium) [47]. An on-site BESS is similar to a UPS and can provide a variety of ancillary services to the grid while only considering a portion of the battery to be accessible for system services and the rest for site reliability, as shown in Fig. 8. The figure illustrates how modern UPS and backup BESS models can operate in different control modes to respond to the power setpoint by increasing or decreasing demand from the utility while supporting the important load. The graph depicts 1N and 2N storage topologies with no backup and a fully redundant mirrored system with two independent sources, respectively. The latter means that even if one power source failed, the system should still be powered and able to handle its full load, preventing any potential downtime caused by the loss of one of the system's sources [65].

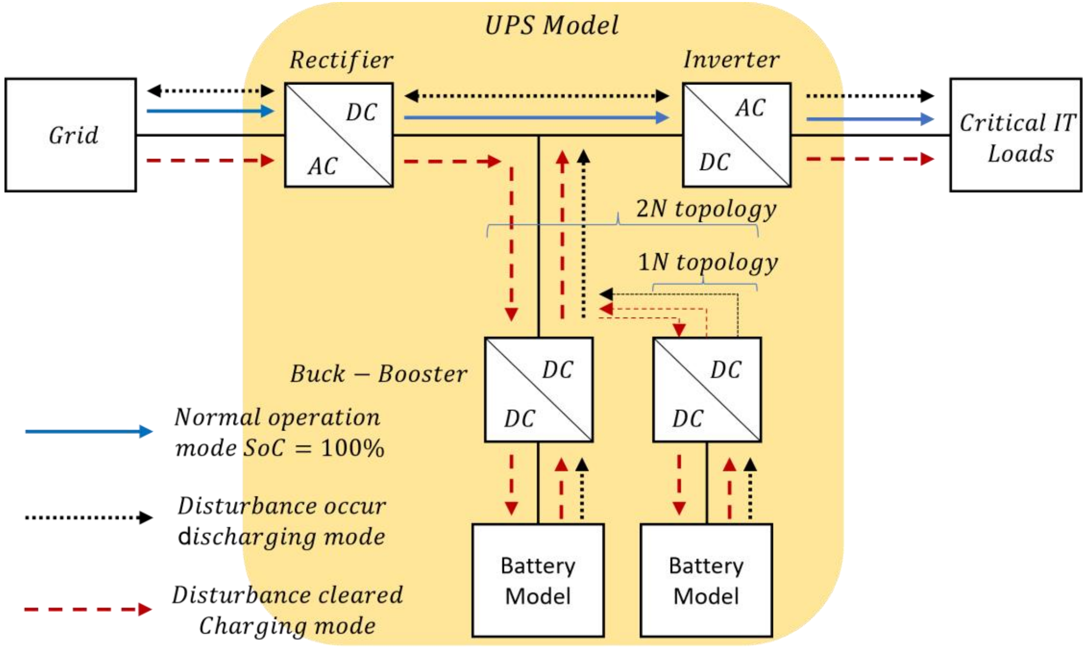

Fig. 8. Modern data center UPS 1N and 2N configurations to participate in different system services.

It is to be noted that the availability of on-site BESS, similar to other components, is typically classified by Uptime Institute (UI) as Tier I, Tier II, Tier III, and Tier IV [66]. These Tiers mean nonredundant capacity, Tier I plus redundant capacity, Tier II + dual-powered equipment, Tier III + all components are fully fault-tolerant and dual-powered including chillers, cooling systems, and servers, respectively. Data centers are mostly developed to fulfill resilience criteria to ensure uptime and performance in Tier III with 99.982% availability and Tier IV with 99.995% availability [67]. Data center operation at higher Tiers implies greater flexibility in providing FFR services due to the availability of redundant components and the ability to rectify issues without disrupting IT operations.

