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5th Edition
World® Utility Summit

23-25 February 2025
India Expo Mart, Greater Noida, Delhi NCR, India

MEGAWATTS TO MEGABYTES: CONFLUENCE OF UTILITIES AND EMERGING TECHNOLOGIES

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5th Edition

World® Utility Summit

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Empowering Utilities:
Transforming Energy Challenges into Resilient Future

ABOUT WUS 2025

The World Utility Summit (WUS) has been at the forefront of empowering utilities to navigate the future with resilience and transformation. The 2025 edition marks the 5th iteration of this prestigious summit, which will focus on the cutting-edge technologies that will reshape the utility industry. In this Edition - Regulators, Tech Companies, Consultants, Government Officials, and Utility Leaders will all be there to share their perspectives on the challenges and opportunities that lie ahead. This gathering offers unparalleled opportunities for networking, knowledge sharing, and collaboration in

SUMMIT TRACKS:

Energizing a Greener Grid: Decarbonization Meets Distributed Solutions

This theme will explore the ongoing shift towards renewable energy sources and distributed generation models (e.g., rooftop solar) to achieve net-zero emissions. Sessions could discuss:

- Transition to Renewable energy sources & its integration
- Advancements in Energy Storage Technologies
- Policy & economic implications of decarbonization
- Innovation in Renewable Energy: advancements in solar, wind, geothermal, Hydrogen and other renewable energy technologies

Bytes & Breakers: Navigating the Digital Revolution in Utilities

This theme will delve into the impact of digital technologies on the utility industry. Sessions could address:

- Connecting to the cloud & the data landscape: Discuss how utilities can leverage cloud computing and big data for better decision-making
- Leveraging big data and analytics for optimizing grid operations and maintenance
- The changing customer experience in a digital utility environment
- Smart storage: Explore solutions for integrating energy storage into the grid to optimize renewable energy usage
- A smarter energy system: examining the risks, unlocking resilience: Explore how digitalization can build a more resilient grid
- Blockchain for Utilities amid the Energy Transition
- Big Data, Blockchain, IOT & Analytics for Grid
- Accelerated use of AI & Cloud
- Growing adoption of Modernization and Automation with Cybersecurity

Investing in Future: Building Climate Resiliency in the Energy Ecosystem

This theme will focus on strategies for building climate resilience into utility infrastructure to withstand extreme weather events like storms and floods. Sessions could explore:

- Strengthening and modernization grid infrastructure for improved resilience & to with stand extreme weather events
- Early warning systems and emergency response plans for utilities
- The role of distributed generation in enhancing grid resilience
- Adapting utility business models to account for climate risks
- Emergency preparedness and response: Developing robust plans for responding to and recovering from extreme weather events
- Expeditated the development & deployment of new technologies for managing extreme weather events
- Make Climate resilience a central part of policy framework and system planning

Harmonizing Grid Horizons: Evolving Regulatory & Policy Landscape

This theme will examine the evolving regulatory environment for the utility sector, considering the need for innovation and investment. Sessions could discuss:

- Policy frameworks for encouraging renewable energy development and distributed generation
- Regulatory reforms to promote grid modernization and digitalization
- The role of regulators in ensuring fair competition and consumer protection in the changing utility landscape
- Policy approaches for achieving national and international climate goals
- Regulation for the future: Explore how regulations can incentivize innovation in renewable energy and grid modernization
- Changing regulatory landscape: Discuss the ongoing regulatory changes impacting the utility sector

MegaWatts to MegaBytes: Confluence of Utilities and Emerging Technologies

This theme will explore the potential of emerging technologies (e.g., blockchain, Internet of Things) to revolutionize the utility sector. Sessions could address:

- Financing the Future: Unlocking the Financing for Renewable & Efficiency Projects
- Workforce Transformation: Skill & Training for Renewable Energy Economy?
- Key disruptive energy technologies: Explore technologies like small modular reactors, advanced battery storage, and hydrogen fuel cells

Session with eTECHnxt: Energy Storage – Enabling RTC Renewable Energy

- Enhancing Grid Efficiency and Reliability by Integration of Battery Storage with Renewable Energy Forecasting and Scheduling
- Role of Battery Storage in Enabling Round-the-Clock Renewable Energy Systems: Challenges, Opportunities, and Policy Implications
- Roadmap for Utilities & Industries to achieve Flexibility, Resilience, and Decarbonization

MESSAGE FROM KNOWLEDGE PARTNER

Mr. Anujesh Dwivedi
Partner, Deloitte

The World Utility Summit (WUS) 2025 serves as a vital platform, bringing together key stakeholders from across the power and utility sector to address emerging challenges and opportunities. In an era of rapid energy transition, digital transformation, and sustainability imperatives, this forum plays a crucial role in shaping the future of utilities. Deloitte is honoured to be a Knowledge Partner for WUS 2025 under the theme 'MegaWatts to MegaBytes: Confluence of Utilities & Emerging Technologies'. As the sector undergoes profound shifts ranging from decentralized energy generation, rising demands, changing demand profiles, smart grid deployment to regulatory evolution and enhanced customer expectations, it is of utmost importance to reimagine how business is conducted.

Innovation is essential to foster insightful discussions that can drive actionable strategies.

At Deloitte, we are committed to supporting utilities in navigating energy transition, enhancing operational efficiencies, and ensuring financial sustainability.

This whitepaper is aimed at understanding the evolutions in the sector and how the data generated from the different smart grid components can be harnessed by, analytics and AI which can make measurable impacts to provide a delicate balance between energy security, affordability, and environmental responsibility. This summit provides an excellent opportunity to engage with policymakers, regulators, industry leaders, and technology innovators to create a roadmap for a more resilient and adaptive utility ecosystem.

We look forward to an engaging and thought-provoking dialogue at WUS 2025 and to collectively shaping a sustainable and future-ready power sector.

Best wishes for a successful summit

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1 Introduction

Electric utility, encompassing power generation, distribution, and consumption, forms the backbone of modern society, powering homes, industries, healthcare, transportation, and communication systems. Reliable electricity is not merely a convenience, it underpins economic growth, public safety, and societal well-being. The utility sector, categorized as critical infrastructure is undergoing a profound transformation driven by technological innovations, regulatory changes, and environmental concerns. Traditionally, utilities focused primarily on the generation, transmission, and distribution of energy. However, the rise of digitalization has introduced a new paradigm where data and data-driven insights are as critical as energy itself.

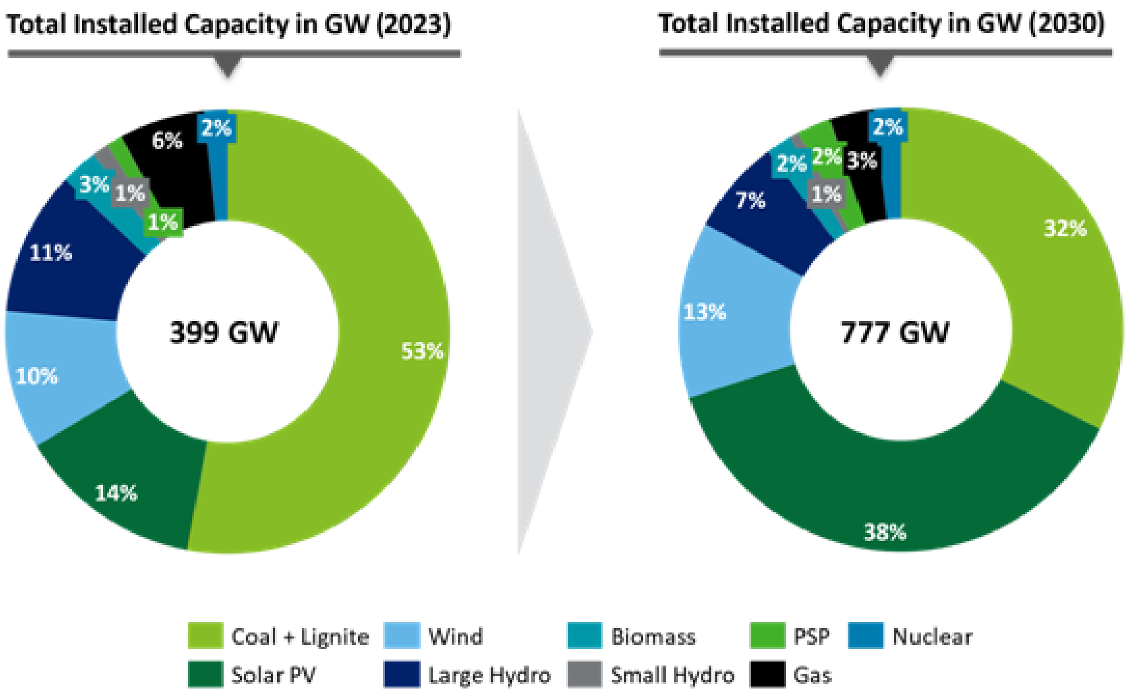
The convergence of physical and digital domains, symbolized by the shift from "megawatts" to "megabytes," epitomizes this transformation. The shift is deeply rooted in the principles of Industry 4.0, which emphasizes the integration of cyber-physical systems, Internet of Things (IoT), cloud computing, and artificial intelligence into operations and planning. In this digitally transformed and interconnected ecosystem, utilities are no longer just energy providers but are evolving into dynamic digital enterprises. Every touchpoint, from grid operations to customer interactions, is being reimagined with the aid of data, digital tools, and real-time analytics.

1.1 Overview of the Utility Sector's Transformation

The need to expand and modernize grid infrastructure is driven by two converging forces. First, growing global electricity demand that is expected to grow by 150% by 2050 majorly by increasing energy needs of rapid urbanization and industrialization, data centers, artificial intelligence, and the cryptocurrency sector. Second, the rapid rise of new generation sources, particularly renewables and distributed energy resources (DERs), is reshaping the energy profile. These sources alter electricity flow and introduce intermittency, posing significant challenges for grid planners and operators.

