Optimizing the energy grid

Considerations for a resilient and flexible grid in an uncertain future

White paper

Power utilities have a duty to provide safe, reliable power to meet consumer demand, yet increasingly the resiliency of the grid is tested by climate related weather events, wildfires and instability due to rapidly increasing demand, distributed aggregation and renewable genearation.

Consumer demand, corporate initiatives as well as new regulations have opened the markets to allow prosumer and independent market participants to flourish. The market and grid, once dominated by large, centralized fossil fuel plants are now increasing private investment in behind-the-meter , small scale distributed assets for resiliency, and the need for demand/response flexibility in the low voltage grid to work alongside utility scale renewables and storage.

Understanding the impact of energy transition including the electrification of transportation, and fluctuating demand driven by technologies like AI and cryptocurrency are creating unprecedented challenges for utilities in planning and operating such increases and the need for coordination due to the distributed nature of the assets in the medium voltage (MV) and low voltage (LV) network.

This white paper explores three foundational components to address the challenge of distributed system operation and proposes a reference architecture for large and small utilities to tackle the complexity of this new reality.

1. Communication is a requirement for any measurement, monitoring or control in the grid
2. Edge compute provides efficiency in utilization of IT/OT infrastructure
3. Real-time intelligent orchestration provides the automation that will be required to manage the flexibility in an increasingly complex, multi-stakeholder grid.

The paper acknowledges outstanding challenges and offers actionable solutions to move from innovation to business as usual.

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A new distributed paradigm

Historically, the electric grid existed as a centralized system with large power plants (usually fueled by coal, natural gas and nuclear energy) generating electricity to meet the demand of the end consumer. Focused on downstream delivery, this system required limited flexibility and minimal consumer interactions to accommodate fluctuations in supply and demand. In contrast, the modern grid is increasingly characterized by the integration of distributed energy resources (DERs). DERs enable localized generation but increase the volatility and security of energy supply while creating new system balancing challenges at the distribution grid level. Flexibility is a key part of the solution but with limited visibility at the edge where much of the flexibility can be aggregated, transmission system operators are left in a difficult position as the number of miles of distribution grid deployed is exponentially higher than transmission.

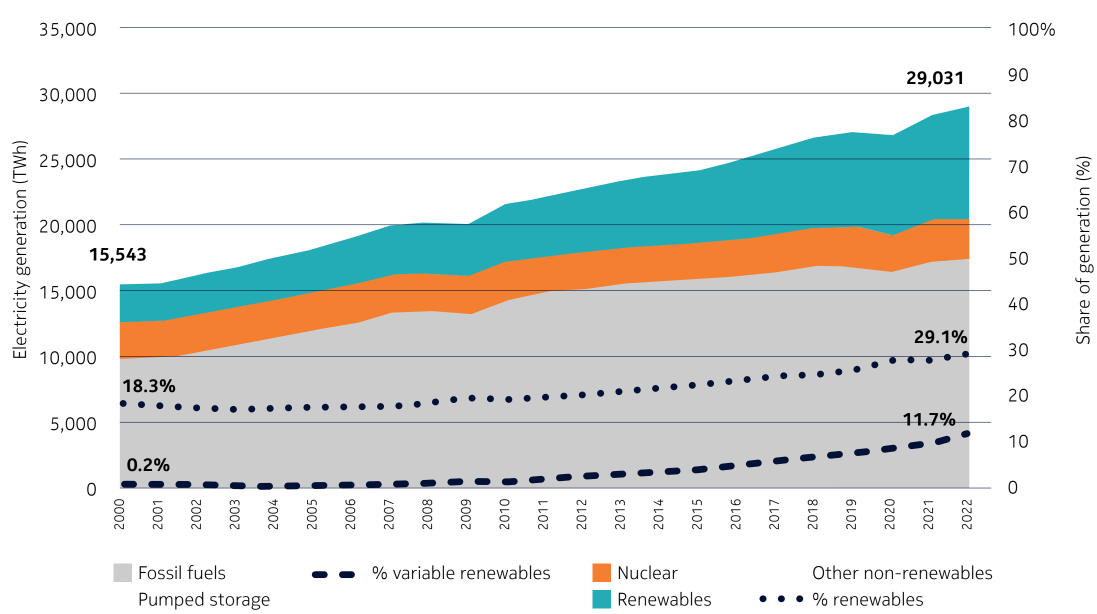
In addition, storm outage impacts with a centralized grid can result in higher number of outages due to reliance on long transmission lines. Past attempts at outage mitigation with automated reclosers and sectionalizers in the MV grid have been largely successful, but the increased number and severity of storms are creating challenges with the traditional model of delivery. Government funding for infrastructure is a good step, however, the time and cost to deploy will continue to fall on rate payers and the environmental impact of new transmission infrastructure creates controversy.

Distributed generation can increase resiliency and decrease congestion. Examples from the latest storm Helene show how local microgrids and energy communities can increase resiliency and reduce local energy costs [1]. Other non-wire solutions (NWS) are currently being explored yet will require a more granular approach to system operation visibility in the distribution grid and an increase in security, communication and automation at the edge. Coupled with new market participation and business models, NWS could prove to be a good interim solution liberating capital for areas with more demand while filling the gap with supply side flexibility.

Supply is changing

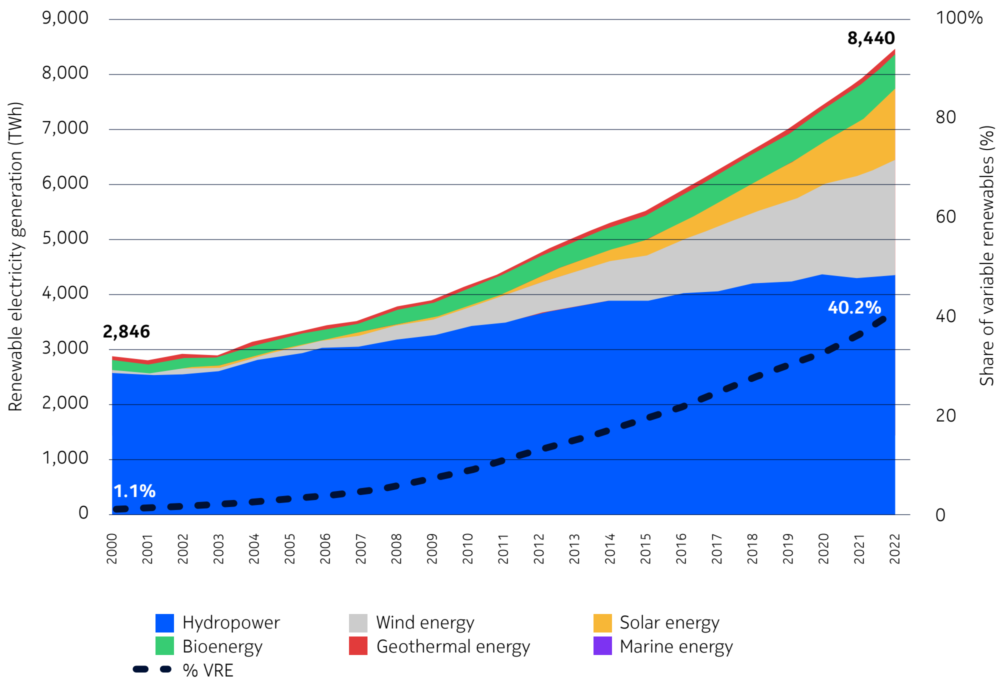
According to the International Renewable Energy Agency (IRENA), renewable energy sources accounted for 29.1% of the electricity generated globally in 2022, up 10.8% from 2000 [2].

Figure 1. Global electricity generation by energy source



The largest growth within the renewable energy sources has been solar and wind energy, which reached 11.7% of the global electricity mix in 2022 [2].