3.3 Back-up generation

The simplest and most obvious form of DR participation from the perspective of a data center is load shedding, in which the data center transfers its connection from the grid and operates solely on its backup generators in an island mode. Dispatchable power generation (i.e., diesel, natural gas, and hydrogen) sources are co-located with the data centers in the event of a power outage. In comparison to UPS, Gensets are even less used due to their long starting times, which make them incapable of starting and accepting load during a utility outage. On-site generators could also provide grid operators with significant flexibility, particularly as a black start generation asset to restore power to larger conventional power plants and bring the grid back online [68]. They are also appropriate for the slow SOR and TOR ancillary service markets, which many data center operators now use, because of the long start-up time required [50]. With emerging shares of variable renewable power generation, many data center operators already started to offer their backup generation to actively provide ancillary services as a secondary reserve for peak shaving, and frequency management in power networks is growing [69].

While the majority of this capacity is currently diesel, which is too polluting to use except in an emergency. Microsoft is exploring both short-term and long-term alternatives as part of its commitment to phase out diesel fuel and become carbon-neutral by 2030 [70]. Eventually, alternative fuels, LIBs, or hydrogen storage via fuel cells could replace diesel generators in the mid-term future scenarios [71]. For instance, Microsoft opened its sustainable data center region in Sweden in November 2021, using Preem's Evolution Diesel Plus as generator fuel for a mid-term solution. In comparison to conventional fossil diesel blends, this diesel has approximately a comparable reduction in net carbon dioxide emissions and at least 50% renewable raw material content. Furthermore, hydrogen Proton-Exchange Membrane (PEM) fuel cells are a long-term solution that use the chemical reaction between hydrogen and oxygen to produce electricity, heat, and water without burning, emitting any particulates, or emitting any carbon dioxide. The 3 MW PEM fuel cell test in Latham United States, which was the first to use the size of a backup generator at a data center, showed that this technology is viable [70]. Due to their relatively slow load following capability, solid oxide fuel cells (SOFC) may not be suitable for providing real-time frequency support services [18]. Hydrogen PEM fuel cells, on the other hand, have a faster ability to follow loads and can be used to provide FFR and other slow frequency services. In principle, both SOFC and PEM can provide load curtailment, load shifting, and slow system services.

3.4 Cooling loads temperature setting

The heat generated by data center IT loads is approximately proportionate to the electricity consumed, and it must be removed to prevent server equipment from overheating. Overheating resources can cause a loss of availability (e.g., emergency shutdown), efficiency drop (e.g., thermal throttling), or even hardware degradation, resulting in early system failure. Data centers are constantly cooled to address these issues, with cooling energy accounting for about 50% of the overall data center energy usage [72]. Historically, two cooling solutions have been deployed to cool data center IT loads, including a combination of raised floors and computer room air conditioners (CRAC) or computer room air handlers (CRAH) [73]. These two strategies were further enhanced by adding a free cooling mode that uses ambient air.

Data centers can tolerate a wide variety of temperatures, resulting in a variety of power consumptions. The American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), for example, divides data centers into four classes (A1 - A4) based on their thermal requirements. According to ASHRAE, the supply air temperature of these classes is specifically designated within a range of 5 and 45 °C, while class A1 data centers typically provide mission-critical activities and require a closely controlled thermal environment between 15 and 32 °C [74]. A study in [52] claimed that increasing the temperature setpoint by 1 °C, from the recommended to the allowable range, saves between 4.3 and 9.8% of the power used for cooling. Further savings can be realized by removing local hotspots and smoothing the airflow, which reduces the amount of electricity necessary to run the fans that circulate the air [75]. This technique could also be employed as a form of virtual energy storage. It is possible to lower the operating temperature set point and so cool down the complete data center when there is a surplus of energy (e.g., from renewables). This produces a thermal buffer that can subsequently be turned off to reduce cooling power demand until the crucial set-point is reached. Because the response of this system is greatly dependent on the size of the data center and the internal architectural decisions made, cooling or heating a typical data centre can take up to 5 minutes [76].