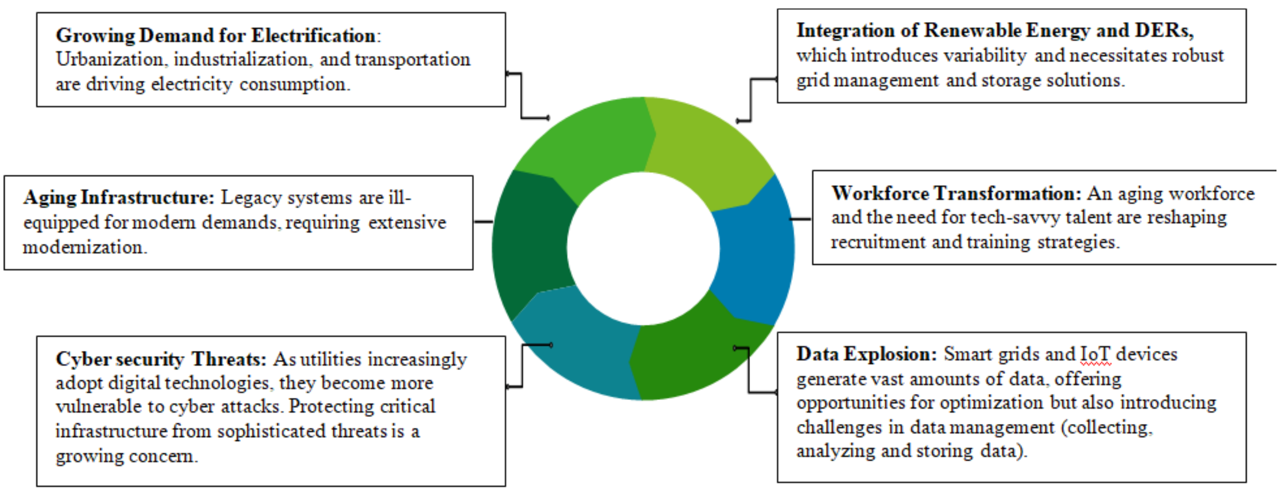
Utilities are tasked with ensuring energy that is safe, secure, reliable, affordable, and progressively sustainable that necessitates grid modernization. Governments and organizations worldwide are advocating for smarter, greener, affordable, resilient, and efficient energy systems, aligning with global agreements like the Paris Agreement. As projected by the International Renewable Energy Agency (IRENA), renewables could account for 85% of global electricity generation by 2050. India's ambitious renewable energy target of 500 GW of non-fossil fuel capacity by 2030 (Figure 1) exemplifies such commitment. Yet, the International Energy Agency (IEA) warns that current trajectories must accelerate to achieve COP28's goal of tripling global renewable capacity by 2030.

Figure 1: Comparison of Total Installed Capacity in GW (2023 V/s 2030) – India



Traditionally, utilities were structured around centralized power generation, hierarchical control systems, one-way energy flows, and minimal customer interaction. Power plants were the dominant hubs, transmitting electricity to passive consumers through static grids. However, this legacy framework is increasingly incompatible with modern challenges such as climate change, intermittent renewable sources, fluctuating energy demand, cyber threats, and evolving customer expectations. These array of challenges (Figure 2) demand innovation and resilience to navigate an increasingly complex and dynamic energy landscape.

Figure 2: Top 6 Challenges Faced by Utilities



Electric power utilities are responding to this dynamic landscape with record capital expenditures, which could reach US$174 billion by the end of 2024. Of these expenditures, 42% are expected to be allocated to transmission and distribution systems [6]. Many are revising their integrated resource plans (IRPs) to accommodate higher load growth projections. India had an overall outlay of US$37 billion for 2021-2026 for modernization of power distribution sector. However, amid increasing demand, utilities are also facing challenges, such as supply chain disruptions, extreme weather events, and shifting regulatory landscapes. Despite these challenges, the opportunities far outweigh the risks. Addressing these multifaceted challenges requires making strategic choices and technology-driven approach as they keep a focus on reliability, affordability, and sustainability. With the advent of smart technologies, the utility is shifting toward dynamic, decentralized, data centric approach that prioritize efficiency, reliability, and customer-centric services.

At its core, three pivotal drivers underpin this transition:

- **Decarbonization:** Utilities are actively embracing renewable energy sources such as solar, wind, and hydroelectric power to mitigate carbon emissions and align with global climate action targets. The integration of renewables into the grid brings significant environmental benefits but also poses operational challenges, including intermittency and grid balancing. Advanced digital tools, such as Artificial Intelligence (AI) driven predictive models, are enabling utilities to manage these complexities effectively while optimizing renewable energy integration and supporting net-zero carbon goals.

- **Decentralization:** The traditional centralized grid model is evolving to incorporate DERs, such as rooftop solar panels, battery storage systems, and microgrids. These localized solutions empower consumers to become "prosumers"—both producers and consumers of energy—contributing directly to the grid. Decentralization not only enhances energy resilience and reliability but also harness local energy generation. Digital platforms and peer-to-peer energy trading systems, often powered by blockchain, are facilitating seamless interactions within these decentralized networks.

- **Digitalization:** Digital transformation is the cornerstone of the utility sector's modernization efforts. Emerging technologies such as the IoT, AI, blockchain, and big data analytics are redefining grid operations, customer engagement, and decision-making processes.

As the industry continues to embrace these drivers, the focus shifts from merely delivering energy to providing intelligent, adaptive, and sustainable energy solutions. Utilities that embrace digital transformation stand to gain competitive advantages, improve customer satisfaction, and contribute to global sustainability goals. The utilities' ability to adapt to these changes will determine their role in enabling a resilient and technology-driven future

1.2 Scope of the White Paper

The transformative shift from traditional power suppliers to integrated energy service providers, driven by digitization and innovation, has given rise to the concept of "smart grids". Smart Grids are dynamic, adaptive, autonomous, and capable of integrating DERs, renewable sources, and energy storage systems (ESSs). Unlike traditional grids, smart grids enable two-way communication between utilities and consumers, allowing real-time data exchange. IoT sensors, controls, and software help detect and respond to issues, such as outages or equipment failures, automatically and quickly. A report by the International Energy Agency (IEA) highlights that global investment in smart grids is expected to reach $400 billion in 2024.

This white paper delves into the pivotal intersection where the vast volume of data generated by smart infrastructure and technologies serve as the “fuel” that powers innovation, enabling utilities to adopt and leverage emerging technologies. Emerging technologies such as AI, ML, IoT, Digital Twins, Cloud, Edge Computing, blockchain, etc. is redefining how utility plan, operate and generate value by improving situational awareness, enabling data-driven decision-making, and fostering more meaningful consumer engagement.

In the chapters ahead, we will discuss strategic framework that illustrate how utilities are navigating this confluence of energy and emerging technologies in transitioning from reactive to proactive operations. It explores how the overwhelming influx of data can be transformed from a challenge into an opportunity by adopting effective strategies to manage, analyze, and harness the vast data streams produced by connected infrastructure and equipment. In this rapidly evolving digital landscape, robust cyber defense is not optional but an absolute necessity to protect critical infrastructure and ensure operational resilience against ever-increasing cyber threats. The paper also highlights the significance of workforce empowerment, effective change management, and streamlined processes in adapting to new operational paradigms.

Moreover, the integration of megabytes into megawatt systems is reshaping utility business models from static, supply-driven frameworks to dynamic, customer-driven ecosystems. Utilities are diversifying their offerings, moving beyond just selling electricity to delivering value-added services like energy efficiency consulting, EV charging solutions, and subscription-based energy storage services. The adoption of the Energy-as-a-Service model further provides utilities with new revenue streams, supporting their business objectives.

Advanced digital technologies can serve as catalysts developing new innovative business and operation models – for example using AI to understand consumer behavior and energy patterns to recommend personized energy savings options. Or they can be disrupters making way for new market entrants - for example aggregator platform that aggregates DER owners and demand-side flexibility and bid it into multiple electricity markets. They can also be enablers, unlocking unprecedented levels of performance - reducing maintenance time and costs by deploying automated drones with cognitive capabilities to inspect field assets [8]. By exploring these dimensions, the paper aims to provide actionable insights, equipping utilities to thrive in a digital-first era while addressing the critical challenges of rising demand, energy security, affordability, and net zero goals.

1.3 Framework for Modern Utilities: Three pillars of Transition

The evolution of modern electric utilities is driven by the integration of three foundational pillars: Smart Equipment & Infrastructure, Data & Intelligence, and People & Processes. Together, these pillars form a cohesive framework for next-generation utility that not only enhances operational performance but also supports sustainability and innovation.

Smart Equipment and Infrastructure

At the core of modern utilities lies smart infrastructure, which integrates advanced digital technologies with physical assets. This infrastructure includes IoT devices (such as sensors, meters, and other devices that collect and transmit data), DERs like PV systems, electric vehicles and charging points, batteries, heat pumps, and microgrids, as well as smart substation equipment (e.g., switches, transformers, and circuit breakers). It also encompasses renewable energy systems (such as solar, wind, and hydro), ESS like batteries and flywheels, smart home automation, advanced communication networks, and grid monitoring and control systems, including Supervisory Control and Data Acquisition (SCADA), Advanced Distribution Management Systems (ADMS), Energy Management Systems (EMS), Outage Management System (OMS), Advanced metering infrastructure (AMI), Distributed Energy Resources Management System (DERMS), and Wide Area Management System (WAMS). Additionally, it integrates enterprise solutions like Enterprise Asset Management (EAM), Geographic Information System (GIS), Enterprise Resource Planning (ERP), Customer Information Systems (CIS)/customer relationship management (CRM) and warehouse management system (WMS). This smart infrastructure interacts with the physical environment, generating real-time data on energy flow, equipment health, and grid stability automate and optimize grid operations, enhance energy efficiency, and enable real-time decision-making.

