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Energy Supplies for Future Data Centers

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Fueled by an unprecedented adoption of artificial intelligence, data centers are becoming the largest growing consumers of energy. This results in both an opportunity and necessity to reinvent a tighter relationship between IT and sustainable energy supplies.

Artificial intelligence[1] and digital transformation[2] have resulted in tremendous growth of data centers. This is true for public clouds, private clouds, and on-premises data centers. Growth is expressed in terms of data center size, power consumption of individual components (for example, accelerators, processors, switches, memories, and storage), as well as the overall number of data centers, and the cooling required to remove the produced heat. As an example, the most recently deployed largest supercomputer Frontier consumes 30 MW and requires liquid cooling because traditional air cooling is insufficient.

Cloud data centers are using substantially more energy that is not always readily available at every location.[3] At the same time, companies are making pledges to reduce their energy footprint and make the source of energy more sustainable.[4] Hyperscale data centers are massive facilities operated by the biggest tech companies, dealing with enormous amounts of data and services. This massive scale of operation has led to equally massive energy consumption, often exceeding 100 MW and creating a challenge for the energy suppliers.

Consequently, the concept of sustainable data centers has emerged, focusing on being environmentally friendly by using less energy and, often, renewable energy sources. This

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ultimate goal has led to a systematic approach to integrating data centers into the existing electrical power systems which, over the last two decades, have already experienced massive energy resource and operational changes.

Historically, power systems relied on large-scale fossil fuel, hydro, or nuclear power plants that are geographically close to energy sources. Electricity produced was transmitted through high-voltage transmission networks to medium-voltage distribution substations and finally then to consumers via a passive distribution grid. This approach was characterized by unidirectional energy flow operations, enabling the use of simple deterministic mathematical models and minimal real-time intervention by system operators.[5] Given this approach, it is also noteworthy that a fraction of the available energy in the source reaches the demand given the losses in available energy in the distribution chain. As an example, 5% to 15% of the energy available at an energy source (natural gas 45 MJ/kg, or at a hydroelectric dam, the potential energy at the top water level) reaches a chip in a server in a data center.[6] The rest of the available energy is destroyed because of mechanical irreversibilities such as friction at the source, transmission losses, and conversion losses from the source all the way through the server to the chip.

The last two decades have marked a notable evolution in electrical power systems, transitioning from a traditional approach toward incorporating distributed energy resources (DERs). These DERs are mostly based on renewable energy sources and energy storage systems. DERs are a good match for the requirements of data centers, and they also enable and require tighter integration with the end consumers. While DERs may not be the eventual answer and replacement for traditional power and energy supplies, they are a superior complement to improve the sustainability of data centers. We foresee a future confluence of the IT and power and energy sectors that will enable cross-domain control and management (see Figure 1).

Horizontally, one can see each technology area having its management loops (large blue circles) that connect producers to consumers (either power and energy or IT services) through their networks (either power transmission or Internet). These sectors have worked independently so far. In the future, we envision a much tighter loop (see green circle) with the ability to control supply and demand and to dynamically react to changes (fluctuations, failures, security, and so on) across domains.

However, data centers are growing so fast, and their influence on everyone's life is much broader. The implications of data centers go far beyond information and communications technology (ICT) companies and the power and energy sector. As society becomes increasingly dependent on services delivered by data centers, they are the responsibility of society as a whole, especially 20–30 years out. Consequently, data centers should be addressed at national and regional levels. Because they are becoming a concern for national security, governments should regulate data center requirements at the national level. The EU, through the Energy Efficiency Directive, for example, will require data centers more than 500 kW to report key operational metrics like energy consumption beginning in 2024.

In the rest of the article, we will discuss the landscape of tomorrow, challenges and opportunities, and conclude with some recommendations for key stakeholders.