3.5 Delay tolerant workload shifting

A variety of computational workloads are served by data centers that can be deferred or rescheduled to times when power system demands are more favorable [77]. Some activities occur in real-time, like video calls or financial trading, while others, like data storage backup or machine learning training, do not have to happen immediately and are known as delay-tolerant workloads. The amount of real-time and delay-tolerant workloads in a data center varies depending on data center users, type of service, and time of day. Although reports suggest that 30-50% of computing workloads are delay-tolerant, there is little to no evidence that these amounts will vary as the Internet of things (IoT) and machine learning become more prevalent [47].

The ability to postpone a task is highly dependent on the user's willingness to shift the task, the estimated time to complete the task, and the desired completion time [78]. Unlike UPS, load shifting may directly affect the service level agreement (SLA), potentially delaying the completion of a task by several hours. Thus, data center operators will require detailed information on the user tasks as well as appropriate signaling from the system operator to encourage load rescheduling. It is feasible to postpone and reschedule a task on short notice, but this has not yet been implemented for FFR services. However, long-time shifting is well suited to energy market operations such as peak shaving or matching renewable production [79].

3.6 Load migration and virtualization

The ability to undertake computing operations at different data center locations aligns with times and locations where renewable production is more abundant. Data center operators at numerous locations may transfer jobs to improve efficiency and take advantage of reduced energy prices in specific areas [51]. The ability to shift load is contingent on the availability of computing capacity and proper hardware and software for data transfer at the colocation destination site. Transferring computational tasks to provide emergency demand response schemes from one location to another necessitates energy use, which the data center operator should consider while evaluating the cost and carbon implications of relocating workloads [80]. Shifting the load would most likely result in the task being moved further away from the user, increasing the task's delay. Microsoft, for example, observed that shifting video tasks inside the EU could increase delay times by 10.5% [81]. Another example is Google's adoption of "carbon-aware computing" which entails forecasting power emissions intensities for various data center sites and arranging computing operations to correspond to those intensities [82].

Fig. 9 depicts the technical response time capability of the aforementioned data center resources. As demonstrated, data center resources are well suited to participate in the balancing market (i.e., inertia and FFR services) and in energy management, which necessitates the ability to endure for long durations (i.e., reserves and peak shaving). For example, UPS and onsite BESS units can provide most ancillary system services due to their potential to instantly respond to frequency deviations that last less than a few seconds. The fast response capability of UPS and onsite BESS can assist in power system stabilization and secure integration of higher levels of renewable energy sources [55]. Nonetheless, their limited energy supply prevents them from sustaining for an extended time (i.e., hours or days). Due to their high power capacity and limited energy duration, UPS systems are well suited to provide FFR ancillary services that require blast power for a short duration. The full UPS power capability might be made available to provide grid services at the same time, data center operators would constrain the dip of discharge rate of the battery by controlling the SoC limit to assure the primary role of the UPS for IT load security.