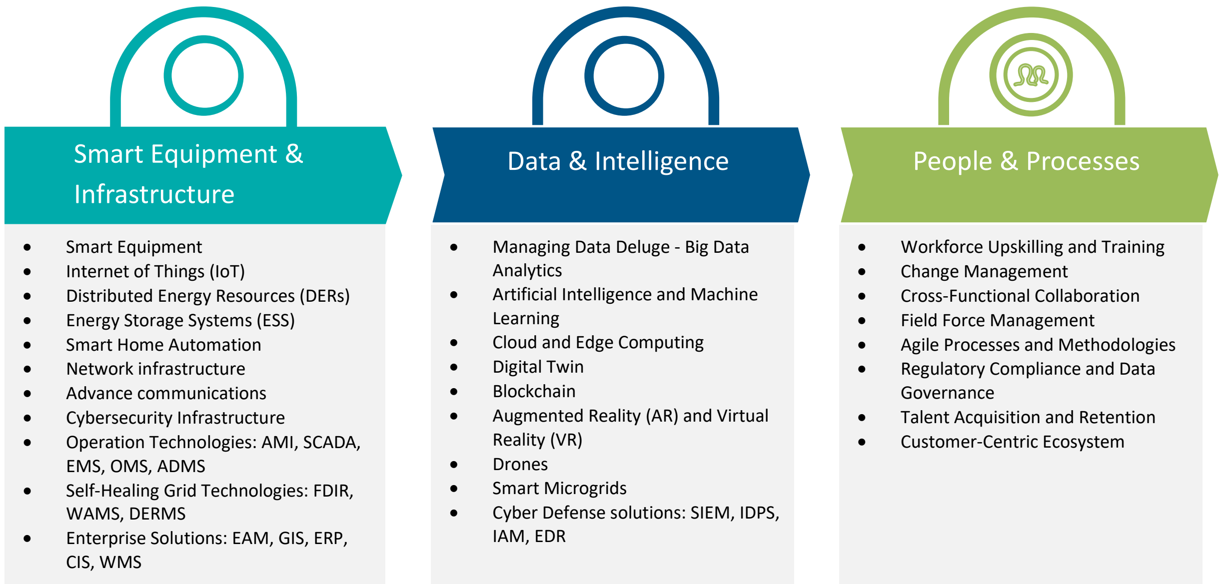
Data and Intelligence

Data is the driving force behind utility sector transformation. The “data deluge” from increasing volume of data generated by smart infrastructure presents both challenges and opportunities. By leveraging advanced data analytics, utilities can go beyond the core operational use of data and technology today, unlocking immense potential to derive actionable insights and move to a completely autonomous grid management. The convergence of emerging technologies such as AI, machine learning, digital twins, cloud computing, and edge computing adds a layer of intelligence, enabling sophisticated processing of big data. Additionally, the cross-usage of data between applications—such as integrating energy usage patterns with predictive maintenance insights or combining weather data with load forecasting—further amplifies operational efficiency and decision-making. This empowers utilities to address multiple use cases, including energy efficiency, energy transition, predictive maintenance, load forecasting, demand response, and advanced applications like AR/VR-assisted workforce training, drones for infrastructure inspection, and smart microgrids for localized energy management. Moreover, technologies like blockchain, quantum computing, and robust cybersecurity ensure data integrity and security within this highly interconnected ecosystem.

People and Processes

While technology and data form the backbone of modern utilities, it is the people and processes that drive successful transformation. Utility companies must invest in upskilling their workforce to fully capitalize on advanced technologies for faster return on investments. This includes not only training on emerging technologies like AI, IoT, and digital twins but also develop expertise in critical areas such as regulatory compliance, data governance, and cybersecurity. As utilities adopt data-rich technologies, robust data governance frameworks are essential to ensure the ethical use of data, compliance with regulations, and protection of customer privacy. Talent acquisition and retention also play a pivotal role, as utilities must attract a diverse and highly skilled workforce while creating an environment that promotes employee engagement, professional growth, and long-term commitment. At the same time, processes within the sector are evolving to become more agile and responsive to rapidly changing energy landscape. Collaboration among diverse stakeholders—such as energy providers, regulators, technology providers, and consumers—is crucial for developing and implementing data-driven strategies that improves service delivery and support sustainability goals. By fostering a culture of innovation, empowering cross-functional teams, and adopting flexible governance models, utilities can successfully navigate complexities of today's data-intensive and interconnected environment.

Figure 3: Framework for Modern Utilities: Three pillars of Transition



This three-pillar framework provides a holistic approach for utilities to not only embrace digital transformation but also adapt to the challenges and opportunities of the energy transition. By aligning smart infrastructure, big data, advance technologies, and human-centric processes, utilities can create a resilient, efficient energy, and sustainable ecosystem for the future.

2 Smart Equipment and Infrastructure: Increasing Visibility and Control

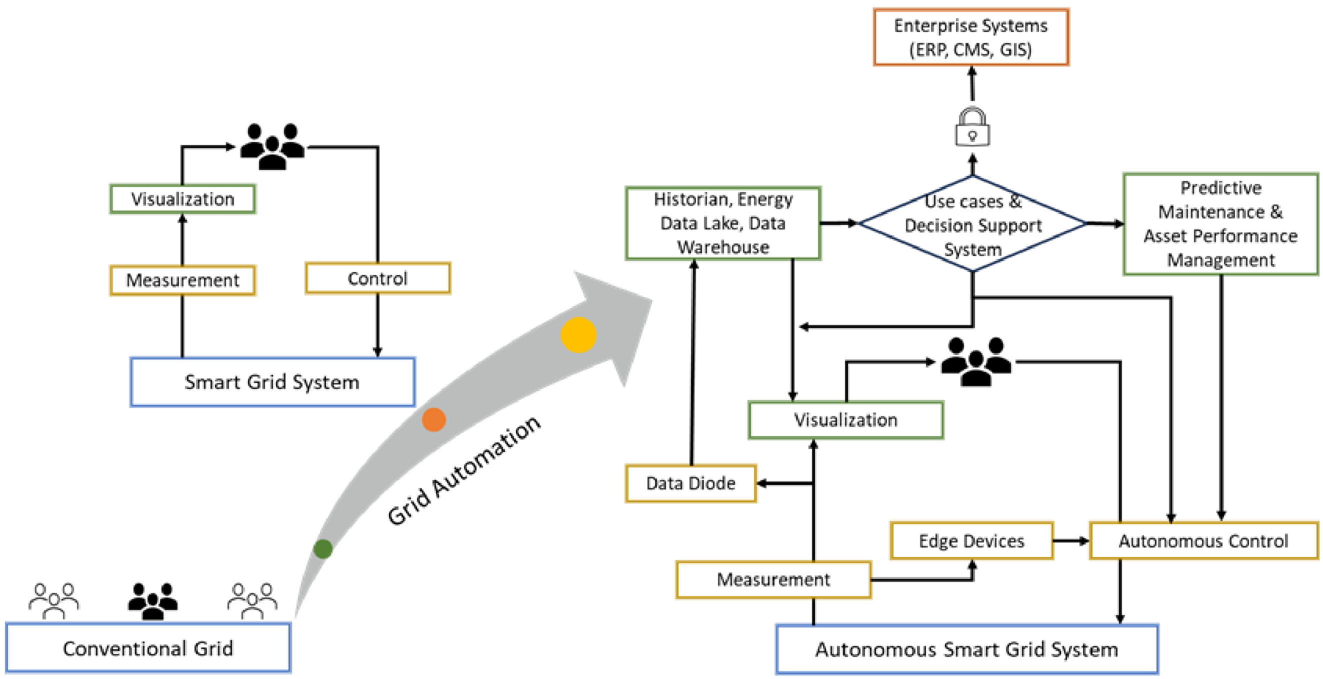
The integration of smart equipment, digital systems, and networks designed to generate, collect, process, and communicate data in real-time is transforming how energy is generated, transmitted, distributed, and consumed. Advances in computing power, reduced technology costs, and enhanced connectivity are accelerating the adoption of intelligent devices with two-way communication capabilities, such as sensors, mobiles, IoT, DERs, ESSs, and smart home automation. These advancements are introducing both disruptive risks and transformative opportunities for enterprises, including the power industry [8]. Furthermore, the adoption of smart infrastructure facilitates greater penetration of renewable energy sources, enhances grid resilience, and supports the shift toward decentralized energy models.

The proliferation of new sensors and equipment has also significantly impacted data acquisition systems like SCADA & Edge devices. This data deluge has necessitated adjustments to accommodate the exponential growth in data volume, variety, and velocity. Traditional SCADA systems, designed to handle limited data points are now struggling to cope with the sheer volume and variety of data generated by advanced sensors, such as phasor measurement units (PMUs), smart meters and intelligent electronic devices (IEDs). While traditional SCADA systems were able to process up to a 1000 data points/second, modern SCADA systems can process up to 100 times this. Data storage has shot up from a few 10s of gigabytes (GBs) to IoT systems capable of storing petabytes (PBs) of data. To address this challenge, SCADA and IoT systems are leveraging edge computing and cloud-based technologies to process data closer to the source, reducing latency and bandwidth constraints. Additionally, technologies like historians or other time-series databases using data compression techniques and edge analytics are being employed to ensure data integrity and prevent data loss. Furthermore, the adoption of industry-specific protocols is ensuring seamless communication between devices and systems, thereby ensuring interoperability and data consistency.