THE LANDSCAPE OF TOMORROW

With the increasing use of generative artificial intelligence (AI) both for inference and training, we expect that

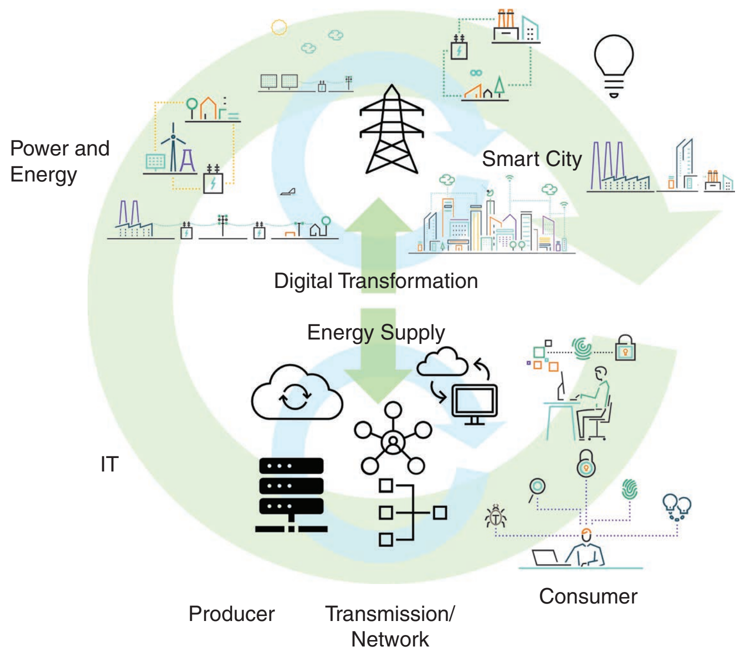

FIGURE 1. Evolution of power and energy and IT domains, from independent toward integrated and cross-domain.

the growth of data centers will continue to increase in the foreseeable future. The growth of the data centers of tomorrow is shaped by the following main megatrends and factors:[7]

- *The increasing use of digital transformation*: This is driving data center growth both at the data center/cloud side, where services are delivered, and at the edge (client side), where services are invoked.
- *Broad AI application to a variety of services*: This is consuming substantial energy for training and inference, in addition, data center digital twins will become a large consumer of AI for fulfilling predictions and what-if analysis.
- *New technologies, such as quantum*: These may revolutionize how computing is conducted today, but as of today, their requirements for cooling are substantially higher than traditional computing.
- *Cryptocurrency mining, particularly bitcoin mining*: It has nearly doubled between 2019 and 2021, and its annual worldwide electricity consumption is around 131 TWh.
- *Improved connectivity*: With the introduction of 6G, increased satellite communication, and continued deployment of traditional networks, there will be more service requests coming from anywhere in the world and more data to be stored, processed, and analyzed.
- *Commitment by industry and governments to reduce greenhouse gasses and brown energy consumption*: This will force the usage of new energy sources and supplement traditional ones with DERs.
- *Increasing use of modular data centers*: These can be flexibly deployed enabling colocation with DERs to form microgrids.

In line with existing market data and modeling projections in Great Britain, annual data center electricity consumption could rise from 3.6 TWh in 2020 to as much as 35 TWh by 2050.[8]

The traditional power and energy paradigm has shifted significantly due to the following main factors:

- *Integration of renewable energy sources (RESs)*: There has been a concerted effort to introduce substantial RESs into the electrical grid. This shift aims at ensuring sustainability and reducing the carbon footprint of the electrical energy sector and involves incorporating RESs like wind, solar, and hydroelectric power.[5]
- *Rise of DERs*: The decentralization of energy production, such as solar photovoltaic (PV) panels, wind turbines, small hydroelectric plants, biomass energy systems, energy storage systems, combined heat and power (CHP) systems, and electric vehicles are now directly connected to the electrical distribution grids. This development represents a move away from fuel-centered power generation to a distributed model, where energy is produced closer to where it is consumed, directly contributing to lowering energy losses and increasing energy efficiency, as well as offering enhanced energy security, increased grid resilience, and reduced greenhouse gas emissions.[5]
- *Advancements in digital and control technologies*: The integration of DERs has been facilitated by significant advancements in monitoring, control, and management technologies. Energy management systems (EMSs), advanced distribution management systems (ADMSs), and distributed energy resources management systems (DERMS) have played critical roles.[9] These technologies enable more sophisticated monitoring, control, and optimization of both the supply and demand sides of the power grid, promising an easier and more streamlined transition to a new power system model.
- *Implementation of advanced metering infrastructure*: This is a system that consists of an integrated network of smart meters, communication networks, and data management systems that enable two-way communication between utilities and their customers. It is one of the key enablers of the smart grid concept which represents a significant evolution in electricity network management, leveraging digital technology to create a more efficient, reliable, and sustainable energy future. This is further enabled by the extensive integration of inverter based resources.
- *The integration of different energy sectors*: Integration, for example, of electricity, gas, heat, hydrogen, and electromobility, has moved the entire assessment to a multi-energy systems level, offering enhanced operational flexibility, resilience, and optimal usage of renewable primary energy sources (wind, solar, biomass). In this context, data centers fully fit this agenda, considering a need for secure power supply, cooling, or support of the transition to net zero.