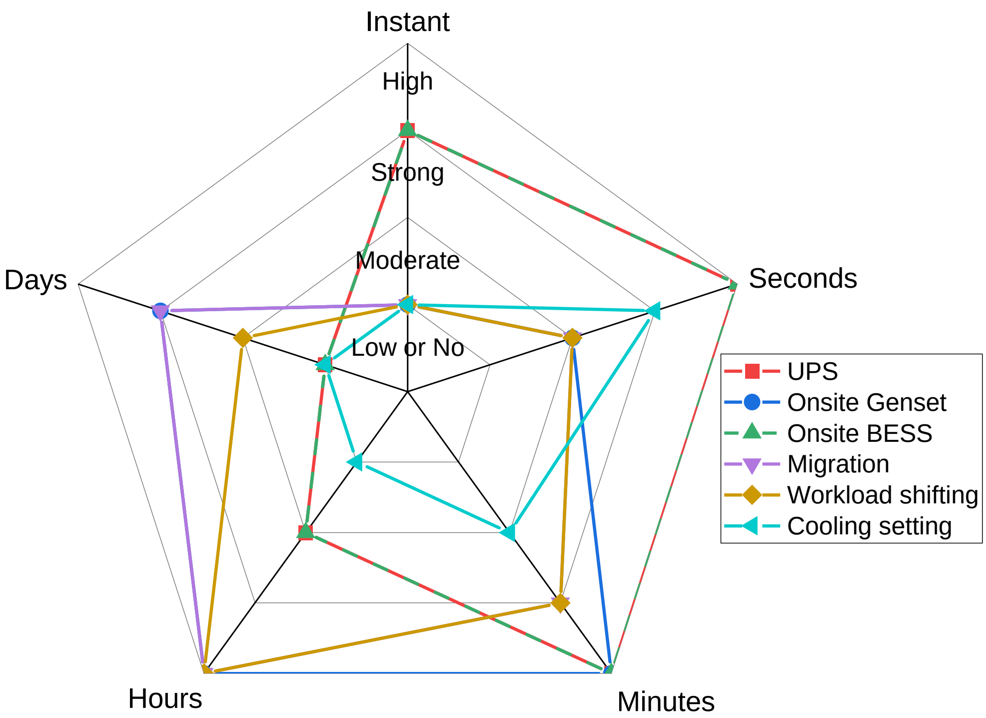

Fig. 9. The capability of data center resource response time and duration flexibilities.

In contrast, onsite Genset systems cannot respond to frequency changes instantaneously but can endure for a long time, which is desirable for peak shaving or energy balancing. This type of response makes Gensets ideal for TOR system services that require a participant to be activated after 90 s from the start of the imbalance. The TOR service will be dispatched if actual demand exceeds forecasted demand or if an unforeseen generation trip occurs. When operating in grid connected mode, data center participants in the TOR must power both onsite equipment and the main grid, so the generating capacity must be much greater than the load. Overall, these results suggest that data centers can play a significant and beneficial role in the electricity sector's low-carbon transformation.

3.7 Data center potential capability

The technical capabilities of a data center's resources allow it to meet a variety of flexibility and ancillary service requirements. The most significant technical capabilities for each resource are its ramp rate, the time it takes to achieve maximum capacity, and a practical notice period for responding to an activation signal [55]. The UPS, backup generation, and the ability to change energy usage by time or place are the key sources of flexibility inside data centers. These resources are expected to provide a total of 16.9 GW of flexible capacity in the EU by 2030, as shown in Fig. 10 [47].

As depicted, although data centers have such huge potential for flexibility, an assessment based on data center operators' willingness estimate that 3.8 GW of this capacity could be available for grid services in 2030 [47]. This is because the main objective of data center operators has been to provide customers with dependable computing power. Offering their capacity to participate in ancillary system services may place this in jeopardy for many of them, either through slower computation performance or a less stable service. While data center flexibility has clear economic, regulatory, and climatic benefits, these benefits are not well recognized, and there are currently no government signals incentivizing most data center operators to accept this perceived risk [83]. Data centers have not yet been major targets of specific regulations aimed at increasing power system flexibility. This could change as data center capacity grows in tandem with the expansion of renewable energy and other sectors like transportation and domestic electrification.