Operational decision making in utilities is shifting from human-centred processes (“in the loop”) to autonomous operations with humans assuming supervisory roles (“on the loop”), as permitted by regulatory frameworks. Automation is no longer limited to control rooms but is increasingly being delegated to intelligent field assets. These assets leverage edge computing, integrated with edge-to-cloud strategies, to enable real-time automation, including self-healing capabilities. The stages for grid automation progresses from a human-centric, conventional grid to a smart grid equipped with advanced monitoring and control systems (Figure 4). In the initial stages, smart grid technologies enable real-time data collection, enhancing situational awareness. As the grid evolves, it integrates autonomous systems with intelligent analytics, allowing for predictive maintenance, asset management, and optimized energy distribution. This transition empowers the grid to make informed decisions with minimal human intervention, ultimately leading to a fully autonomous, self-healing, and highly resilient energy infrastructure. This evolution enhances decision-making, operational excellence, and system resilience.

Communication networks in the energy sector have evolved from slow, proprietary systems to high-speed, interoperable technologies that support real-time data transfer and advanced automation. Legacy communication protocols like microwave, radio waves, and IEC-101 are being replaced by modern systems underpinned by technologies such as Wi-Fi, LTE, fiber-optic, and 5G. Protocols like MQTT and ultra-low-latency 4G/5G networks now enable seamless communication between grid components in real time. These advanced systems allow utilities to manage complex grid dynamics, make faster decisions, optimize operations, and integrate DERs and renewable energy sources more effectively. Distributed smart devices continuously collect and transmit data, delivering unprecedented visibility into grid performance, asset health, and consumer behaviour.

Figure 4: Stages of Grid Automation



Key components of smart grid infrastructure

- **Smart Equipment:** Devices such as intelligent switches, circuit breakers, and transformers equipped with sensors and communication capabilities to monitor performance in real-time. They enable early anomaly detection, operational optimization, and reduce downtime.

- **Intelligent Electronic Devices (IEDs):** Devices like smart meters, IoT sensors, Remote Terminal Units (RTUs), Programmable Logic Controllers (PLCs), barcode readers, and handheld devices that collect asset data in the field and execute remote commands for control

- **Distributed Energy Resources (DERs):** Localized energy generation and storage systems, including PV panels, microgrids, heat pumps, and Electric Vehicle and Charging Stations, which support decentralized power generation and improve grid resilience. DERs can provide a variety of capabilities, including energy efficiency, demand response, power generation, and energy storage to the grid.

- **Virtual Power Plants:** By combining these capabilities, utilities can create smart systems such as non-wire alternatives, microgrids, and virtual power plants (VPPs), optimizing grid operations and enhancing resilience. As the industry prepares for rising demand from data centres, VPP platforms leveraging AI and ML algorithms can aid in managing power generation assets, understanding customer behaviour, and adjusting output levels based on demand and forecast consumption.

- **Energy Storage Solutions:** Smart ESS such as battery energy storage (BESS), pumped hydro, flywheels, etc. that store excess energy and facilitate better integration of renewable sources for a stable energy supply.

- **Grid Edge Devices:** A growing array of behind the meter, third party owned devices that operate at the grid's edge, contributing to distributed energy management and customer-driven energy initiatives.

- **IoT Hub or Data Concentrators:** Devices that enable the management and communication of IoT sensors and devices, facilitating centralized data collection, control, and analysis.

- **Communication Networks:** High-speed communication technologies like 5G, Wi-Fi, LTE, and fibre optics, ensure real-time data transmission between devices, central control systems, and end-users, supporting automated operations.

- **Automation and Control Systems:** Automation solutions like SCADA, ADMS, AMI, and OMS help utilities monitor, control, and optimize infrastructure remotely while responding swiftly to disruptions

- **Data storage and Analytics:** Data generated by smart grid devices is stored on-premises, in the cloud, or at the edge, depending on volume and analytical requirements. Cloud-based platforms offer software-as-a-service analytics to derive actionable insights.

- **Cybersecurity Infrastructure:** Security measures, including firewalls, security gateways, encryption, software-defined networks, and intrusion detection systems, safeguard critical infrastructure and ensure system integrity against cyber threats

- **Interconnectivity and Integration:** Cloud platforms provide APIs, dashboards, and tools that integrate seamlessly with enterprise solutions like ERP, GIS, Historian, and CIS, ensuring a unified approach to grid management.

Case Study

A U.S.-based utility company strategically installed sensors on two 230-kilovolt lines for less than $300,000. This innovative approach eliminated the need for expensive reconductoring, saving approximately $50 million in infrastructure costs. Moreover, the upgrade boosted line capacity by 18% to 19% and reduced annual congestion costs from over $60 million to just $1.6 million. This example highlights how adopting advanced technologies can drive substantial operational efficiencies and deliver significant financial benefits in the energy

These smart grid components serve information to various departments within utilities, including operations and maintenance staff, dispatchers, and decision-makers. Traditional grid management was hampered by inaccurate load forecasting due to outdated statistical models, delayed responses to grid disturbances caused by manual operations, limited real-time monitoring of critical assets, and reliance on multiple applications for decision-making. Today, smart infrastructure overcomes these challenges by enabling real-time visibility, interoperability and integration of applications, and advance analytics for decision-making. This transformation, driven by innovations in infrastructure and technologies, has enabled utilities to optimize operations, improve energy efficiency, enhance service reliability, and meet the growing demand for sustainable energy solutions.

3 Data and Intelligence - The New Utility Fuel

The utility sector has seen a remarkable evolution in its approach to data, driven by technological advancements and changing market dynamics. Data and intelligence serve as the “fuel” that powers innovation enabling utilities to embrace advanced technologies to gather, process, and leverage vast amounts of data. Transitioning from localized, limited analogue systems and manual data readings to interconnected and autonomous digital systems has transformed electric utilities into data-centric enterprises. With the proliferation of IoT devices, smart meters, and advanced sensors, utilities are now generating unprecedented volumes of data. The evolution is not only characterized by significant growth in data sources and volume, but also by speed and variety of data. This data, when harnessed effectively, transforms into actionable intelligence, enabling utilities to enhance efficiency, reduce costs, and improve customer satisfaction.

Table 1: Data Transformation

Category	Past (Pre-Smart Grid Era)	Present (Smart Grid Era)	Future (Autonomous, self-healing, and Beyond)
Data Sources	• Manual meter readings conducted monthly or quarterly • Basic grid sensors with limited deployment • Historical weather data	• Smart meters providing consumption data at 15-minute to hourly intervals • IoT sensors monitoring grid health and power quality • IEDs and network devices • Renewable and distributed energy resources • Real-time weather and environmental data • Customer Applications like Mobile apps and online portals that track consumer energy usage.	• Expanded use of IoT devices, including smart meters and DERs (solar panels, EVs, batteries) • Integration of microgrids, virtual power plants, and 5G-enabled smart appliances • Advanced edge devices and AI-enabled systems for predictive and real-time analytics
Volume	• 100,000 readings per month for a city of 100,000 customers • Data limited to megabytes per day of operational insights	• ~1-2 million data points per day for a city with 1 million customers • Data volumes reaching terabytes per day, driven by IoT devices, sensors, and DERs	• ~10 billion data points per day for larger utilities as smart grid adoption scales • Data volumes expected to grow to petabytes to exabytes per year, necessitating advanced infrastructure for storage and processing
Variety	• Limited: Numerical data (kWh readings) and binary states (on/off) • Lacks diversity in data types	• Diverse: Numerical (consumption), categorical (status), geospatial (GIS), environmental (weather, solar output), and operational data	• Highly Diverse: Multimodal data, including geospatial analytics, video feeds, operational logs, AI-generated forecasts, and customer behavior insights

Speed	• Manual and slow: Data collected periodically with substantial delays in processing	• Near real-time: Data captured at regular intervals (15 minutes to hourly) and processed quickly	• Sub-second speeds: Real-time data streams enabled by 5G, edge computing, and AI-driven processing systems, reducing latency significantly
Storage	• On-premise: Legacy servers with limited capacity (tens of gigabytes per year) • Localized storage with minimal scalability	• Cloud-enabled: Cloud platforms managing terabytes to petabytes annually with scalable and secure data lakes	• Cloud-edge hybrid infrastructure: Distributed systems capable of storing and processing exabytes annually, optimized for real-time analytics and decision-making

To bring some perspective, modern substations, equipped with Intelligent Electronic Devices (IEDs), now generate real-time data streams, producing anywhere from 50GB to 200GB of operational data per day, covering parameters such as voltage, current, power, energy, fault diagnostics, and event waveforms. In comparison, legacy systems typically generated less than 10GB of data daily. Smart meters, once limited to periodic consumption readings, now capture granular usage patterns, power quality metrics, and time-of-use data, providing up to 10,000 data points per day per meter, compared to the previous 1-2 data points per day. Another example can be given for call centre operations that have evolved from managing a few hundred voice interactions per day to handling thousands of multi-channel communications, including email, social media, and chatbot interactions, with an average call centre now processing over 10,000 interactions per day across various platforms. This surge in data diversity and scale demands robust analytics and infrastructure, with utilities now managing petabytes of data annually, to unlock actionable insights and drive innovation.

The journey toward a data-driven utility ecosystem is not without challenges. Not enough penetration of smart devices in the utility sector limits data collection and real-time insights. Aging infrastructure further complicates the integration of advanced technologies, as many legacy systems are incompatible with modern data solutions. Additionally, the sheer volume of data being generated presents challenges in gathering, storing, and processing it efficiently. Issues related to data deluge, cybersecurity, interoperability, and the digital divide must be addressed to fully realize the potential of this new utility fuel. Establishing robust cybersecurity measures, adopting universal data standards, and investing in digital literacy programs are essential steps toward overcoming these hurdles.