These developments have led to a more dynamic, uncertain, and complex power system, requiring advanced models and real-time management to ensure optimal system operation. The shift toward mass amounts of DERs is a fundamental change in how energy is produced, managed, and consumed, reflecting a broader trend toward sustainability and technological innovation in the energy sector. However, management and coordination of large amounts of DERs, on a large scale, presents a significant challenge.[10]

To enhance the reliability and energy efficiency of electrical distribution grids, the concept of electrical microgrids has become increasingly prominent.

A microgrid is formally defined as "a group of interconnected loads and DERs with clearly defined electrical boundaries that act as a single controllable entity for the main grid and can connect and disconnect from the main grid to enable it to operate in both grid-connected or islanded modes."[11]

The microgrid's ability to operate autonomously in an island mode or cohesively in conjunction with the main grid offers several crucial benefits. These include enhanced resilience to grid disturbances (increased reliability), flexible local energy management, decreased energy losses, improved energy efficiency, and the potential to integrate a higher proportion of RESs efficiently. As a result, microgrids are increasingly viewed as a crucial component in the evolving landscape of DERs, offering a versatile and sustainable solution to modern energy challenges. The following example is one of the potential options.

To power the servers and cooling system, a dedicated power supply is essential. Renewable power sources like solar PV and wind turbines can't reliably meet the IT infrastructure's power needs due to their intermittent and stochastic nature, as well as lack of flexibility and controllability. Therefore, three types of storage units can be used: supercapacitors for short-term power fluctuations and system stability, batteries for managing load over minutes or hours due to their higher energy capacity, and hydrogen storage for longer-term variations, including seasonal trends. These components connect to a dc bus alongside dc/dc and dc/ac converters for voltage regulation, forming a dc microgrid. This microgrid presented in Figure 2 is a self-contained power system that can operate independently from the main power grid. The intermittent and uncertain nature of the generation (PV and wind) is compensated for by the flexible storage units (battery, supercapacitor, and fuel cells).

This recognition has become particularly relevant in the context of data centers, which are on a continual quest for clean, dependable energy sources. Data centers are characterized by their stringent requirements for the reliability and security of their power supply. The concept of integrating data centers within the framework of electrical microgrids presents an intriguing approach,[12] particularly with the use of modular data centers (MDCs). MDCs offer containerized infrastructure inclusive of power, cooling, and networking, which can be deployed rapidly and colocated with DERs. This integration addresses not only the need for sustainable and efficient energy utilization but also ensures the uninterrupted operation of these facilities. In the event of main grid instability, the microgrid can transition to an island mode, maintaining a stable and continuous power supply to the data center, thereby safeguarding data integrity and operational continuity. This synergy between microgrids and data centers represents a forward-thinking strategy, balancing the demands for energy efficiency, environmental responsibility, and operational reliability in the digital age.

DATA CENTER REQUIREMENTS

Data center demand-side requirements continue to rely on large-scale power systems for renewable energy such as hydroelectric projects. Indeed, data center location decisions are often driven by the cost of electricity, for example, low pricing available at a hydroelectric dam built decades ago to provide clean power to manufacturing units such as an aluminum factory.[13,14] Moving the needle in sustainability, available energy, and not the pricing ought to be our mantra.[6] Furthermore, low-cost electricity options are fleeting anyway. Available energy, in Joules/GWs, from the second law of thermodynamics, is the currency.[15] Therefore, the IT industry, particularly data centers, ought to build its power plant with multiple sources of power, that is, a local power microgrid as described in Figure 2, in the previous section.