Figure 2. Breakdown of global renewable electricity generation

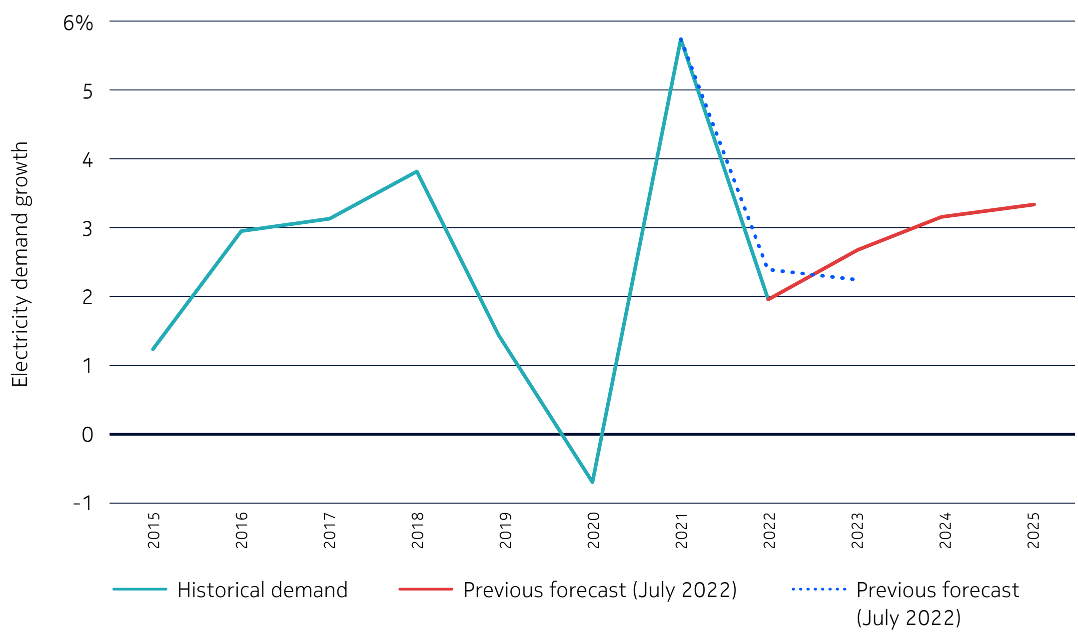


This trend of increased penetration of distributed renewables is expected to continue as the world races to meet net zero targets. According to the International Energy Agency (IEA), under existing policies and market conditions, global renewable capacity will increase from just over 4,000 GW in 2023 to 7,300 GW by 2028, which is still 3,700 GW short of the 2030 renewable capacity goal [3].

Electricity demand is growing

Demand is also changing shape. IEA's Electricity Market Report 2023 states that global energy demand grew by 2.6% in 2023 and is set to rise to 3.2% by 2025 [3].

Figure 3. Historical and projected changes in global energy demand

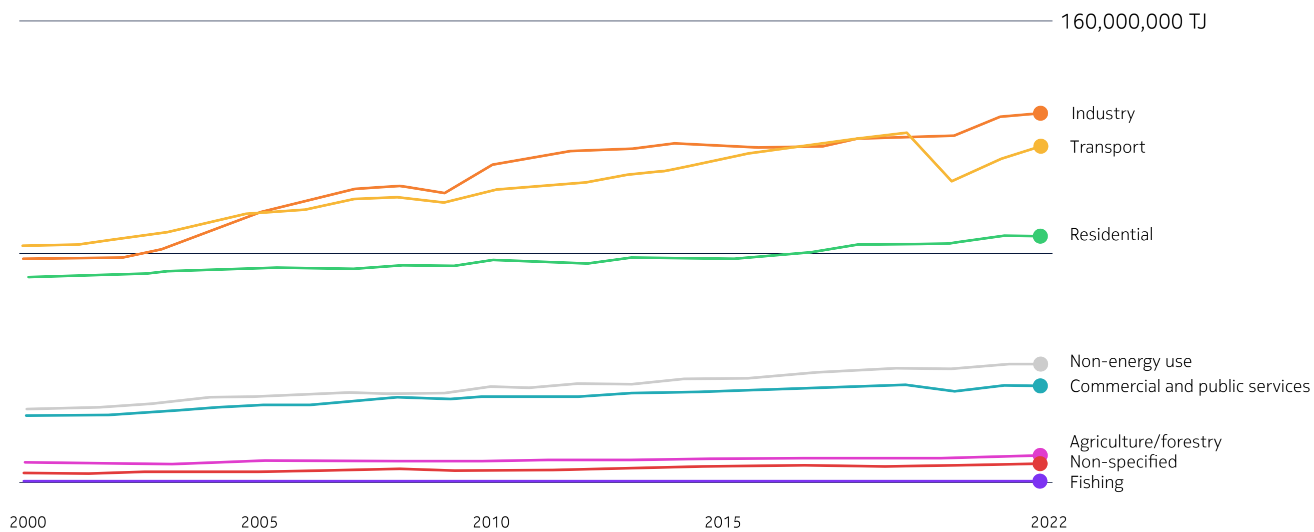


Notable factors in the demand growth are:

1. Data center load growth
2. The electrification of transport and heating.

Industry alone accounted for 30% of the total global energy consumption in 2022, transportation was not far behind at 28%, and residential, at 20%, according to the IEA [4]. Goldman Sachs research estimates that data center power demand will grow 160% by 2030 [5]. Worldwide electric vehicle (EV) sales were 14 million units last year in an upward trend that is expected to accelerate as battery costs continue to fall. The impact of EV growth on the grid will be further increased by the need for infrastructure such as rapid chargers and the electrification of large-scale vehicle fleets and public transportation. In most countries, heating and cooling make up the largest share of energy use in residential homes. Traditionally, heating comes from fossil fuels, which will need to be replaced by electricity, and, with rising temperatures, air conditioning will only go up.

Figure 4. Global total energy consumption by sector



Source: International Energy Association. Licence: CC BY 4.0

Factors influencing the new paradigm

There are a few major drivers of the trend to renewable and local assets:

1. Local resiliency and affordability

Local generation and storage are becoming more economically attractive as regulatory frameworks provide incentives and facilitate the integration of small-scale generation assets. This enables greater self-sustainability and diversifies the energy market, transforming the distribution grid into a dynamic, multiparticipant network where energy can be produced, consumed, stored and traded locally.

2. Regulation changes

Regulations such as the US Federal Energy Regulatory Commission's (FERC) order 2222 and the EU directive 944/2019 have opened electricity markets to prosumers and independent participants, enabling more decentralized, competitive energy production and aggregation of both generation- and demandside curtailment, which are contributing to overall grid stability.

3. Climate change and decarbonization goals

The preliminary factor in the shift to renewable generation is the urgent need to address climate change. The EPA's Climate Indicator Report [6] stated that 2023 was the warmest year on record and that 2013-2024 was the warmest decade on record. Sea surface temperatures continue to rise, coastal flooding is increasing, wildfires are increasing, and the snowpack season is decreasing. The physical signs of harm to the planet can no longer be ignored.

4. Technological advancements

A few technological advancements have significantly supported the shift to renewables, making them more cost effective and efficient for consumers. The largest contributors to the opportunity for this shift are advancements in solar photovoltaics (PV), wind turbines, energy storage, and smart grid technologies. Without these advancements, there would not be a viable path to a sustainable future.

The role of flexibility

The evolving energy landscape poses significant challenges and opportunities for the distribution grid. The stability and predictability of large, centralized generation with fast response peaking plants is being replaced with decentralized resources requiring the grid to manage dynamic interactions of both fluctuating generation and prosumers who generate and consume electricity simultaneously.

Demand-side flexibility, the ability to shift or reduce electricity use during peak times, becomes crucial to balance the supply and demand of the grid, as weather increases unpredictability in demand and renewables increase intermittent supply. Flexible load (EV, water heaters, and heat pumps) has a huge role to play in demand side flexibility since they can be signaled to shift demand away from times of peak stress. Controllable generation sources (such as grid forming inverters combined with inverter-based resources) can increase grid stability by supporting or even conforming to the voltage and frequency of the grid as needed. Both flexible loads and controllable generation are beneficial to a dynamic grid due to their ability to adjust parameters in real time based on grid conditions. They enable a shift away from binary 'on/off' signals towards a more granular steerability without impacting power quality. To gain the value of these assets, fast and reliable communication infrastructure, combined with edge compute, and a fine-grained resource steering engine is necessary for optimal utilization.