Electric grid resilience builds on a digital foundation, with utilities embracing real-time control and operational decentralization (Grid-edge) to maximize value and support decarbonization. Record utility investments in 2023 focused on adaptation, hardening, and resilience, driven by advanced digital technologies. The U.S. leads globally, with digital power sector projects quadrupling since 2021, starting with control technologies and expanding to analytics for forecasting. The surge in distributed devices is exponentially increasing data volumes and processing needs, pushing utilities to adopt AI-powered algorithms to optimize diverse device aggregations. Robust data management is essential, with utilities developing in-house solutions, leasing third-party platforms, or both

3.1 Extracting Value from Data

Emerging technologies find application in several areas within smart energy grid systems, such as power generation infrastructure management, SCADA systems for transmission and distribution operations, AMI, GIS for asset management, and environmental monitoring for carbon footprint management. The business intelligence systems, data analytics tools and cloud-based applications, help utilities manage and analyze financial, customer, and supply chain data. For example, CRM systems powered by data analytics enable personalized customer interactions, while ERP systems optimize resource allocation and supply chain management. These systems integrate various data sources, including customer, operational, financial, and market data, into a unified platform, enabling real-time analytics and insights across all business functions, thereby fostering a competitive edge in today's data-centric business environment

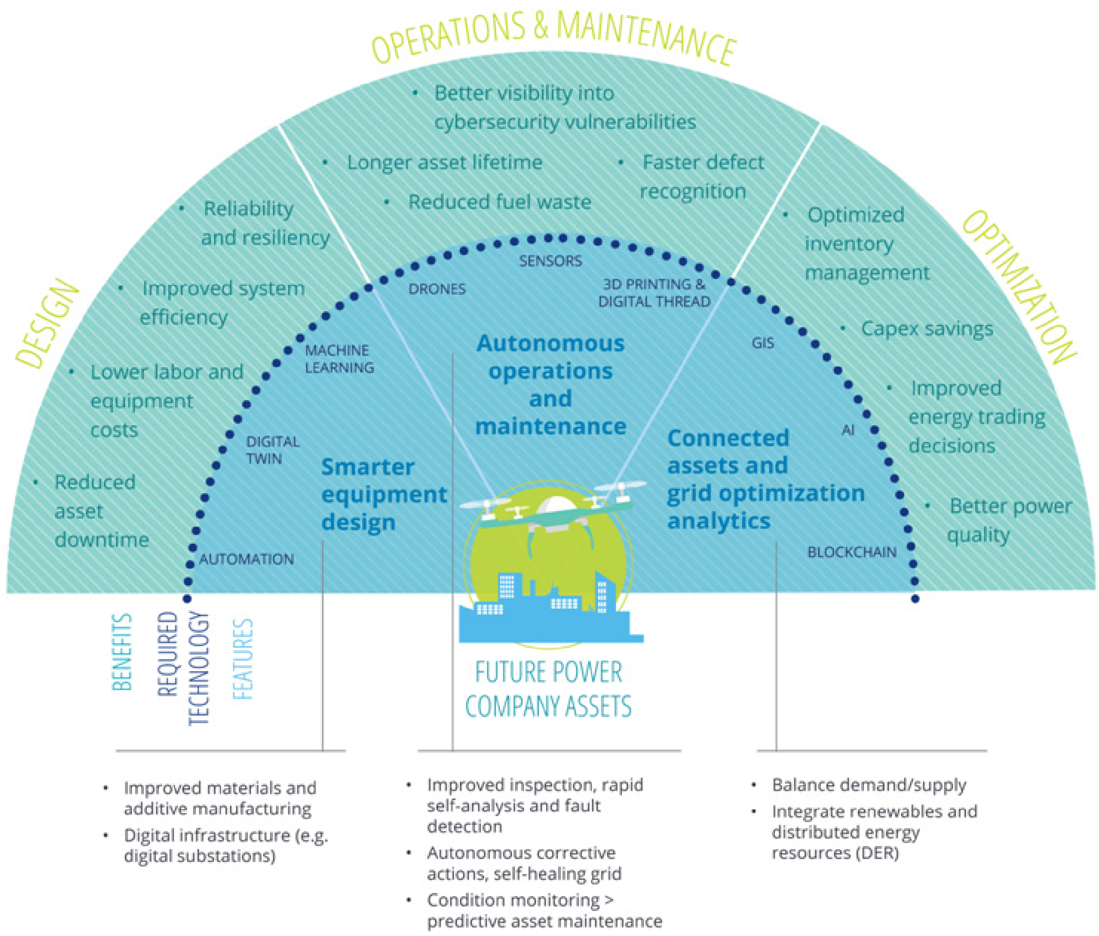
The role of data analytics and AI extends beyond operational efficiencies. Predictive analytics, for instance, allows for proactive maintenance of assets, significantly reducing downtime and extending the lifecycle of critical infrastructure (Figure 5). ML algorithms can forecast energy demand with remarkable precision, facilitating better load management and reducing the reliance on costly peaking power plants. Additionally, AI-driven insights empower utilities to design and implement dynamic pricing models that reflect real-time market conditions, ensuring both profitability and consumer fairness. Data pool allows utilities to create demand response programs that incentivize consumers to reduce energy usage during peak demand, helping balance grid loads.

At the grid level, data intelligence plays a pivotal role in ensuring reliability and resilience. Real-time monitoring of grid performance and the use of digital twins allow utilities to simulate potential disruptions and devise effective mitigation strategies. Furthermore, the integration of DERs such as solar panels and battery storage relies heavily on advanced data systems to optimize their deployment and manage their impact on the grid. Data analytics is crucial for identifying grid vulnerabilities and enhancing performance, ensuring greater reliability.

Case Study

A European Distribution System Operator (DSO) implements an asset analytics platform for risk-based asset management and investment planning. By integrating data on voltage, load, grid topology, and other critical factors, the platform helps operators assess system capacity and plan for future needs. This technology enhances asset utilization and extend asset useful life, while managing DERs, achieving EUR 9.44 million in savings over a decade and improving efficiency by 50% [7].

Figure 5: Assets of the Future for a Power Company



Note: Required technologies listed are not comprehensive.
Source: Deloitte analysis.

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3.2 Managing the Data Deluge

As the electric grid evolves into a more dynamic and decentralized system, it is experiencing an unprecedented surge in data generation, driven by the proliferation of smart devices, faster communications, and scalability. It is not just the volume of data, but the variety and velocity of data generated has also exponentially increased. This data deluge presents a significant challenge for utilities, demanding sophisticated strategies for data management, analysis, and integration. It requires effective handling, transfer, processing, and storage of this substantial data to enable informed decision-making. The challenge of data deluge can be managed with robust storage solutions, real-time processing capabilities, and advanced analytics to extract actionable insights. Ensuring data integrity, security and compliance with regulations further complicates data management efforts.

Utilities must implement scalable data architectures capable of handling terabytes or even petabytes of real-time data from thousands of grid assets and devices. Cloud-based solutions and edge computing are becoming essential in distributing and processing data closer to its source, ensuring faster decision-making while reducing latency. Advanced analytics platforms, powered by AI/ML, can sift through this vast amount of data to extract actionable insights, such as predicting equipment failures, optimizing energy distribution, and enhancing grid resilience during extreme weather events

Ultimately, to manage the data deluge effectively, utilities must adopt a holistic approach, combining cutting-edge technology, secure infrastructure, and advanced data analytics. Realizing their full potential requires strategic investments in infrastructure, workforce training, and the development of interoperable platforms This will ensure the electric grid is not only ready to meet the demands of tomorrow's energy landscape but is also adaptable, resilient, and efficient in managing the complexities of an increasingly data-driven world.

3.3 Integration and Interoperability

The major aspect of managing data deluge is ensuring data interoperability. Open-source platforms and common standards promote adaptable, evolving technological integration and interoperability across the grid. The adoption of standardized communication protocols such as IEC 61850 and common data formats, such as OpenADR for demand response or CIM (Common Information Model) for grid data, enables systems to communicate efficiently across a diverse ecosystem of smart grid technologies. Additionally, OT Data Lakes bridge the gap between operational technology (OT) and information technology (IT) systems. For instance, a major utility reported a 25% improvement in fault detection times and a 40% reduction in data retrieval latency after adopting OT Data Lakes, which enabled faster, more accurate decision-making during critical grid operations.

Integrating applications such as GIS, Asset Performance Management (APM), ERP, CRM, etc. has become essential for maximizing the potential of vast data pools within power systems. These integrations significantly enhance situational awareness and deliver measurable operational benefits. For example, utilities combining GIS and APM have seen a 30% reduction in outage response times and a 20% improvement in resource utilization, demonstrating the tangible advantages of these technologies. A leading utility implementing GIS to optimize its distribution operations had seen its infrastructure evaluation time requirement reduce from 2 weeks to 5 minutes [11]. A major European Utility implemented a CRM solution which saw a 30% faster order processing and a reduction of 60% in the customer onboarding time due to automation enablement [12].

3.4 Enhancing Cyber Resilience in the Digital Age

Traditionally, IT and OT systems operated independently, with distinct purposes and security paradigms. Security in OT environments was often minimal, relying on air-gapped networks and proprietary protocols to isolate systems from external threats. OT security was managed by control system engineers or plant managers, focusing on the integrity and availability of OT systems. However, as digital transformation and IoT technologies have converged IT and OT, traditional security measures are no longer sufficient, necessitating a unified approach to safeguard interconnected infrastructures. Consequently, the Chief Security Officer (CSO) role has evolved to encompass OT security, including grid security. Today, CSOs oversee both the physical and cyber aspects of grid security, recognizing the interconnected nature of modern systems. They must ensure robust cybersecurity measures are in place to manage attack surface area and protect against potential threats.

As the energy sector embraces digital transformation, vast amounts of customer and operational data is being collected that brings unprecedented opportunities and risks. The rise of cyber threats targeting critical infrastructure poses a significant risk to electric utilities. Ransomware, phishing, and advanced persistent threats (APTs) are increasingly sophisticated, targeting vulnerabilities across IT and OT systems. High-profile attacks, such as the Ukraine power grid cyberattack in 2015, underscore the severe consequences of security breaches, including widespread outages and economic losses. Similarly, the 2021 Colonial Pipeline ransomware attack underscored the economic and operational risks associated with compromised energy systems.