Available energy articulates the quality of energy available in each given source, like the potential energy due to the height of water at a dam, the useful energy (1 KW per square meter) from the sun, available energy from waste streams such as anaerobic digestion of manure from dairy cows, or available energy in waste flue gases from a factory. Given the available energy, strategies must be developed to power the data centers. After all, data centers are tantamount to factories. So,

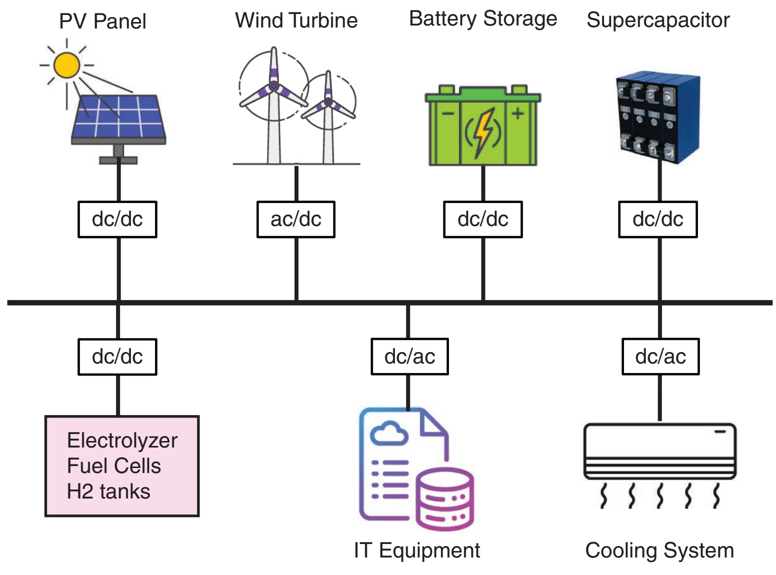

FIGURE 2. Structure of a dc microgrid supplying the data center loads.

just as our ancestors embraced clean energy by building hydropower plants for aluminum factories, we too must return to sustainable practices.

Figure 3 shows a holistic view of power and cooling in data centers.[6,16] It starts with available energy at the source. The figure shows various sources such as solar as a diurnal variable source of power produced by the photovoltaic panels given the incidence of the sun while a fuel cell provides the baseload source. Together, the sources provide uninterrupted power to the data center. The consumers of power in the data center are information technology equipment (computer, storage, networking, and so on), cooling, and other facility elements. The power ($P_{\text{data center}}$) supplied to the data center is used for IT equipment, cooling, and other building equipment. The power supplied to the IT equipment is dissipated as heat, and the total heat removed from the data ($Q_{\text{data center}}$) is the sum of heat dissipated by the IT equipment and other equipment such as pumps and compressors that are part of the cooling network. Figure 3 shows a holistic view of available energy flow from the power sources to the IT equipment (chips, systems, racks) and the work required to remove the heat generated by the IT equipment. The work required is shown as *W*, and the heat dissipated as Q. The subscripts refer to components from the chip to the cooling tower. Given this holistic view, a key performance indicator (KPI) of power and cooling is introduced. The KPI is called the *coefficient of performance of the ensemble* (COP_G). It is the ratio of heat dissipated to the work required for transferring the heat out to the ambiance. The cooling work is the flow work, that is, the work required to move the fluid, and the thermodynamic work, that is, the work required to reduce the temperature of the cooling medium, for example, in a chiller. The goal of the data center design is to maximize the COP_G to achieve an efficient cooling design. Further efficiency is driven by designing power-efficient IT equipment (hardware and software) and enabling the ability to scale down power given the workload.

Some municipalities, particularly in colder climates, are mandating that waste heat be reused as a condition for permitting construction and operation, for example, to heat buildings or agricultural operations like greenhouses or fish farming. Alternatively, some DERs within a microgrid can utilize the waste heat to improve the efficiency of power generation (for example, biomass). As an example, with reference to Figure 3, the production of hydrogen for the fuel cell requires a steam reforming reaction. This is an endothermic reaction that requires heat and that can be waste heat. The use of waste heat can improve fuel cell efficiency.

CHALLENGES AND FUTURE OPPORTUNITIES

For decades, data center operators have preferred the eastern regions of Oregon and Washington, USA, drawn by the flat terrain, distinctive seasonal climate, and economic incentives such as affordable land, tax breaks, and low-cost hydroelectric power.[12,17] This has transformed the area into a significant hub for data center development in the United States, attracting substantial investments from leading companies like Amazon, Apple, Google, Meta, and Microsoft.