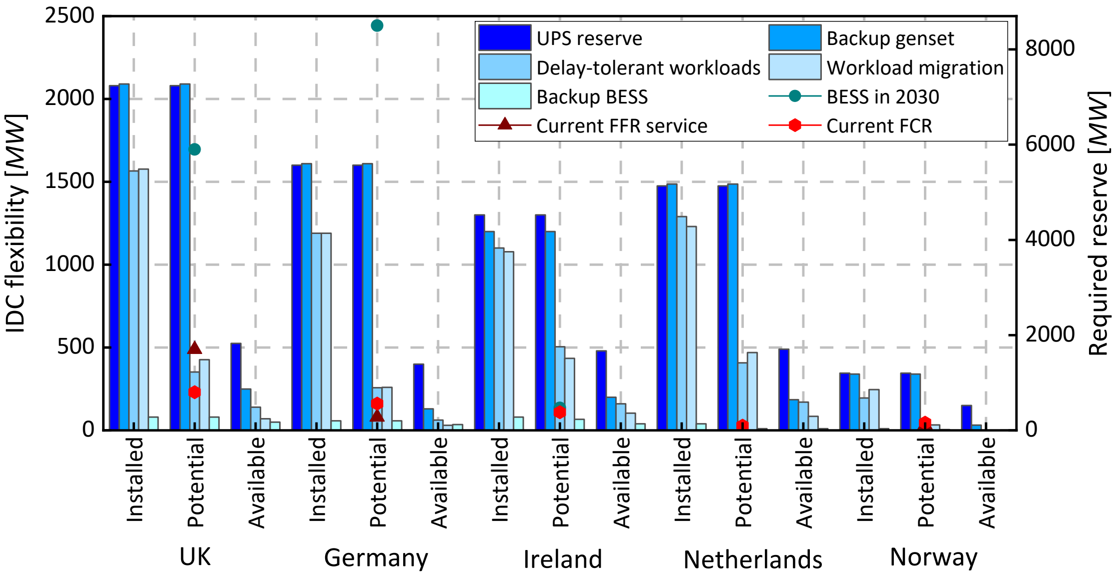

Fig. 10. Potential flexibility of data center in 2030 with the current FFR and frequency containment reserve (FCR) and anticipated required BESS capacity in 2030.

In the UK, data center resources are anticipated to have a cumulative installed flexible capacity of about 7.3 GW in 2030, whereas the potential capacity is substantially lower nearly 5 GW. This decrease represents the operational constraints of the resources, taking into account capacity that must be reserved solely to maintain data center security [84]. In comparison to the other four countries, Ireland has a special circumstance due to the projected installation of a high number of data centers. As illustrated, there is a potential installed UPS capacity of 1.3 GW and only 480 MW of this figure is predicted to provide grid service actively [47]. This value is comparable to the current operational constraints on the FCR of 698 MW (i.e., primary operating reserve (POR) and secondary operating reserve (SOR)) [85]. Furthermore, the total data center available flexible capacity is anticipated to be 1 GW, accounting for over 15% of peak demand across the country in 2030, as illustrated in Fig. 5. This is a significant capacity that doubled the expected BESS capacity of 470 MW by 2030 [47]. Ireland has the biggest share of adaptable capacity to peak demand among the five countries, which is unsurprising given the country's huge data center capacity and a large number of hyperscale operators [49].

4. Demand response barriers and limitations

The previous sections have highlighted that data centers participating in the DR markets can facilitate the integration of high IBR and reduce the need for the system operator to invest in massive energy storage deployment or bring thermal generators online to protect against transients. Such an approach could represent an extra revenue stream for data center operators while reducing electricity bills [86]. This new business model is a win-win scenario for data centers, utilities, and service providers if implemented effectively. It could also support carbon emissions reduction targets for data center customers, grid operators, and power producers. However, despite this, the majority of data centers do not actively participate in the DR programs due to several technical, regulatory, social, and economic barriers, as depicted in Fig. 11.