However, deploying the technology necessary for real-time, dynamic control of energy flows in the distribution grid introduces significant challenges, such as:

1. The need for advanced, distributed intelligence capable of processing data and making decisions locally
2. Setting up a secure, efficient, and low-cost edge computing platform combined with communication infrastructure
3. Maintaining a cyber-secure environment with many new decentralized points of entry as potential threats
4. The need to do all of this while keeping rates affordable for end consumers.

In response, a hybrid edge compute and application approach shows promise by enhancing the grid's flexibility while managing costs and security risks. It allows for localized, real-time processing that supports demand-side flexibility and optimizes DER integration, addressing the dual challenges of keeping the lights on and maintaining an affordable, resilient, low carbon, and secure grid infrastructure.

Private distributed compute

Private cloud edge management

This shift toward a more decentralized and intelligent grid demands infrastructure capable of operating reliably at the edge, where real-time decisions leveraging autonomous AI-enabled systems are critical. Energy providers require solutions that can support advanced analytics, integrate seamlessly with existing systems, and minimize the carbon intensity of their operations. Furthermore, these solutions require a robust infrastructure with secure cloud management that is hardened and resilient against environmental and cybersecurity challenges. Also, as AI applications continue to grow, data centers are experiencing significant load increases, imposing advanced cooling solutions and energy-efficient hardware to manage the heightened demand. Edge computing is critical here, enabling computational resources to handle high volumes of data without delay. Deploying these capabilities at the edge enables a new class of operational technology (OT) workloads that support demand-side management, enabling utility companies to minimize the carbon intensity of consumed energy and align with sustainability goals.

Dell Technologies plays a critical role in enabling the operational requirements that are essential to this solution. They provide modular, resilient and highly efficient edge computing capabilities that align well with the demands of modern grid management. With generation occurring across a broad geographic footprint, Dell's XR ruggedized series of PowerEdge servers address DERs by providing high-performance computing capabilities directly at the edge. Deployed at energy generation sites, the PowerEdge servers process large volumes of data in real time, enabling faster, more accurate decisions on energy production, grid balancing and equipment maintenance. By processing data locally, the server reduces the need to transmit large datasets to centralized facilities, lowering energy consumption and latency—both critical factors in building a more sustainable energy system.

The PowerEdge servers' ruggedized design makes them ideal for deployment in the challenging environments often encountered in the energy industry. From remote wind farms exposed to extreme temperatures to solar arrays in dusty, arid regions, the servers' durability ensures reliable performance in conditions where conventional data center equipment might fail. This ruggedness is complemented by strong cybersecurity features, including encryption, secure boot and real-time threat detection, which are essential as energy systems become more interconnected and vulnerable to cyber threats.

Dell's OpenManage Enterprise software provides advanced tools to monitor and control the energy usage of PowerEdge servers. This includes customizable power policies that adapt server energy consumption to workload demand, ensuring resources are used efficiently without overprovisioning. This granular control over power use, coupled with the inherent energy efficiency of the servers, enables this solution to maintain high levels of performance and reliability in line with regulated carbon consumption.

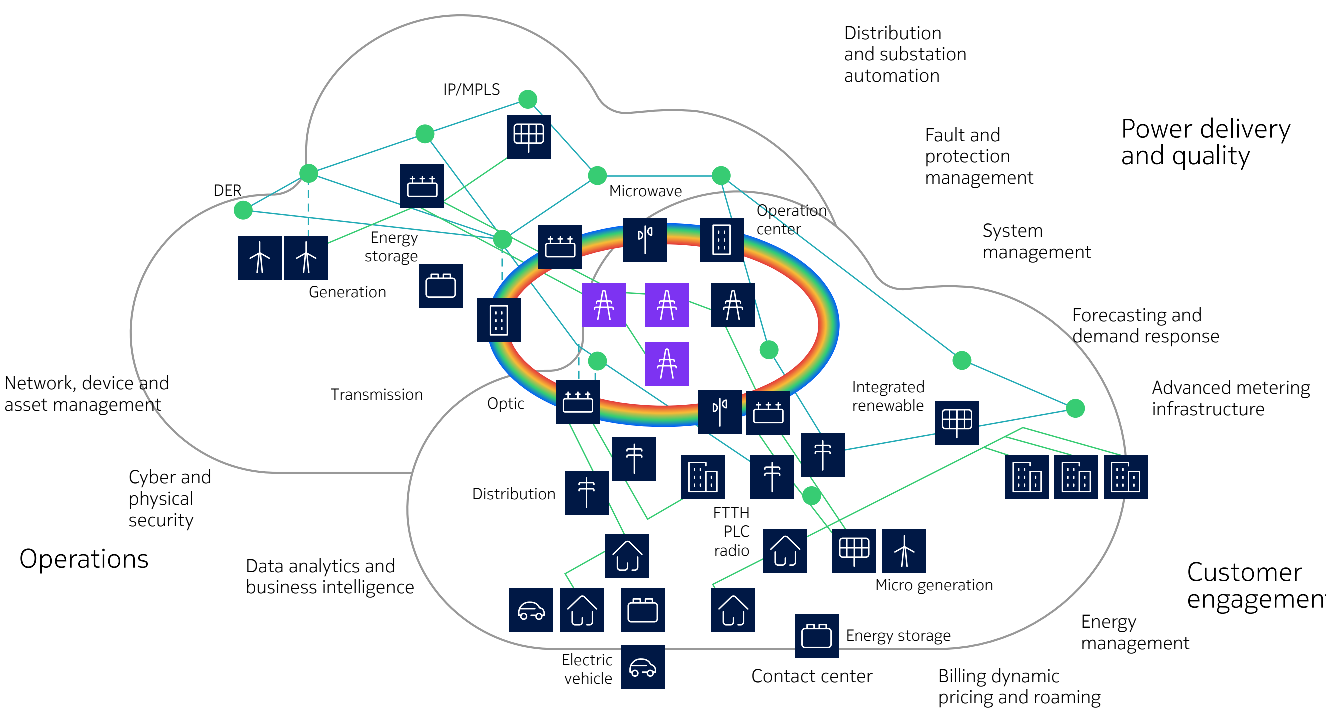
In a rapidly evolving energy landscape, contemporary technology like the XR ruggedized series of PowerEdge servers and NativeEdge represent a necessary step forward. Whether through reducing energy use at the edge, consolidating hardware to lower emissions, or providing the tools to optimize power management across an entire fleet of devices, Dell infrastructure is directly addressing the most pressing challenges the grid is facing today.

Private network where you need it

Private high-level utility architecture

A private power utility network is a secure, reliable and flexible network that connects power systems and other utility assets, allowing for greater control, connectivity and information flow.

Figure 5. Power utility private adaptive network



Performance, resiliency, security, availability, management

The safe and reliable delivery of power is essential overall and considering what elements of private communications will impact delivery of data from the grid is critical. Many utilities are undergoing a digital transformation that includes adopting distributed edge processing for better grid performance or faster response to changing conditions.

There are five considerations for private communications to support an edge strategy in a modern and reliable power grid:

1. **Interoperability:** open standards on private networks provides a common language for communication between different devices and systems, enabling seamless interoperability, reducing the risk of communication failures, and making integration of devices from different vendors and manufacturers possible
2. **Flexibility:** open standards on private networks enable more flexibility with late-stage design changes by removing most of the hard-wired components from the picture—design changes no longer require days of field time to implement

3. **Scalability:** open standards on private networks provide a scalable communication framework that can accommodate the increasing complexity of the power grid, which allows utilities to add new devices and systems without significant changes to the communication infrastructure
4. **Management:** open standards on private networks provide a standardized approach for data exchange, ensuring data quality and consistency enabling utilities to use data from different devices and systems for advanced analytics, optimization and decision-making
5. **Cybersecurity:** open standards on private networks include security features that enable secure communication between devices and systems, protect against cyber threats such as hacking, malware and data breaches, and ensure the integrity, confidentiality and availability of critical power system data.