However, increasing public concerns over the high energy and water demands of these data centers have led to legislative actions in both states. Proposed laws aim to enforce new clean energy standards within the industry.[5] In Oregon, HB2816 seeks to incrementally reduce greenhouse gas emissions,

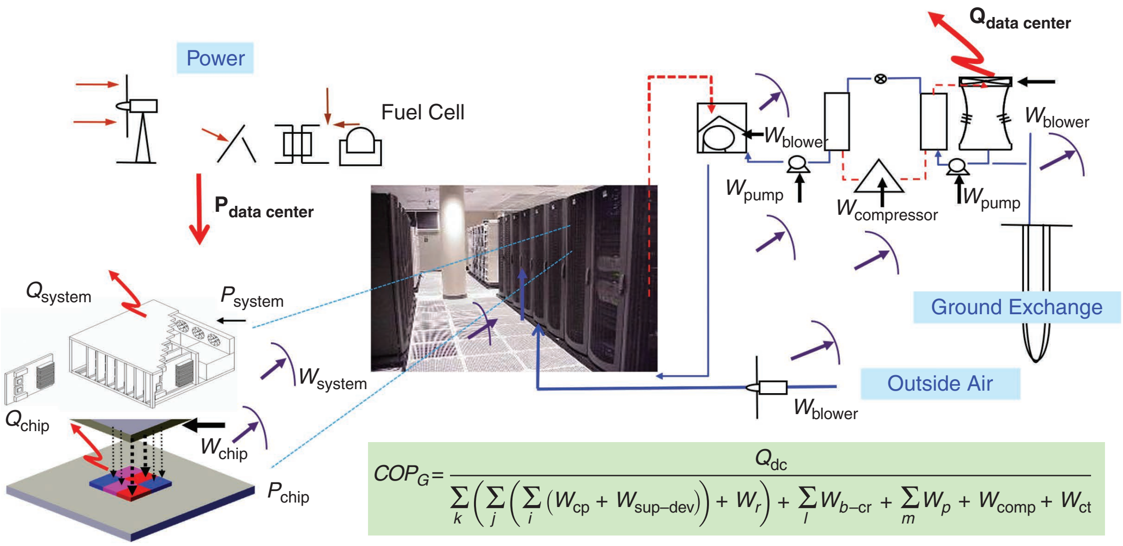

FIGURE 3. Data center infrastructure from chip to cooling tower introducing a KPI for cooling called COP_G (originally a version published in HP Labs Technical Report, HPL-2006-55, 21 March 2006).

targeting a complete elimination by 2040. A comparable initiative in Washington intends to synchronize the decarbonization schedule of data centers with that of the power sector.

If these regulations are enacted, they will necessitate data center operators to revise their design and power management strategies to meet both public and regulatory expectations. In this context, renewable-based microgrids emerge as a viable solution to address these challenges.

Yet, transitioning to renewable energy-based net-zero microgrids is not without its hurdles. A primary concern is the intermittency of renewable DERs like PVs and wind turbines. This intermittency contrasts with the high-reliability requirements of data centers, up to "five 9s" of uptime for highly available data centers (99.999%) presenting a significant obstacle that must be addressed. A potential solution lies in the advancements of energy storage technologies. These technologies are critical in bridging the gap between the fluctuating supply of renewable energy sources and the consistent energy demands of data centers. However, considering the substantial energy needs of these facilities, energy storage solutions would need to be almost on a gigawatt scale to be effective. Nonetheless, as of now, storage options of such magnitude are either not commercially available or not economically viable.

The transition toward renewable-based microgrids, supplemented by large-scale energy storage, could provide a resilient and sustainable solution for data centers. However, significant technological advancements and economic considerations must be addressed to make this a feasible reality. This necessitates continued research and investment in energy storage technologies, as well as supportive policies and incentives to facilitate their development and integration at the scale required by data centers.

Furthermore, the escalating energy demands of data centers, as highlighted earlier, pose a substantial risk to the existing power grid infrastructure. These facilities have the potential to strain grid constraints and cause congestion in both transmission and distribution networks, as discussed in the example of a national grid's electrical system.[18] This challenge asks for the implementation of grid-enhancing technologies (GETs), supporting optimal utilization of the existing assets, for example, transmission lines, underground cables, or power transformers. GETs are part of a broader strategy to modernize the power grid, making it more capable of handling variable renewable energy sources and meeting increasing electricity demands without substantial new infrastructure investments. This is possible through the implementation of different strategies like dynamic line rating,[19] coordinated grid power flow control, real-time situational awareness based on advanced sensor and ICT technology,[20] or integration of different types of energy storage units.