Smart devices and infrastructure, integral to modern utilities, often lack robust security protocols, making them attractive targets for attackers. Communication networks that transmit real-time data are susceptible to interception, spoofing, and denial-of-service attacks, jeopardizing grid reliability. Legacy OT systems, not originally designed with cybersecurity in mind, remain particularly vulnerable to modern attack vectors. Additionally, dependencies on third-party vendors for hardware and software components create potential risks through compromised supply chains. These vulnerabilities highlight the need for comprehensive cybersecurity strategies to safeguard smart grid infrastructure.

Several frameworks and standards guide utilities in fortifying their cybersecurity measures. The NIST Cybersecurity Framework provides a structured approach to identifying, protecting, detecting, responding to, and recovering from cyber threats. IEC 62443 focuses specifically on industrial automation and control system security, while the Cybersecurity Capability Maturity Model (C2M2) helps utilities assess and enhance their cybersecurity capabilities. Regulatory advancements, such as NERC CIP v6 standards, emphasize the importance of collaboration and information sharing with industry peers, regulatory bodies, and law enforcement to stay ahead of emerging threats. Adopting these frameworks enables utilities to establish a robust, systematic security posture that addresses current and emerging threats.

Best practices for securing utility infrastructure includes network segmentation to isolate critical systems, regular patching to address known vulnerabilities, implementing multi-factor authentication to enhance access control, encryption, whitelisting, and data protection. Leveraging zero-trust architectures and endpoint protection to secure the rapidly growing network of connected devices. Employee training plays a crucial role in mitigating human error, empowering staff to recognize phishing attempts and other attack methods. Additionally, having well-defined incident response plans ensures swift containment and recovery in the event of a breach. A strategic approach and methodology should be built to protect critical assets that uses people, processes, and technology to become secure, vigilant, and resilient (Figure 6)

Emerging technologies can play a vital role in transforming cyber defence strategies in electric utilities. AI/ML enable proactive threat detection and response through real-time anomaly detection, automated threat hunting, and efficient incident response mechanisms. Future AI systems will autonomously patch vulnerabilities, recover from cyber incidents, and prevent further intrusions, providing robust security with minimal human intervention. Digital twin technology allows utilities to create virtual replicas of their infrastructure, enabling risk-free testing of cyber defences and vulnerability assessments. Blockchain technology enhances security by providing tamper-proof energy transactions, device authentication, and supply chain integrity. Quantum cryptography, though in its early stages, offers unbreakable encryption via quantum key distribution, safeguarding sensitive communications. These technologies collectively fortify the resilience and reliability of electric utilities, ensuring the safety of critical infrastructure in an era of increasing cyber risks.

	PEOPLE	PROCESSES	TECHNOLOGY
SECURE	Evaluating employees and vendors for **cyber risk potential**, including screening for malicious actors; engaging supply chain procurement function to ensure suppliers follow applicable security practices; reducing number of suppliers	**Restricting and documenting** access to control systems and other high-risk cyber/physical interfaces; using unique rather than default system passwords; managing risks that can "walk past" controls, e.g., vendor firmware updates	Air gapping or otherwise separating high-risk processes, including **plant-level IoT infrastructure**, from the business network; requiring software "bill of materials" to track software provenance, or using blockchain to track products through the lifecycle
VIGILANT	Implementing security awareness training for all employees, not just those directly involved with **sensitive systems;** obtaining reliable ongoing supplier risk intelligence	Designing **triage protocols** to systematically identify potential cyber incidents and assess risk severity, including incidents resulting from attacks on supply chain partners	Deploying **automated monitoring software** to identify potential breaches or equipment misoperation/failure; understanding ongoing vendor security practices once product is fielded
RESILIENT	Developing incident response and **forensic training** for key IT and OT personnel to reduce impact and prevent future incursions; participating in drills with key suppliers and partners	Expanding management of **change protocol** to include cybersecurity impacts from operational and business shifts; preparing for attacks on key supply chain partners	**Building redundancy** into key processes through duplication of physical equipment, cyber/physical interfaces, or backups of software; identifying alternate suppliers with compatible technologies in case primary supplier is attacked

Figure 6: Advancing cybersecurity maturity by becoming more secure, vigilant, and resilient

3.5 Regulatory Compliance and Data Governance

Utilities must navigate a landscape of changing regulations that govern everything from data privacy to environmental sustainability. With the convergence of utilities and emerging technologies, regulatory compliance becomes even more complex. Compliance frameworks must be adapted to incorporate emerging technologies, and utilities need to maintain rigorous reporting standards. Automation and data analytics can help ensure that compliance efforts are efficient, accurate, and timely with reduced manual errors. Blockchain can be used for transparent and tamper-proof regulatory tracking. Additionally, regulatory changes must be integrated into strategic planning processes, ensuring that utilities stay ahead of legal requirements and mitigate potential risks.

Digital technologies rely heavily on vast amount of data. Ensuring the protection of individual privacy and maintaining proper governance becomes essential. The ethical handling of customer and operational data is paramount. Utilities must implement a comprehensive data privacy and governance framework for managing data, ensuring that information is collected, stored, and shared in compliance with relevant regulations. Data quality standards should be maintained by implementing protocols for accurate, consistent, and reliable data. The framework could include robust encryption methods, clear data ownership policies, and strong consent protocols, along with transparent auditing processes. Utilities need to establish clear policies around data privacy, data security, and data ownership, ensuring that data is used responsibly and transparently. Utilities must also ensure compliance with regulations like DPDP Act, GDPR and CCPA to protect customer information. Such robust framework would not only safeguard sensitive information but also foster trust between organizations and users. Establishing trust with customers and stakeholders is key to the long-term success of any digital transformation initiative.

4 Emerging Technologies– Its Impact and Promise in Shaping the Next-Gen Utilities

Over the years, the power and utility sector has witnessed a profound shift in its perception and adoption of digital technologies. A key question often posed to industry leaders is: What is the most important digital technology for utilities right now? A decade ago, the answer would have been Operational Technology (OT) encompassing systems like SCADA, ADMS, EMS, OMS, AMI, etc. These technologies, cornerstone of utility operations, provided the backbone for monitoring, controlling, and automating physical processes critical to power generation, transmission, and distribution. The focus was on stability, reliability, and ensuring seamless energy delivery, with minimal emphasis on advanced analytics or predictive capabilities. The systems were largely siloed, designed to optimize operational efficiency in a world where centralization and one-way energy flows were the norm.

Today, however, the answer has evolved dramatically to reflect the transformative potential of emerging technologies such as AI/ML, digital twin, cloud and edge computing, big data analytics, blockchain, etc. In a survey conducted by Deloitte (Figure 7) on the most important digital technology for the power and utility sector, AI/ML stood first (55%) followed by Cloud (21%) and IoT (14%) [14]. Emerging technologies have become indispensable in modern utilities, driving innovations in predictive maintenance, grid optimization, demand forecasting, energy trading, and customer engagement. Unlike OT, which was primarily reactive, advance technologies such as AI/ML empowers utilities to be proactive and predictive, analysing vast amounts of real-time data to uncover patterns, anticipate failures, and optimize resource allocation.

This evolution also represents a broader paradigm shift from "MegaWatts to MegaBytes". Utilities are no longer just energy providers but are transforming into data-driven organizations. The focus is expanding from merely generating and distributing electricity to leveraging vast volume of data available and digital technologies to optimize operations, integrate renewable energy sources, and deliver personalized energy solutions. Data—generated by smart meters, IoT devices, and sensors—is now as valuable as the energy itself, serving as the foundation for informed decision-making and autonomous grid management.

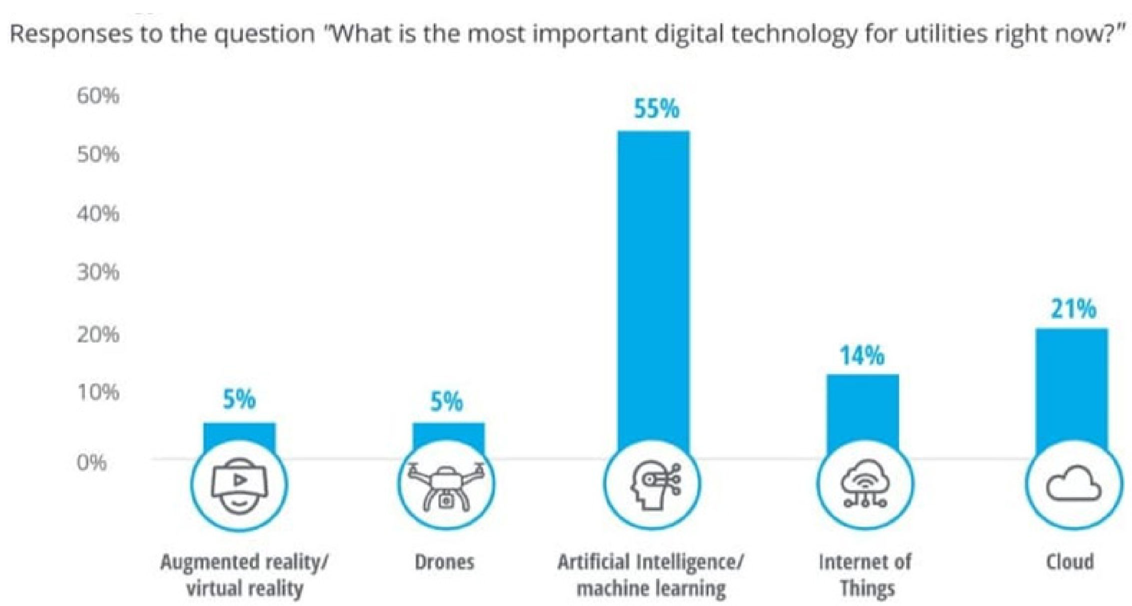


Figure 6: Deloitte Survey Results - The Most Important Digital Technology for Utilities Right Now?