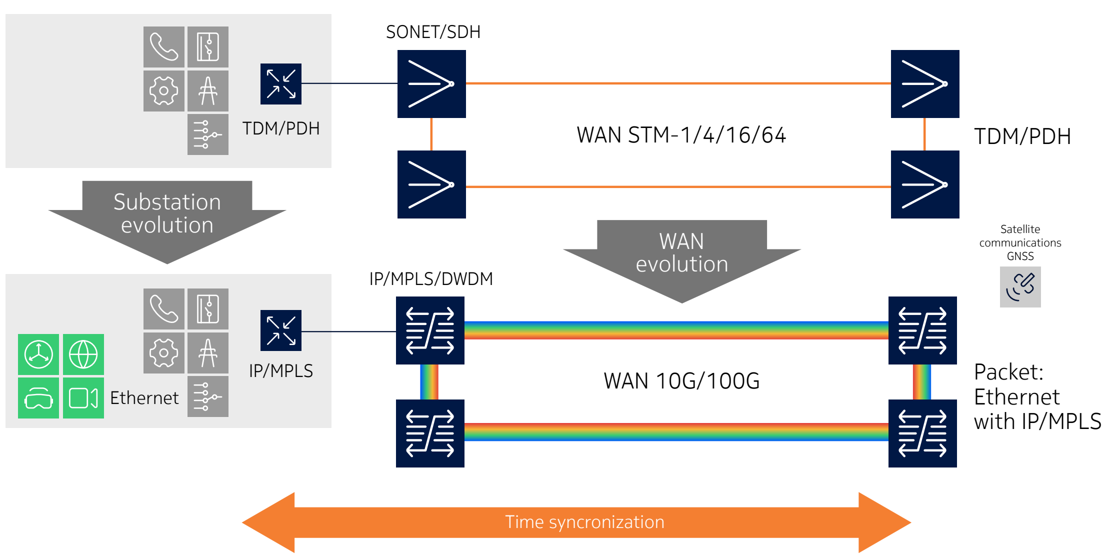
In addition to the above-mentioned benefits, recent research suggests that open standards on private networks can also improve the reliability of power grid systems, reduce outage times, and increase the efficiency of power generation and transmission. These benefits are critical for designing, operating and maintaining a modern power grid that is reliable, resilient and secure.

Why consider IEC 61850 for grid communications?

Support of telemetry for command and control is essential to the safe and reliable supply of electricity. Real-time data exchange mentioned elsewhere in this paper requires a unification of both power grid network and process automation interfaces. This enables one flexible optimized control system that can utilize both centralized and decentralized approaches to monitor and protect an entire grid.

A standard like IEC 61850 is not just a communications protocol. It is a comprehensive standard for the design of substation automation systems and applications based on modern API languages (XML), data streaming methods (MMS, MQTT) and communications technologies like Ethernet and TCP/IP. By using IEC 61850 standards to define communications between field devices and applications, hardwired interfaces and serial cabling can be replaced with an intelligent interface that provides time synchronization, file transfer and engineering tool access on one physical cable.

Figure 6. Evolution of communications for power utility networks

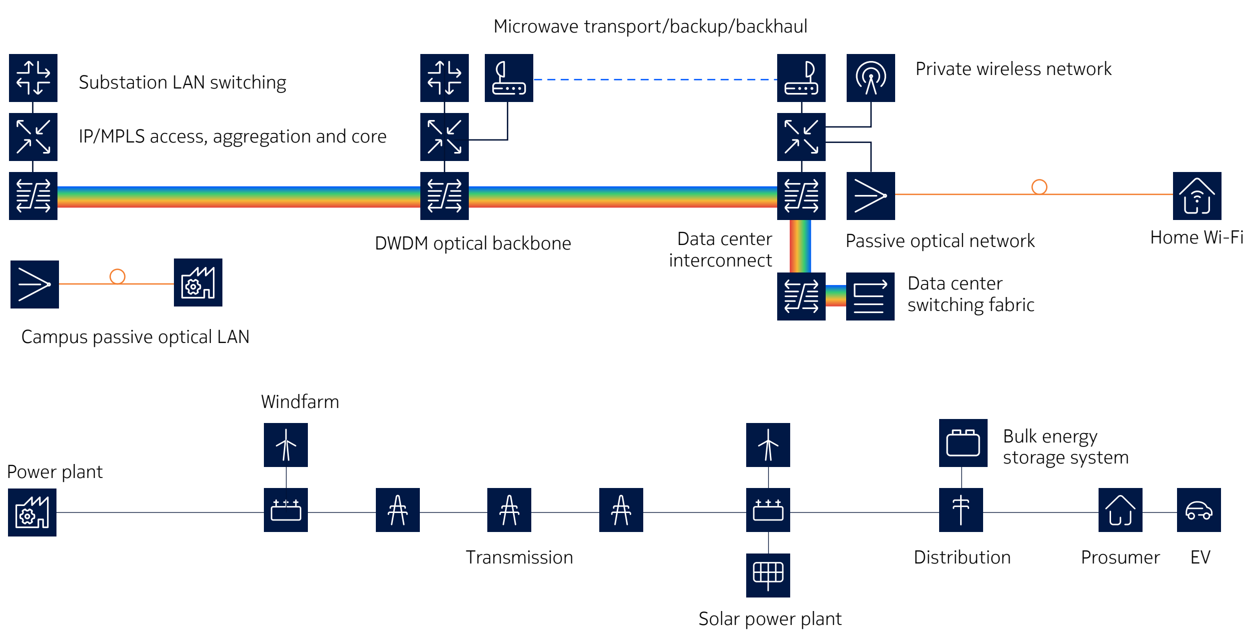


The IEC 61850 standard effectively replaces the numerous buses and interfaces used today by a hierarchy of well specified switched Ethernet and IP networks. The benefits of IEC 61850 are in its object-oriented hierarchical data model approach and its use of mainstream communication technology. The standardization of substation configuration, control logic, control libraries and operation procedures support efficient running of the grid. This will also reduce the engineering and commissioning effort, thereby reducing the time and cost involved. IEC 61850 provides the functional flexibility and delivers savings through simplified substation design, installation, commissioning and operation. It also supports all the new edge compute capabilities discussed in this paper that are not practical or cost effective using legacy approaches.

Why private vs. public networks?

An edge compute network can be built using public (carriers) or private transmission (utility owned) infrastructure. Both are viable options and achieve similar purposes, however, a private network should always be evaluated as it will provide utility edge compute with more precise controls to ensure successful service delivery levels (SLAs), secure flows with a layered approach, reliable communications and data sharing.

Figure 7. Private utility network options



Typically, public networks must be engineered to support many use cases across the carrier customer base. If a utility use case has light SLA requirements this will suffice and performance will be sufficient. However, for many utility OT use cases the requirements for acceptable performance are much tighter and building a private network will lend itself to engineering a network that is built specifically to perform for the utility's use cases and those specific SLAs.

TCO/ROI behind private networks with industrial edge resources

Total cost of ownership (TCO) is the total cost of a private network over its entire service life. TCO includes the costs of equipment, installation, maintenance, operation, deployment and use.

Calculating TCO accurately is important for budgeting and securing funding for a private network project. TCO can help ensure that a project stays on track financially and operationally.