The integration of large-scale data centers into the grid necessitates careful planning and infrastructure upgrades to manage the increased load without compromising the reliability and efficiency of the power system. This challenge is compounded by the proposed clean energy requirements, which add further complexity to managing grid dynamics.

In the context of the burgeoning energy demands of data centers, the digitization of electrical systems' control centers represents both a challenge and an opportunity. Intelligent management of grid components, particularly large loads such as data centers, alongside a diverse array of generating resources, is pivotal. Optimal coordination between these elements offers a significant means to address challenges like grid congestion and operational constraint violations.[10] Key to this transition are advanced technological systems. EMSs are essential for transmission systems, while ADMSs and DERMSs play a crucial role in distribution grids. These systems present substantial opportunities for grid operators to effectively manage, optimize, control, and protect the evolving electrical systems.[9] Moreover, they enable intelligent coordination of existing grid resources. This includes dispatchable loads and generators of varying scales, from large to medium, and aggregated small scale. Such coordination provides so-called nonwire alternatives (NWAs). NWAs are strategies to address grid congestion and constraint violations through the coordinated flexibility of available resources. They offer a cost-effective alternative to traditional grid strengthening methods, like constructing new lines and substations, by deferring or entirely avoiding the need for significant financial and resource investments.

> The intermittent and uncertain nature of the generation (PV and wind) is compensated for by the flexible storage units (battery, supercapacitor, and fuel cells).

However, within the context of integrating advanced technological systems for grid management, transmission system operators, distribution system operators, and associated staff in electrical control centers face a substantial challenge. New policies and regulations are needed to provide incentives for these professionals to embrace and adapt to these systems and deploy tools such as EMS, ADMS, and DERMS on a large scale.

The successful adoption of the management systems is critical in managing the complexities introduced by large loads [the International Energy Agency (IEA) is projecting a possible doubling of energy (not power) consumption from data centers by 2026 (from 2022 levels of 460 TWh globally[21])] from data centers and the integration of diverse generating resources. While these technologies present significant opportunities for optimizing grid performance and mitigating issues like grid congestion, the transition demands a concerted effort in retraining and reorienting the professionals responsible for grid operations. This educational and cultural shift within electrical control centers is as crucial as the technological advancements themselves. It represents a pivotal step in realizing the full potential of digitized electrical systems and addressing the evolving challenges in grid management, particularly in the context of the increasing energy demands from data centers.

As the digital transformation of power and energy systems evolves and as more and more critical infrastructure (hospitals, smart cities, lighting, and so on) is becoming dependent on data centers, the cybersecurity of both data centers and energy supplies becomes exposed to cyberattacks. DERs make attack surfaces much larger. Therefore, new techniques will be required and applied across both sectors of data centers and power and energy.[22]

Small modular reactors (SMRs) that utilize nuclear fission to generate energy are gaining attention as a potential solution for meeting increasing energy demands while reducing greenhouse gas emissions. They present several advantages over traditional nuclear power plants, including lower capital costs, enhanced safety features, and greater siting flexibility. Seen as a reliable and carbon-free electricity source, SMRs are drawing interest from both the public and private sectors. A key benefit of SMRs is their ability to deliver consistent baseload power, unlike intermittent renewable sources like wind and solar. This continuous operation ensures grid stability, especially during peak demand times. Importantly, SMRs are low in greenhouse gas emissions, not directly releasing carbon dioxide, making them vital in efforts to mitigate climate change and reduce dependency on fossil fuels.[23]

The aforementioned attributes of SMRs make them a promising solution for addressing the growing energy demands of data centers. Data centers require a consistent and reliable energy supply to ensure uninterrupted operation. SMRs, with their ability to provide stable baseload power, are well-suited to meet these demands. Unlike intermittent renewable sources, SMRs can operate continuously. Additionally, their low greenhouse gas emissions align with the increasing focus on sustainability in the tech industry. SMRs offer a clean energy alternative that can help reduce the carbon footprint of these critical infrastructures.

> These technologies are critical in bridging the gap between the fluctuating supply of renewable energy sources and the consistent energy demands of data centers.

While offering solutions for cleaner energy production and grid resilience, especially in emergencies, SMRs also face challenges. These include safety concerns, nuclear waste management, construction and decommissioning costs, public perception issues, and regulatory obstacles.[23] These factors need careful consideration in the expansion and development of SMRs.