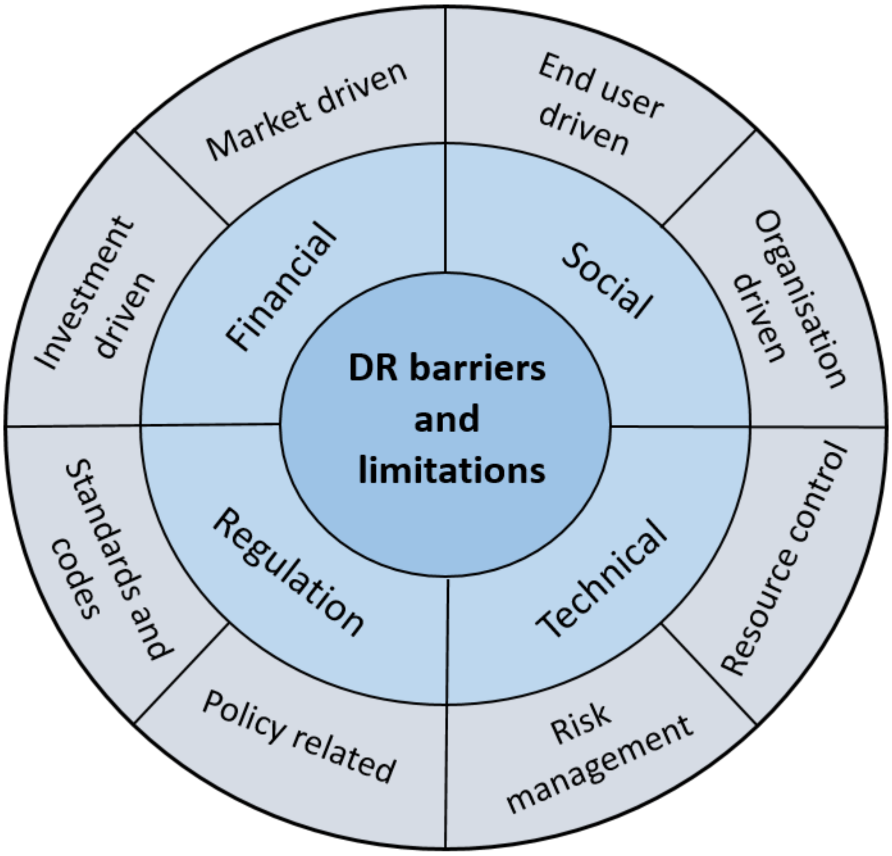

Fig. 11. Classification of barriers to widespread adoption of demand response.

4.1 Risk management

Demand response is not a core business for today's data center industries, which are aimed at continuous uptime maximization. Due to the inherent risk associated with each DR service, risk management is a critical issue for data center participation in DR programs. When participating in price-based programs, the risk can be financial issues, but in incentive-based programs, the risk can also be downtime degradations to critical loads. Data center participation in current market programs is restricted due to serious concerns about taking a significant financial hit because the system operator sends a control signal to curtail power when the data center is heavily loaded. This necessitates an agreement between system operators and data center owners to determine the best ways to deal with control signals and how each onsite resource should respond. This could lead to emergency signals being handled by UPS and data center load shedding, while price-based contracts could be used for delay-tolerant workloads and workload migrations. In this case, the ups must be capable of injecting power back into the utility to participate in the ancillary service market while maintaining a certain limit of power by controlling the depth of discharge of the battery to secure critical loads and allow for normal transfer to onsite Genset in the event of grid failure.

4.2 Challenge of resource control

Data center owners can either participate in DR independently or work with a third-party aggregator. Participating through an aggregator reduces the complexity of the DR process since the aggregator handles the required service, grid integration, control signaling, and practical implementation. However, monitoring data center specific resources through an aggregator or even a system operator must be debated with data center owners. From the perspective of the system operator, a guaranteed response from DR resources when requested is crucial. This means that the system operator can monitor and control the onsite resources directly. Nonetheless, given the uptime risk management for data center service level agreements, this may not be an acceptable case for data center owners, particularly when it comes to workload shifting and migration. Data centers that participate in the program, on the other hand, are willing to accept full responsibility for all operational, commercial, and implementation issues in order to avoid management risk. This implies that special programs must be developed to facilitate data center integration and specifies who has authority over what. This can help to avoid third-party aggregator interfaces, which is especially useful for large data center organizations with a large portfolio and internal technical and commercial expertise.