For most mission-critical utility applications, a private network solution is the most cost-efficient compared to other wireless solutions because it provides:

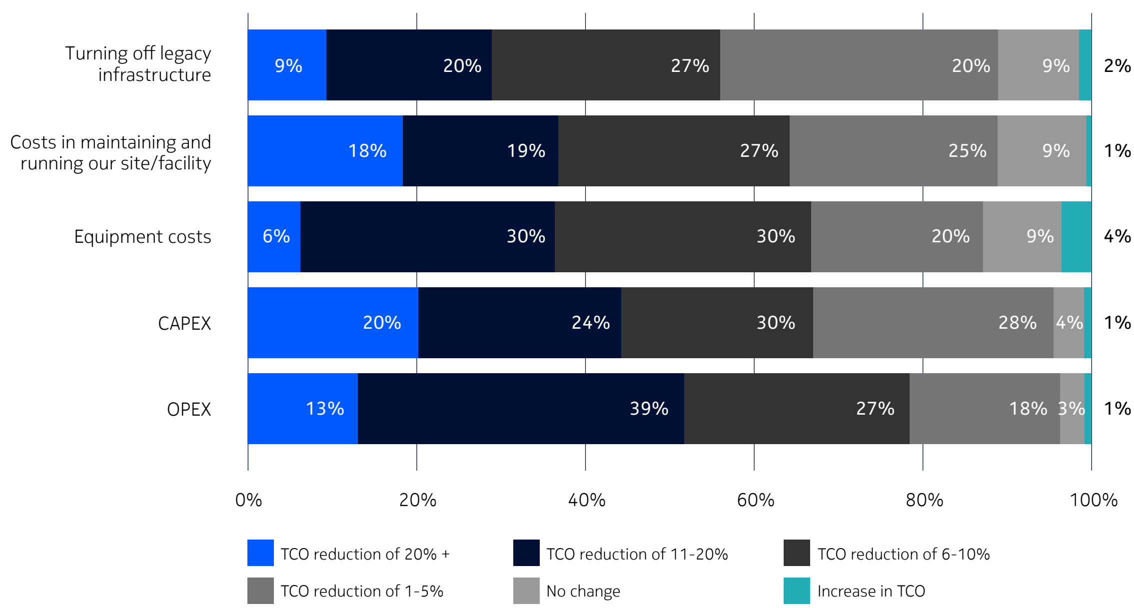
- The greatest capacity and costs less to increase the capacity
- The widest and most exact coverage needed to connect the assets that are the most important
- A purpose-built network able to operate in challenging conditions typical of utility environments for the most resiliency, availability and scalability
- The ability to consolidate multiple or, even, all current networks on a single network, for significant operational cost savings.

Return on investment (ROI) is also a key metric when deploying a private network and industrial edge. The top three results for private network deployments are:

1. Increased worker collaborations and decision making
2. Overall operational cost reduction
3. Reduced site/asset down time.

The ability to easily, cost effectively and reliably access previously unconnected assets (both devices and workers) justifies the investment in the private network.

Figure 8. Impact on the TCO of private network deployments



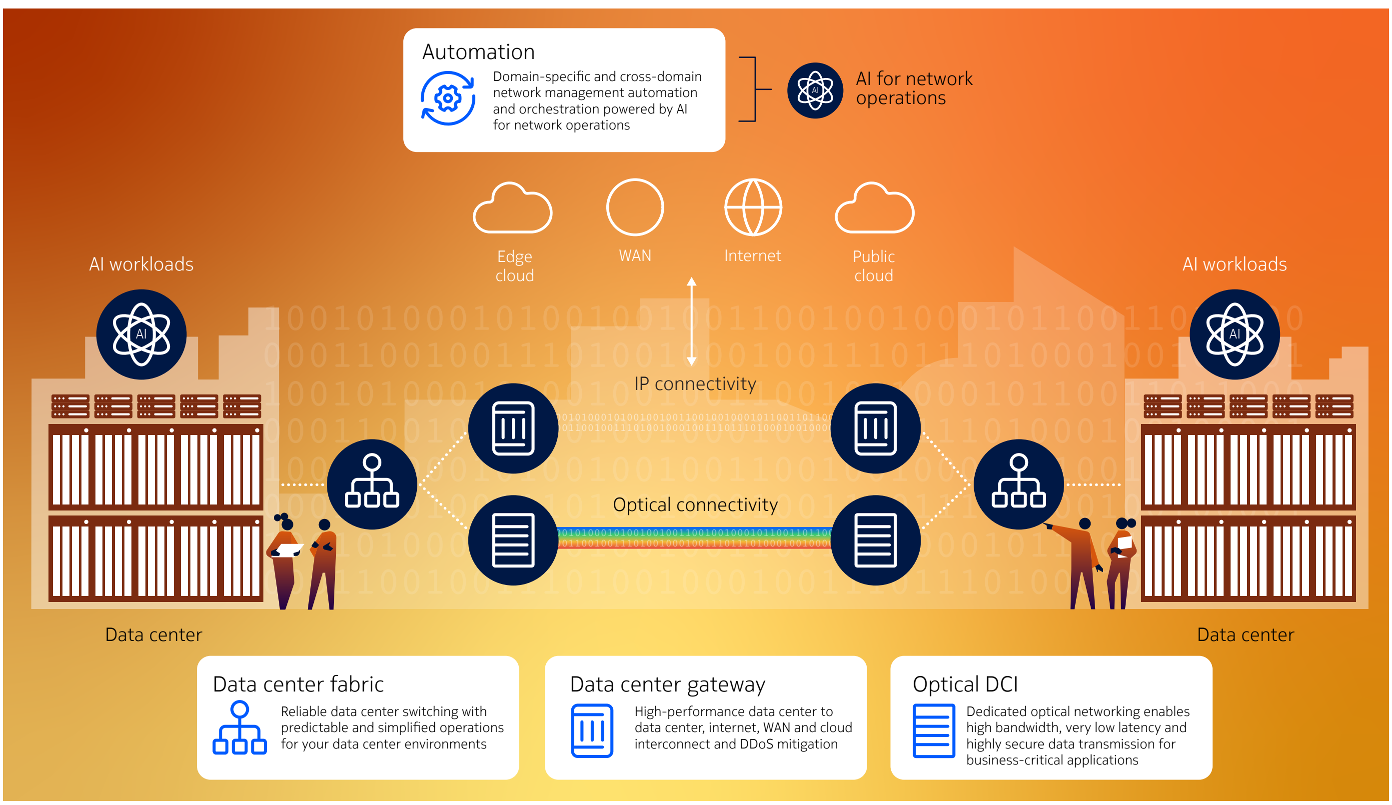
Source: GlobalData

When approaching ROI/TCO, 79% of the early adopters see the benefits of working with pre-integrated vendors who can provide an end-to-end approach when deploying a private network with industrial edge. Reasons given for this are fewer suppliers to manage (46.8%), increased ROI (45.5%), and lower TCO (39%). Reduced deployment time was also mentioned, as some of these solutions are pre-integrated (32.5%). These are some compelling reasons to consider private networks to enhance the success of future utility applications and systems.

Private operational telecom (OT) data center networks

The utility ecosystem and the data centers that control it require highly interconnected network infrastructure to deliver exceptional experiences for grid customers regardless of their location. The general goals of utility data centers are simple — provide connectivity to critical grid applications while avoiding outages. A simple mandate, but a complex problem to solve.

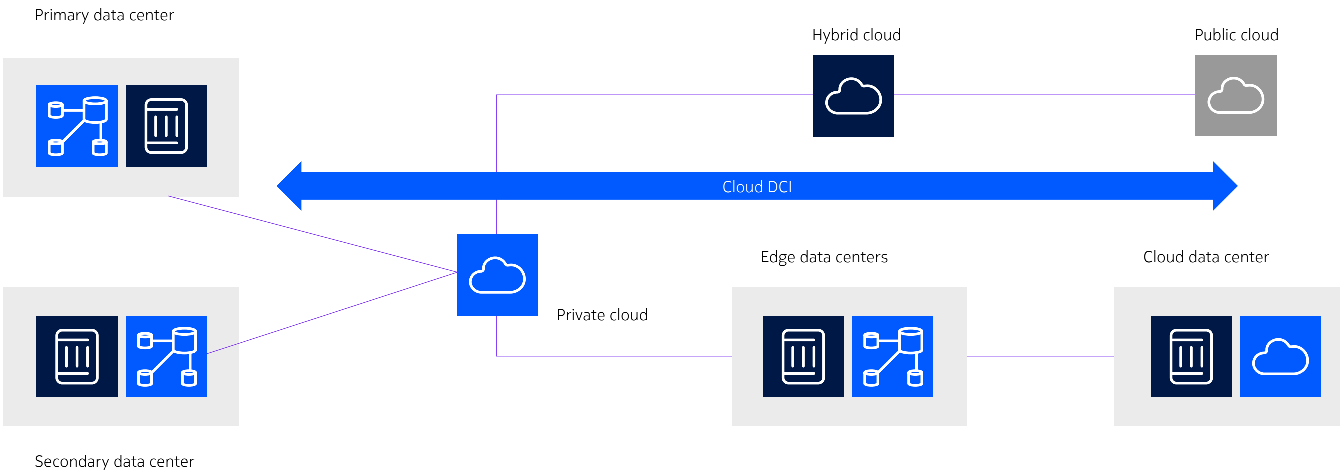
Figure 9. Reliable, automated fabrics and high-performance interconnectivity



Data center interconnect (DCI)

Utility approaches to edge networks expand the need for multi-layer DCI networks and how they need to support dynamic access to distributed utility applications and services. Today's approach with multiple, costly, static networks requires manual provisioning and intervention across multiple layers and domains. They need to evolve to enable an automated, multi-layer data center interconnection fabric that supports DCI to cloud applications and services running in both edge and core data centers. This highlights the need for networks that connect and interconnect data centers in a scalable, secure and reliable way—basically a more agile and flexible approach to connecting data centers and edge networking loads.