The integration of emerging technologies into this data-rich ecosystem enables utilities to tackle challenges brought by decentralization, decarbonization, and digitalization. These technologies enhance the ability to manage DERs, ensure grid reliability amidst renewable energy fluctuations, and offer advanced analytics to improve both customer experiences and operational efficiency. This section explores the key transformative emerging technologies shaping the utility sector today and their potential impact on the future.

4.1 Artificial Intelligence (AI) and Machine Learning (ML)

From enhancing grid reliability and optimizing energy usage to consumer energy management, AI and ML applications are driving innovation across the utility sector reshaping how utilities operate today and paving the way for a more adaptive and resilient energy ecosystem in the future. AI and ML are pivotal in processing vast amounts of utility data and extracting actionable insights. All major technology providers are offering AI-driven solutions for utilities, including energy management systems and grid analytics. AI and ML applications have significantly enhanced situational awareness, enabling faster, data-driven decisions that reduce asset downtime, optimize energy management, and enhance grid security. A study by Deloitte emphasizes that AI can enhance operational efficiency in utilities by up to 30%.

Energy Efficiency Optimization

Energy efficiency calculations and the corresponding actions to optimise grid operations, were previously done, relying on manual processes including historical data analysis using simple statistical models. Though the process was successful to a certain extent, considering it required coordination in data collection, analysis and audits by engineering teams, operations, and energy managers, there was no simple integrated approach possible. Excel sheet-based calculations and spreadsheets meant there was a lot of people dependency, lack of standardisation and impact of using limited data, resulting in reduced accuracy & efficiency of these models.

With the advent of AI, utilities can now analyse energy distribution and consumption patterns, identifying inefficiencies, thefts and recommending optimization strategies to assist in reducing energy losses, improving renewable energy utilization, and enhancing grid performance.

- Predictive maintenance and Asset Management: Utilities currently leverage AI-driven predictive maintenance to monitor equipment health, using data from sensors and historical patterns to identify potential failures before they occur. This reduces unplanned outages, extends asset life, and lowers maintenance costs. For example, transformers and power lines are monitored for anomalies in vibration, temperature, pressure, and load.

- Real-time demand forecasting and load balancing: AI and ML are used for real-time demand forecasting, considering variables like weather, historical usage, consumer behaviour, and real-time grid conditions. Utilities optimize load balancing by predicting usage trends, energy demand fluctuations and adjusting energy supply dynamically. This improves grid stability and enhances the integration of renewable energy sources.

- Smart Meter Data Analytics: Smart meters provide utilities with detailed consumption data, and AI analyses this data to detect usage trends, identify irregularities, and provide insights into energy-saving opportunities. This helps consumers optimize their energy usage and allows utilities to better understand and manage demand. It also identifies real-time issues such as energy theft, power surges, and failures, hence reduce financial loss, improve grid resilience, and enables rapid restoration.

Technology adoption prospects:

- Autonomous Maintenance Systems: Advanced AI models will allow for fully automated maintenance scheduling, further reducing human intervention.

- AI-Enhanced Grid Self-Healing: Fault detection systems will evolve into autonomous self-healing networks, where grids can isolate faults and reroute power without manual intervention

- Self-Optimizing Grids: AI will enable grids to automatically adapt to changing conditions, such as varying energy demand and weather fluctuations, ensuring maximum efficiency.

- Smart Home Integration: AI-driven platforms will collaborate with smart home systems, allowing consumers to contribute to grid efficiency by managing their energy usage dynamically.

- Predictive Energy Usage: AI models will predict future energy needs based on historical consumption, weather data, and other external factors, improving long-term energy and infrastructure planning and cost forecasting.

- Dynamic Microgrid Management: AI will facilitate the seamless operation of interconnected microgrids, dynamically adjusting energy flows to optimize efficiency.

- Integration with Drones and Robotics: AI-driven drones and robotic systems will perform inspections and maintenance, especially in hard-to-reach areas

- Carbon Footprint Reduction: AI systems will play a key role in tracking and minimizing emissions across the grid by optimizing renewable energy integration and improving energy storage utilization.

- Consumer Behaviour Integration: Advanced ML algorithms will incorporate real-time consumer behaviour patterns, enabling utilities to personalize energy services and improve demand response programs.

Case Study

Enel implemented AI-powered predictive maintenance to optimize the operation and maintenance of its renewable energy assets. This involved gathering real-time data from sensors installed on wind turbines, solar panels, and other equipment. This data includes parameters like temperature, vibration, wind speed, solar irradiance, and power output. Using machine learning algorithms to analyse this data and identify patterns that indicate potential failures or performance degradation. Building models to predict the remaining useful life of components and anticipate potential issues before they occur. Scheduling maintenance activities based on these predictions, optimizing interventions to minimize downtime and maximize energy production. There was a significant reduction in asset downtime, improved safety, optimized maintenance, and extended asset lifespan. [21]

Accelerating Energy Transition

From forecasting using Excel sheets basis updates on the weather forecasts and personal experience to relatively modern ways including development of physical and statistical models, artificial neural networks (ANN), increased focus on data availability for ultra-short-term forecasting (less than one hour) based on IoT sensors and satellite imaging, the science behind forecasting has come a long way. Grid operators, planners, traders & regulatory and compliance teams hence benefited from better forecasting accuracy and enhanced situational awareness to better manage risk and optimise resources.

Today, AI-driven algorithms predict renewable energy generation from solar, wind, and hydro sources, improving grid operators' ability to balance supply and demand. Machine learning models analyse weather forecasts, historical production data, and real-time conditions to optimize renewable energy integration. AI systems help utilities manage the growing integration of electric vehicles (EVs) into the grid by analysing charging patterns and adjusting energy distribution to accommodate these needs. This ensures that charging infrastructure is efficiently used without overloading the grid.

Technology adoption prospects:

- Enhanced Grid Stability: AI will facilitate more accurate predictions of renewable energy generation and help utilities predict and manage fluctuations, further reducing reliance on non-renewable backup power.
- Energy Storage Optimization: AI will enhance the efficiency of ESSs, improving the ability to store surplus renewable energy for later use, maximizing grid stability, and supporting 100% renewable energy grids.
- EV Smart Charging: AI will optimize EV charging times to align with low-demand periods, enabling grid balancing and minimizing charging costs for consumers.
- Vehicle-to-Grid (V2G) Solutions: AI will help facilitate bidirectional charging, enabling EVs to return power to the grid during peak demand, enhancing grid stability and supporting energy storage efforts.

Case Study

National Grid, responsible for managing the UK's electricity transmission network, sought to improve the balance between energy supply and demand, especially with the increasing integration of renewable energy sources. To address this challenge, National Grid partnered with Google DeepMind to develop AI-driven solutions capable of predicting energy demand and supply fluctuations. By analyzing extensive datasets, including historical consumption patterns and real-time inputs from IoT sensors, the AI system provides accurate forecasts that enable proactive adjustments in energy distribution. This collaboration has led to significant efficiency improvements and cost reduction by accurately forecasting energy demand and supply, reducing energy waste, and preventing blackouts and environmental benefits by optimizing the use of renewable energy and decreasing dependence on fossil fuels. [20]

Generative AI (Gen AI) in Utilities

Gen AI is a subset of artificial intelligence focused on creating new content, data, or solutions by leveraging existing patterns and datasets. Unlike traditional AI, which mainly focuses on predicting or classifying data, Gen AI can simulate complex scenarios, design systems, and create synthetic data from scratch. In the utility sector, Gen AI is beginning to play a transformative role in solving complex problems that require advanced simulations, including grid planning, energy forecasting, and system optimization. As the technology matures, its role in enhancing the integration of renewable resources, autonomous operations, and dynamic pricing strategies will be crucial in shaping the next generation of energy infrastructure.

Some of the use cases of Gen AI in Utilities are showcased below:

- **AI-Driven Simulation for Grid Design and Optimization:** By analysing vast amounts of historical and real-time data, Gen AI can generate innovative grid designs that maximize efficiency and resilience, considering factors like load balancing, DERs, and renewable energy integration. These AI-generated designs can help utilities reduce operational costs, enhance grid flexibility, and better prepare for future energy demands.

- **Energy Forecasting and Scenario Generation:** Gen AI's ability to generate new data based on historical patterns makes it especially useful for energy demand and generation forecasting especially from renewable sources, which can be highly variable. Instead of relying on traditional forecasting methods, which are often constrained by existing datasets, Gen AI can create new synthetic data points to simulate a wide range of potential scenarios for utilities to better plan for unpredictable events and ensure more stable energy distribution. In the context of energy storage, Gen AI can create models that simulate how energy should be stored and distributed across a grid in real time. For instance, AI could generate optimized charging and discharging schedules for batteries based on demand, pricing fluctuations, and renewable energy generation.

- **Automated Network Restoration:** One of the more innovative uses of Gen AI in electric utilities is the automated generation of solutions for network restoration after outages. During an outage, Gen AI can simulate various recovery scenarios and dynamically generate strategies for rerouting power, isolating faulted sections, and restoring the network with minimal downtime. These AI-generated restoration plans can adapt to changing grid conditions, taking into account factors like available power, equipment status, and energy demand.

- **Synthetic Data for Training and Simulation:** Utilities often face challenges in obtaining sufficient real-world data for training machine learning models due to privacy concerns, the cost of collecting data, or incomplete datasets. Generative AI can overcome this by creating synthetic datasets that replicate real-world conditions, such as energy usage patterns, fault occurrences, or environmental conditions. This synthetic data can be used to train other AI models, improving predictive accuracy without compromising privacy or requiring extensive data collection. A digital twin powered by generative AI could generate realistic, real-time simulations, helping utilities make decisions on grid performance, failure scenarios, and improvements before implementing them in the physical world.