4.3 Regulatory barriers

Although many DR program participation opportunities for data centers are described in this paper, most of these programs are not actually available to data centers in the market. Different countries have different DSM framework rules and policies [87]. While some utilities moved quickly to change regulations to accommodate a large number of participations in the market, many have moved rather slowly. This indicates that the opportunities for data center demand response participation in any given system operator may be restricted to straightforward, traditional smart pricing programs (i.e., peak pricing) which may not be suitable for data centers. The absence of a framework that clearly defines the market participants and their respective roles appears to be the most significant regulatory barrier. A reliable regulatory framework must guarantee that data centers could anticipate investment returns from DSM service provision.

Furthermore, operational regulatory grid codes, such as those defining how to connect data center resources to the main grid, must be developed. These codes must define how data center resources behave during disruptions and how resources respond to system frequency and voltage changes in each service market. The issue is that definitions of ancillary services have typically been designed for conventional power plants. When such definitions are hardwired into the market design for DR resources, they may be perceived as discriminatory and they may also prevent data center resources from participating [88]. Thus, it is strongly advised that ancillary service definitions and market regulations are updated to take into account the physical capabilities of resources on both the generating and demand sides. This might enable greater participation in DR programs and better utilization of the data center resources that are already available.

4.4 Financial barriers

The installation of necessary equipment for the execution of DR signals requires an initial investment from the data center participant. It must be ensured that the level of participation in DR schemes will result in future energy cost savings that are significantly greater than the cost of this initial investment. Furthermore, there are financial and regulatory issues with ToU and dynamic pricing that have yet to be widely implemented. These are load shifting price-based services that discourage data centers from participating in the DR market due to low profit margins, as opposed to incentive-based services. The current DR programs are also very tightly regulated, and it is typically challenging to automate and integrate a data center management system for the bidding required to extract profits. Even though there are lucrative business opportunities, this complexity has kept data centers out of these markets. There are also complexities associated with the implementation and operation of load shifting and migration for certain DR types, which are still evolving. This is because, in the absence of strict codes and regulations, responding to system operator control signals may jeopardize service quality, resulting in a greater financial loss than the gains from DR implementation. As indicated in Section 3.1 each data center resource has a certain level of flexibility, so each resource should be individually assessed by the data center and power system operators.

Along with data centers, there are significant challenges on the grid operator side that are extremely necessary when dealing with data center resources. It is worth noting that data centers, as very large loads, have the potential to manipulate market prices. They can consume up to 50% of the power on their distribution feeder, implying that if they engage in some of these markets aggressively, they have a high possibility of influencing prices in their favor [89]. Given that the current market and regulations are designed for the aggregation of thousands of small loads such as electric vehicles and heat pumps that have little impact on their point of connection to the network, system operators must implement fundamental regulatory changes to allow data center participation.

4.5 Social behavior barriers

Planning for the DR strategies should be in line with the SLA and the targets of the data center business since shutting down or even reducing energy usage can occasionally jeopardize the achievement of the operational strategy and the SLA. However, the introduction of intelligent energy technologies that guarantee zero downtime with no impact on the customer SLA can change data center operators' perception of DR participation. Also, while data centers want to be seen as corporate and socially responsible for the environment, business value, and financial incentives are clearly more essential than desires to support and protect the environment. If data center operators realize the impact of their electricity usage on their operating costs, they may be able to adapt their behavior, assisting in the smoothing of load profiles, accelerating the installation of variable renewables, and lowering expenses. However, saving data center electricity bills is insufficient to encourage them to implement DR programs, invest in supporting equipment, and compensate for any distraction that may occur to the SLA. Although there are significant economical merits to deploying DR programs, if data center operators are unsatisfied with the implementation strategy, they may eventually withdraw from the program or request higher payments or incentives [90]. Thus, creating an effective customer acquisition strategy is crucial for boosting data center willingness to enroll and overcoming barriers to the widespread adoption of DR programs.