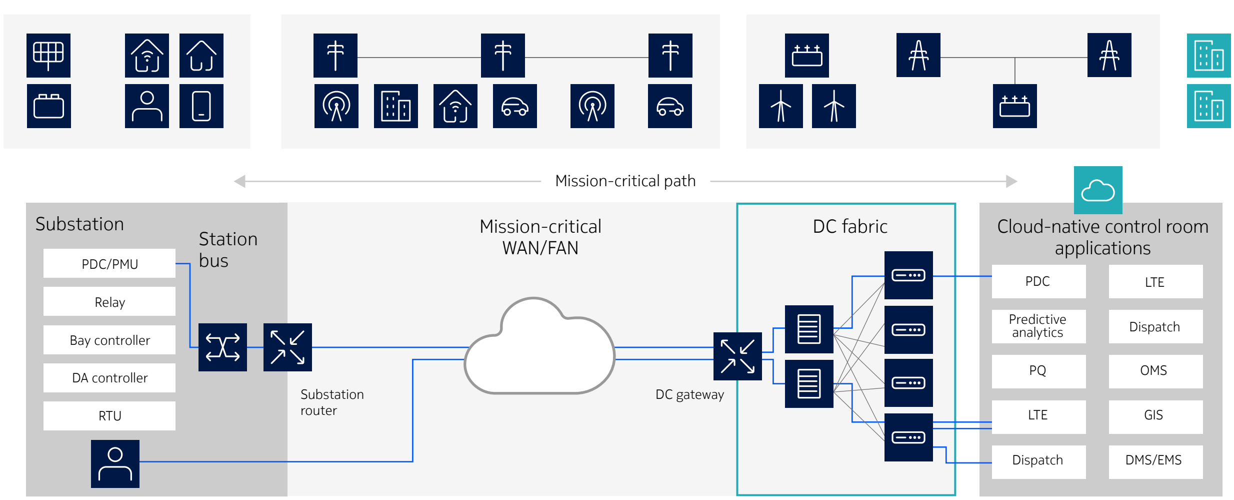
Figure 10. Edge cloud data center interconnection



Data center fabric now part of the mission-critical communications path

As grid applications are evolving to a cloud-native environment, the data center has become a locus for grid operations. An early wave of applications for critical communications utilized field area networks based on cloud-native cores like LTE and 5G core systems and group communications supporting push-to-talk, push-to-video and technician dispatch. Now grid applications including SCADA, distribution automation and synchro phasor monitoring systems are also becoming cloud native. Consequently, the data center network, or simply the DC fabric in IT speak, is a pivotal part of end-to-end critical communications connecting machines and crew in the field with applications in the data center. Hence the fabric would need to seamlessly interwork with mission-critical WAN and FAN with the same level of resiliency.

Figure 11. Grid OT private data center fabric



Additionally, edge networking technologies are raising the bar for the data center fabric. Cloud-native applications are much more dynamic, edge distributed and require more agility, scalability and performance than previous generations of applications. Legacy data center fabrics will not suffice for edge networks deployed with cloud-native applications to support the goals of an adaptive, smart grid.

Modern data center fabrics must:

- Provide the agility, flexibility and performance needed by the new grid applications
- Be easily and intuitively programmable allowing the staff to react quickly to new service demands and business opportunities
- Leverage advanced NetOps automation (DevOps approaches applied to the fabric) to simplify complexity and increase operational scalability
- Adapt to unpredictable disruptions in the network without impacting the service experience
- Span across the service footprint and be compatible with different ecosystems.

Energy orchestration as an edge application

About edge applications

Hybrid edge computing (EC) refers to the process of transferring certain storage and computation resources away from a remote central data center and closer to the data source [7].

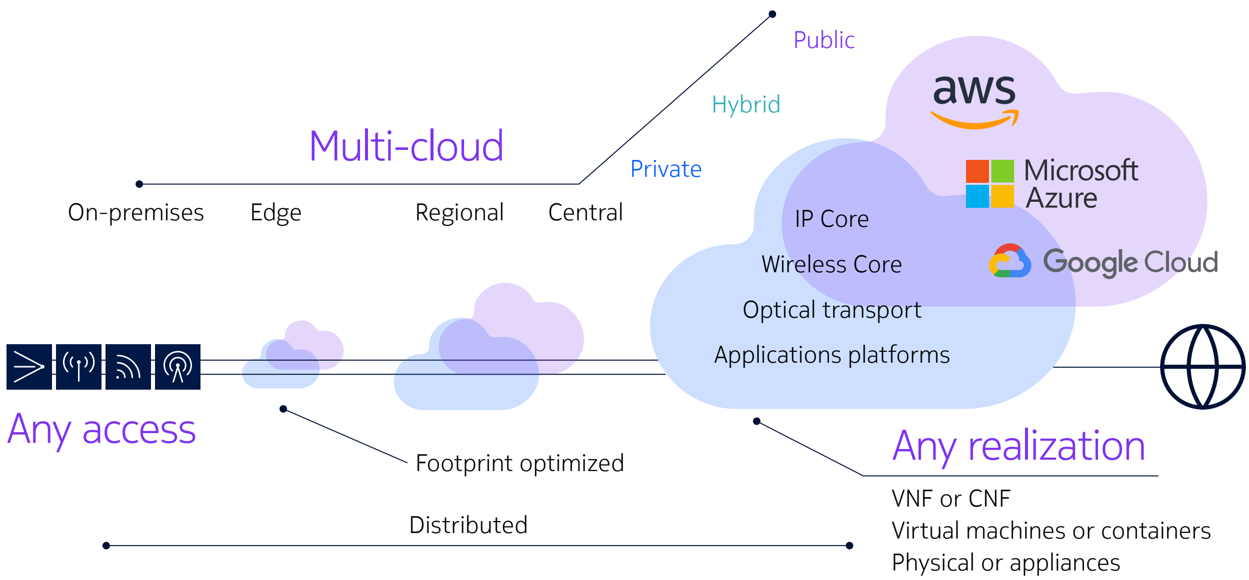
The key to successful use of edge computing capabilities is robust communication infrastructure (as mentioned in the previous section) and the addition of intelligent applications on top of the EC infrastructure. Computationally intensive intelligent models (such as machine learning and data analytics) can be deployed on edge clouds or devices rather than the central cloud [8]. Many different software applications can leverage the value of edge computing in the energy sector. One relevant application is predictive maintenance for the grid, and another is enabling smart grids. But what is the right edge application to get the most out of the evolving distribution grid?

Why edge is enabled by hybrid and multi-cloud networking

Multi-cloud networking is the architectural interconnection of industrial on-premises networks and platforms with public cloud providers or specialized infrastructure providers and their application service layers. While on-premises cloud architectures are popular, hybrid cloud allows for pay-as-you-go infrastructure to scale and support applications. One of the greatest benefits of multi-cloud and hybrid networking is how they enable utilities to scale their technology needs up and down quickly to meet demand with lower CapEx and time commitments.

This approach offers a networking solution made up of two or more cloud infrastructures containing both public and private cloud environments, making resource management across cloud infrastructure more streamlined. This model is gaining popularity among utilities as it offers the flexibility of aligning OT and IT resources with the needs of specific workloads. Public clouds offer scalability and access to advanced technologies like real-time analytics and machine learning, while private clouds are preferred for applications where security, data locality, and low latency are critical. Edge applications that decentralize and distribute processing tasks reduce costs and provide low-latency experiences that are enabled by hybrid or multi-cloud models.