Recent advancement in nuclear fusion also represents another promising opportunity, though it remains unclear when the technology will reach commercial viability. While containing many of the same benefits as SMRs like zero emissions and continuous operation, fusion produces no long-term radioactive waste but rather helium and tritium, the latter of which is radioactive but has a short half-life.

The expected size of future DCs and their integration into microgrids opens opportunities for supporting the existing power grid ancillary services, for example, frequency, or voltage control. Here, the role of the storage units supporting secure and reliable operation of DCs is to quickly provide the grid with, for example, injected active power to support the grid active power balance and consequently frequency stability.

Most of the discussion so far has been based on operations under normal circumstances. However, operations under extreme conditions (severe weather, war, earthquakes, and similar causing massive outages) may require a careful design and usually overprovisioning. The most demanding requirements for data centers both in ICT and power and energy domains are for emergencies. For example, what level of redundancy should be supported, double or triple? These decisions influence system design (for example, Oregon's superfluous power may not be sufficient in emergencies), but also its costs. This is not true for all data centers. However, if we converge two technologies (ICT and the power and energy sector), we may have more flexibility when operating under emergency conditions, trading off redundancy and performance in one domain for those in the other domain, resulting in a more robust and resilient system.

Finally, there will be new technologies in both ICT and power and energy sectors that may radically change the approaches to energy supplies to data centers. Quantum, neuromorphic, and other technologies inspired by these areas are some examples that currently look promising in the ICT space. There is a substantial investment by governments, as well as the private sector, which will eventually lead to their productization. If these products change requirements for power and energy, we may have to redesign current power and energy systems according to new needs.

RECOMMENDATIONS

No single entity in industry or government will be able to carry out this important evolution on its own. Rather, a coherent strategy needs to be put in place, sponsored by governments, executed by industry, and supported by academia and professional organizations. Some examples of activities are listed next.

Industry

- synergistic co-designs of energy production and delivery with data centers, that is, at the same time when data centers are built, build the energy sources and energy transmission/distribution capacities
- deep integration of the operation (supply-demand management) of systems for energy supply and data center consumption, relying on smart-grid technologies and solutions
- feedback loops between energy supplies and data center consumption, for example, participating in demand response programs or ancillary service markets for power balancing and voltage control.

Governments

- designing, implementing, and enforcing regulations crossing power and energy sectors and data centers
- balancing international and local regulations
- new regulatory compliance for DERs and integration at the edge
- providing incentives for power and energy sectors to deploy advanced management systems
- establishing frameworks and rate cases for nonwire alternatives.

Academia

- supporting industry and government with research projects focused on challenges and opportunities related to integrating new sustainable energy supply technologies with future large-scale data center operations
- innovating at a cross-disciplinary level, for example, engineering, social sciences, economics
- curricula steeped in physical fundamentals, IT, and cyber sciences, coupled with learn-by-doing training methods, as well as shaping the next generation of educators.

Professional organizations

- Institute new standards and best practices for data center energy supplies.
- Form industry consortia which will exchange their experiences and share knowledge, eventually leading toward standardized products and solutions, formal or de facto.
- Foster contributions to open source communities that could collaborate toward blueprints, best practices, and open standards.

Data centers will continue to be one of the critical elements of humanity's evolution and survival. The major factor limiting data center deployment will be the ability to deliver increasing amounts of energy for sustainable operations. This will require integration of the IT and energy sectors. In summary, we are predicting the following trends:

- *A confluence of power and energy supply sector and data center consumption*: by integration of control and management loops across two areas.
- *Increased decentralization of both areas*: power and energy from large power sources to DERs, and data centers by moving functionality out toward edge (for example, inference, data reduction, and so on).
- *Governance and regulation will follow the decentralization pattern*: by regulating deeper in the delivery chain while maintaining traditional approaches around country boundaries.
- *Disruptive innovation*: in the power and energy domain includes SMRs and energy storage; in data centers, these include new types of computing such as quantum, quantum-inspired, and neuromorphic, new types of nonvolatile memories, and new types of interconnects, such as silicon photonics

We are witnessing exciting times, where changes introduced now could stay there for multiple decades. Technologists in the ICT and energy sectors should carefully make architectural choices as they will be here to stay potentially long term, both the right and wrong choices. These choices will have to support new technologies from both sectors, and the rate of technological evolution will continue to increase. C

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