Finally, the level of trust among parties should be high enough to overcome DR barriers. In other words, DR providers must rely on power system operator signals and reliably treat them. This guarantees that the information transferred between the DR provider and the industries is accurate and meets expectations.

5. Discussion and recommendations

Large-scale data centers are integrated with installed reasonably large UPS systems to provide sufficient backup in the event of an emergency. However, due to the rarity of power outages, these storages are actually left unused most of the time. Today's hyperscale and large data center operators have the opportunity to profit from this untapped asset, making their UPS a source of revenue and assisting the grid's transition to variable renewable energy sources. Smart UPS devices can smooth out renewable energy variability, balancing energy supply and demand, and reducing or delaying the investment in power system infrastructure. Data centers can make use of their current assets to generate new revenue, reduce energy expenses, and still afford a crucial backup solution. Despite the numerous benefits provided by data centers, they remain underutilized due to a variety of technical, regulatory, and social barriers. Some of the reforms that can be implemented to successfully introduce data centers into the market and make the change a reality are discussed here.

- Industries must fill the knowledge gap that conceivably exists before they can participate in DR programs. Besides this, they must continuously observe and perceive the complex design of the market schemes that are appearing in the energy sector. In order to fully liberalize the electricity market, regulatory authorities must act quickly in response to potential challenges, establishing standards for the involved parties.

- The willingness of consumers to participate in DR programs is poorly understood, and ensuring participation is a key obstacle to the demand response's success. With the help of advanced control technologies found in the smart grid and energy information, DR programs should help customers better understand the advantages that come with DR and enhance their ability to participate in DR programs.

- The potential of DR based smart grid systems in the industrial sector is significant but has not yet been realized. Due in part to a lack of awareness, concerns about downtime, and difficulties in the utility and regulatory domains, the data center industry has not traditionally used demand response. For electricity markets to more effectively benefit from the flexibility that resources from data centers can offer, new regulatory frameworks would be needed.

- Utilities will need to adapt to industry requirements and allow data centers to provide multiple stacked DR services. Setting up a suitable mechanism for DR's simultaneous participation in the wholesale, ancillary, and capacity markets would encourage private parties to invest in DR services. This requires equitable DR programs that benefit both the utility and data center operators.

- Redefining the utility-data center interface through the use of digital platforms and the adoption of new cutting-edge technologies. This assists in managing who controls what equipment while participating in DR services.

- Developing risk management strategies for the DR program using data gathered from data center operators and smart meters. This ensures that the participant in the DR programs does not experience any downtime.

6. Conclusions

This research conducted a comprehensive review of data center resources as a source for DR flexibilities in various EU data center dominant countries. It was shown that data centers are excellent candidates to participate in demand response, generating a business model while reducing the impact of ever increasing load growth on the grid. Data centers, as opposed to traditional DR service providers, have the intrinsic capability to offer multiple stacked DR services from a single site including ancillary services, peak shaving, and valley filling. Combining data center on-site resources should allow utility regulators and data center operators to work and collaborate in a symbiotic way to approach carbon emission targets and gain operational and financial benefits. Given the sustainability imperatives and the obvious desire to improve margins, it seems logical that the data center industry will increasingly participate in DR programs. This will most likely begin with load curtailment (i.e., operating in island mode), but as the industry gains confidence and regulatory authorities recognize the enormous potential of the data center sector, this will be followed by ancillary system services. The analysis also illustrated that data centers have a great potential to play a significant role in the electricity transition to variable renewables. As an example, in the Irish power system, flexibility within the data center UPS system alone is expected to reach 1 GW, almost double the required FFR capacity to meet the grid needs in 2030. This implies a significant untapped future flexibility for emergency and rapid grid balancing services, for which the system operator must provide special incentive mechanisms. Thus, future research should look into appropriate policies and regulations to inspire data center participation in DR programs.

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