Figure 12. Deploy without limitations: network core and edge are agile



Why orchestration is the ideal edge application for utilities

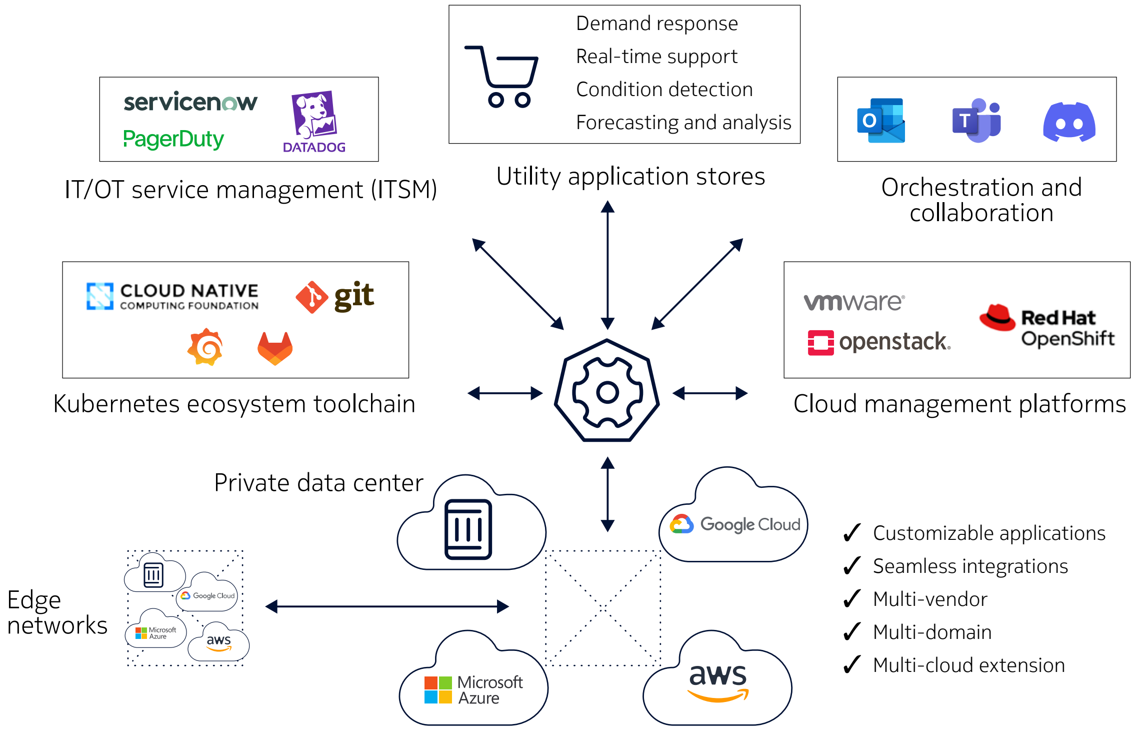
The main missing ingredient for efficient use of a distributed energy grid is automated orchestration. The ability to make the most efficient use of the energy generated from these distributed assets starts with local optimization. Beyond the local resiliency obtained from this optimization, there is a need to consider more objectives and constraints at an aggregated level to optimize for the overall effectiveness of the grid infrastructure. As a result of the local-aggregate interaction, loads can be shifted to get an optimized overall behavior of the grid. Not only can orchestration help to offset infrastructure investment, but it can also decrease the need for curtailment, provide congestion relief, and open new revenue streams.

Requirements for energy orchestration

Orchestration would need to eventually cover all DER, static and flex loads, and distribution grids at varying levels of granularity, while also being versatile and moldable enough for the different balancing and transactional objectives that individuals or collaborating stakeholders, policy makers and regulators aim to achieve by steering their assets in real time.

Energy orchestration is a multi-stakeholder, multi-objective, decentralized, real-time control challenge that needs to obey real-time physical constraints. However, evolving business objectives and asset portfolio changes may need to be addressed over its lifecycle. The solution must be versatile and provide proper tools to simulate, validate, deploy and monitor orchestration within the desired time span.

Figure 13. Flexible to quickly adapt to utility demand

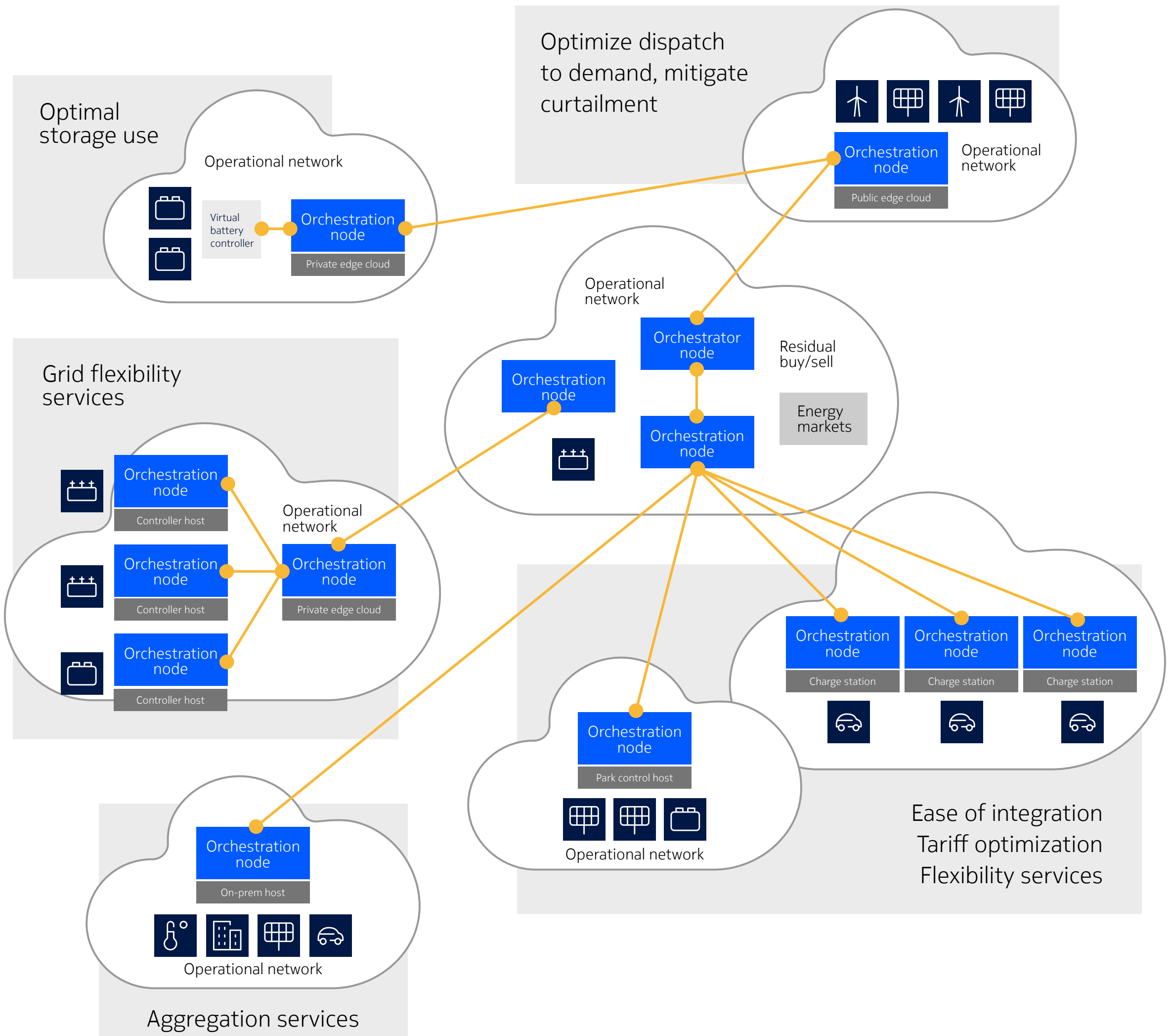


Enscryb orchestration nodes

The Enscryb solution is built around the concept of an orchestration node. These nodes can be seen as software agents that can run as containers on any execution environment, in a hybrid cloud setting, including far-edge, on-premises machines. They orchestrate among energy resources locally, according to a configured power steering (multi-) objective, obeying any relevant grid constraints or user policies.

Orchestration nodes negotiate live flexibility constraints with their peers in a distributed node topology. An asset owner or a service provider to asset owners can compose orchestration nodes into topologies covering a single site or a large, distributed set of many sites, scalable for any portfolio size.

Figure 14. Enscryb orchestration nodes concept



The Enscryb simulator

The initial application of the orchestration nodes in an edge compute system is through a simulation. With the Enscryb Simulator, asset owners and service providers can validate scenarios before deploying them. Using simulation copies of the relevant assets (distributed generation, load, storage, etc.) and resources (such as price streams and contracts), an orchestration topology can be designed and configured to represent both the current state and a potential future state.

Since it is fully cloud based, the entire orchestration topology simulation can be run many times faster than real time while reporting all effects and relevant benefits that the orchestration logic can bring. Simulator users gain valuable insights into how effectively the chosen orchestration configuration reached it targets with detailed views into both the span of time considered and the level of asset aggregation configured. Users can quickly identify any unexpected or long-term undesirable effects of the configuration. They can then quickly iterate with different variants and extensions of the proposed configuration and compare results across them.

The Enscryb vision

While simulation reports can enable informed real-time decision making, the ultimate vision is to use the simulator to define and refine the orchestration configuration before deploying that configuration automatically to the orchestration nodes through a digital portal. The deployment can be done via the cloud or on-premises, using the Nokia communications and Dell computational equipment that most suits the topology under consideration.

Once deployed, any status data from the orchestration can be monitored similarly to how it is done with simulation, in real time. Operational staff can always verify that the orchestration is executing according to specifications and, if needed (e.g., unforeseen event), they can intervene using the control means of choice.

The benefits of the Enscryb application to utilities

System-architectural and operational flexibility can incrementally facilitate quicker interconnection and implementation of new assets as necessary. The Enscryb Simulator provides tools for simulation, analysis and planning to obtain the ideal optimized configuration based on both local and regional objectives and constraints. Adding virtual assets during simulation can assist in identification, planning and dimensioning of justified, well-sized investments and show the dynamic grid behavior implied by the new additions. The solution is designed to enable grid operators and asset owners to create and incrementally update the configuration as needed, without requiring any coding or data science skills, so that new configurations can be evaluated swiftly and with confidence.

In the future, these validated configurations can be seamlessly used in an actual orchestration deployment steering the physical assets. There is the added option of monitoring the actual live system, comparing it to the original simulations, side by side, for intuitive, real-time comparative analysis before deploying any new assets, new objectives or constraint changes.

Business impact

Edge computing and edge software applications are becoming necessities as more devices are connected to the grid. When combined, they have many benefits, such as [9]:

- **Scalability:** edge nodes can be deployed as needed and scaled when needed
- **Flexibility:** easily adaptable to evolving requirements such as emerging technologies
- **Efficient use of bandwidth:** transmission of data to central servers can be drastically reduced, thereby reducing congestion and cost of the network
- **Reduced latency:** data can be processed locally to support real-time decision making for critical processes
- **Operational resiliency:** operations can continue even when disconnected from the central system
- **Enhanced privacy and security:** sensitive data can be kept locally, reducing the associated risks with data transmission.

Edge computing combined with edge applications enables management of the increasingly complex and decentralized energy grid, enhances grid reliability, optimizes operational efficiency, and helps to meet compliance requirements (e.g., government regulations and cybersecurity). Utilities need scalable and flexible tools to adapt to a dynamic energy landscape while maintaining efficient and resilient operations.

Use cases for edge compute and edge applications to manage DER

Real-time monitoring and control

Distributed energy resources (DER) such as solar, wind and batteries can be continuously monitored for performance metrics such as power output and available flexibility. Local data processing enables immediate control and optimization of each device without a need to communicate with the centralized cloud system.

Localized, real-time management supports grid stability by ensuring that DERs operate at optimal performance levels and quickly respond to any fluctuations in demand or generation.

Load balancing and optimization

DERs can be used to balance and optimize power production and consumption dynamically. For example, a solar panel may lose output due to cloud cover, but an intelligent edge system could instruct the local battery unit to discharge energy, or demand response programs could be used to match demand to the available supply.

By making these adjustments at the edge, the system can efficiently handle the intermittent nature of renewables, maintaining a balanced grid without the intervention of a centralized control system.

Enhanced intelligent demand response

Intelligent edge systems enable local systems to dynamically adjust energy consumption based on grid conditions, price signals or the availability of energy. They can autonomously manage assets such as EV charging stations and smart appliances to reduce or increase demand based on DER output.

The real-time coordination of these assets provides balance between supply and demand at the local level.

Integration with microgrids and islanding capabilities

Microgrids (small, localized energy systems that can operate independently from the main grid) often contain multiple DERs that need to be efficiently coordinated to manage energy production, consumption and storage independently of the main grid. This is particularly relevant if a microgrid is islanded due to an outage or other event.

Intelligent edge systems can ensure continuous operations and self-sufficiency even during grid disturbances.

Autonomous energy trading and peer-to-peer energy exchange

Autonomous decision making in local energy markets is made possible by intelligent edge systems. For example, a battery storage system can be instructed when to sell excess energy back to the grid, consume energy from the grid, or trade energy with other local systems based on grid demand, current market prices, and its own state of charge.

This application supports the development of local energy markets where prosumers can directly exchange energy, reducing dependency on centralized systems.

Predictive maintenance and fault detection

DER data can be analyzed to detect patterns or anomalies that may indicate an issue, enabling immediate identification and classification of potential faults. An intelligent edge application could then automatically send alerts to operators or trigger an immediate response such as isolating the failing unit to prevent further damage to itself and the rest of the system.

By predicting maintenance needs based on actual data and patterns, maintenance activities can be optimized while minimizing asset downtime.

Moving from innovation to business as usual

Innovation is essential for the future power infrastructure to be resilient, secure, sustainable and affordable. Innovation has always been continuous in the utility industry. Technology advancement is iterative and demands attention, but business, regulator and customer expectations have not always been as intense. These gaps can be modeled to identify new business outcomes and help build a robust innovation roadmap supported by key stakeholders.

The journey from innovation to business as usual can be challenging and fraught with barriers of time, budget, scope creep and disappointments. It has already been discussed in detail how the power industry is moving away from a traditional model in which the utility controls all grid assets. Therefore, utilities will be pressured to deploy new capabilities to integrate these new devices and manage two-way flows of energy on local distribution grids. Making the transition to the grid of the future requires new approaches to operating the electricity system, engaging customers, working with third-party power providers, and to the utility business value model.

It is important to foster change by developing best practices that can ease the journey and provide insightful information along the way. Innovation funding can assist in early trials with new technologies, but to make lasting change, the following best practices can create successful change:

- Involve operations across business units early
- Expect changes and manage them effectively
- Create a clear roadmap from innovation to business as usual (BAU)
- Foster an open culture of sharing and communicate honestly and frequently
- Create positive impact on BAU expenses, freeing resources for continued deployment.

This paper discussed what is driving the changes facing the industry, why more flexibility is required, and covered some of the technologies and processes that can help drive successful change. These scenarios can spark discussions that ultimately drive better business model decisions. Moving from these innovation areas to funded projects to adoption as BAU operations has no easy answers. Working in collaboration with partners and vendors that can help develop future utility transformation scenarios and recommend frameworks can significantly reduce the effort and ease the transition.

Abbreviations

BAU	Business as usual
CapEx	Capital expenditure
DC	Data center
DER	Distributed energy resource
DevOps	Development operations (software)
IEA	International Energy Agency
EC	Edge computing
IRENA	International Renewable Energy Agency
EV	Electric vehicle
IT	Information technology
LV	Low voltage
MV	Medium voltage
NetOps	Network operations
OT	Operational technology
NWS	Non-wire solutions
ROI	Return on investment
TCO	Total cost of ownership

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Document code: CID214479 (March)