- **AI-Generated Smart Contracts for Energy Trading:** In energy trading markets, Gen AI could be used to generate smart contracts that automatically execute energy transactions based on predetermined conditions, such as energy price fluctuations or supply-demand imbalances. These AI-generated contracts would not only automate the trading process but also ensure more efficient transactions by continuously adapting to the market, reducing human intervention and improving operational efficiency.

Advent of Agentic AI

The origins of Agentic AI can be traced back to the early 2010s but the concept of autonomous agents and decision-making systems has been around for decades. With the rise of Generative AI, which is reliant on supervised learning basis historical data, Agentic AI emphasises on real-time data collection and processing. It can integrate with various data sources, including IoT devices, sensors, and APIs to access latest information (Figure 8). Workflows will be designed for agentic AI, with humans added at high-value points. This would further enable its users to take informed decisions and take actions to changing situations more rapidly.

Some of the use cases could be around the following areas:

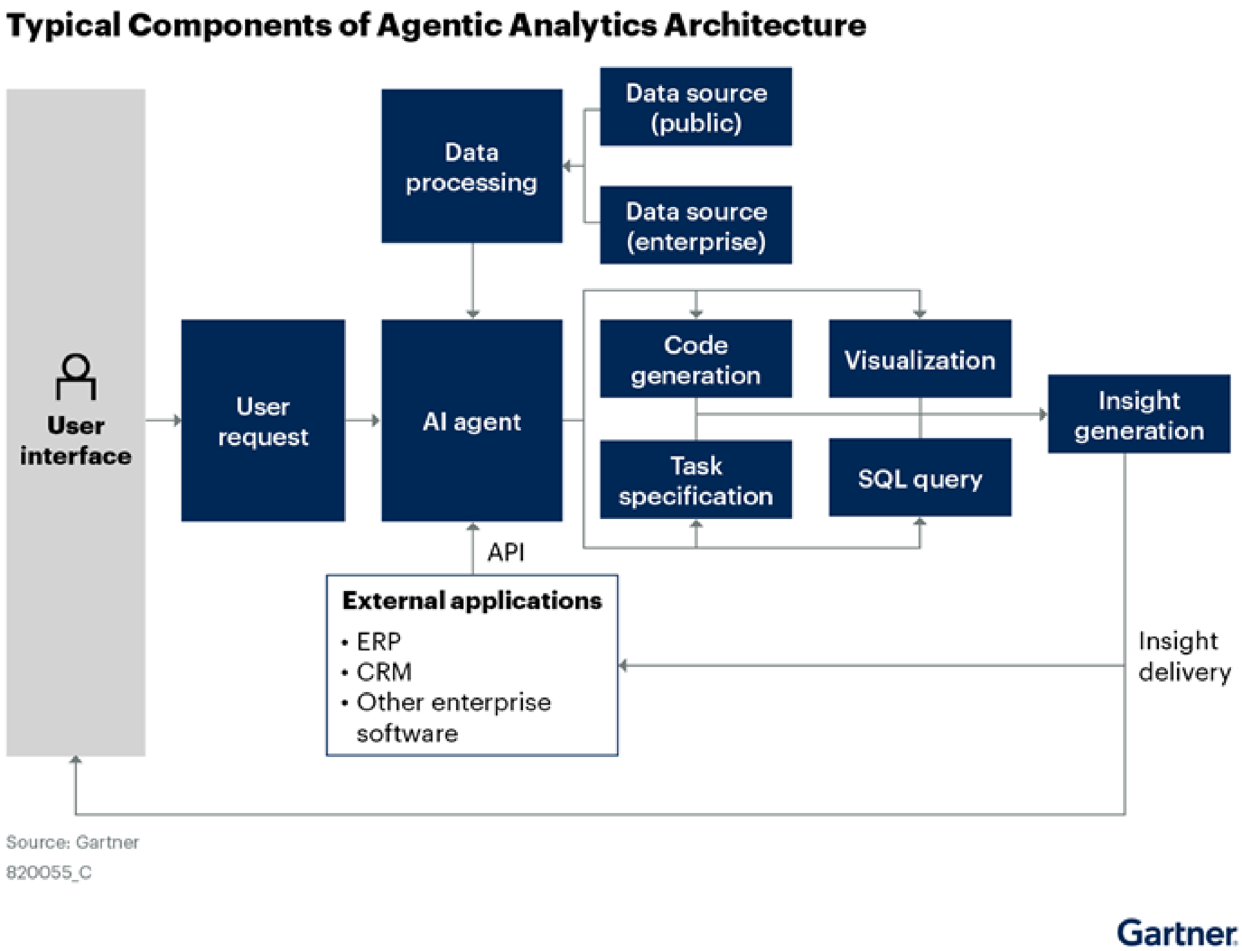
- Condition-based maintenance: AI-powered sensors monitor the condition of transmission and distribution lines predicting potential failure and enabling proactive maintenance. Agentic AI-enabled APIs could connect to systems like Historians and Asset Performance Management and intuitively, without any operator guidance, pull out details which would be relevant to the analysis made, thus enabling more holistic decision making by operations & maintenance teams. Crew management for planning days ahead of the maintenance schedule will enable cost savings and any requirements for pre-site checks could be enabled by drones which will get complete details from multiple systems.

- Anomaly detection: pattern detection and alert generation upon detection of deviation from what is defined as “optimal” equipment behaviour will also be enabled using Agentic AI. With continuous near real-time inputs coming via energy demand, grid conditions and connectivity with ERP would help with proactive event summaries as they happen. Planning and operations teams would then have the ability to validate the incoming inputs for next set of actions – some of which would be provided by Agentic AI as well, basis historical data analysis.

- Demand management: Peak demand prediction periods by integration with weather forecast systems, current demand, historic peak demand analysis and short-term & long-term demand data access would mean grid demand planning teams would be better equipped to optimize energy trading and management. Activities can be proactively planned at the generation end and with their counterparts in neighbouring utilities. In the case of renewable energy too, Agentic AI can optimize integration of solar & wind power to the grid, optimise EV charging, reducing peak demand and strain on the grid.

- Customer experience: Agentic AI are able to analyse consumer energy usage patterns and provide personalised recommendations to optimise energy consumption and reduce waste. Basis this data and the patterns generated, customers can expect utilities to better equip themselves to handle customer enquiries more proactively, resolve issues autonomously thus improving customer satisfaction scores and reducing support costs. Customer service website will become more intuitive, sharing exactly the information sought by the customers via integration with large language model (LLM) tools and would also be capable of suggesting options & optimal plans for next steps, basis customer inputs.

Figure 8: Typical Components of Agentic Analytics Architecture © 2025 Gartner, Inc



Along with the opportunities agentic AI brings, it also poses challenges listed below (Ref: Top Strategic Technology Trends for 2025: Agentic AI from Gartner).

- The danger exists of repeating the robotic process automation problem: organisations created thousands of bots, but nobody remembers what those bots do or why they were built. Employees may additionally deploy their own low-code agentic AI inside the IT/OT stack, which may not meet security or quality standards.

- Agentic AI will make decisions based on its analysis of utilities' data, making plans based on that analysis. From there, it'll act on those plans. This will be dangerous unless an investment is made in the skills, practices, and technologies to deliver trustworthy AI agents. The utilities' data may be of poor quality, further increasing the risk. As well as creating risk, poor data quality and architecture will also inhibit agentic AI's development.

- Although it should help customers, agentic AI could also alienate them if the customer experience is poorly designed. This is where human intelligence is needed. Humans must create customer journey maps to design the ideal customer experience and define guardrails before handing over to AI agents for execution. It'll be a case of trial and error to adjust the agents' settings to achieve optimal results.

- Agentic AI will drive advanced cyberattacks that give rise to "smart malware." This will require innovations to address the unique risks and threats of systems that depend on LLMs and Gen AI. Agentic AI will be at risk from prompt injections, jailbreaks, data security attacks and cyberattacks — including those that other AI agents create and execute.

- The continued growth of agentic AI will also raise serious governance concerns for an organisation as one tries to control a technology that operates autonomously. Orchestration and governance will require advanced tools and strict guardrails.

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4.2 Cloud and Edge Computing

Utilities initial reliance on servers for data storage, processing, and management, required significant capital investment, were costly to maintain, limited in scalability, expensive upgrades, and prone to downtime during peak loads. The evolution to cloud and edge computing has enabled utilities to gather and process big volumes of data, adopt smart grid technologies, integrate renewable energy sources, and implement customer-centric solutions such as mobile apps and dynamic billing. Cloud-based platforms facilitate the integration of AI, ML, and predictive analytics. Edge computing allows handling thousands of sensors & signals at a faster rate along with meta data handling and edge-based analytics capabilities. This further gives rise to a "point-to-point" architecture rather than a "mesh-one" since the number of repeaters required per site are drastically reduced, while maintaining the redundancy of communication lines as well. There are multiple benefits of adopting cloud and edge computing that Utilities are benefiting from including:

- Scalability and Flexibility: Cloud platforms allow utilities to scale their data storage and processing capacity dynamically based on demand.

- Fast Data Processing: Cloud solutions with advanced computing power can process vast datasets in real time, ensuring that utilities can respond swiftly to changing grid conditions.

- Cost Efficiency: By adopting cloud-based solutions, utilities can avoid the heavy upfront investment required for on-premises infrastructure, reduce hardware maintenance costs, and benefit from pay-as-you-go models.

- Real-Time Decision Making: Edge computing processes data closer to its source, reducing latency and enabling rapid responses to critical events. Cloud solutions enable utilities to collect, process, and analyze big real-time data from millions of devices, enhancing grid visibility and operational efficiency.

- Improved Resilience: Cloud platforms offer high availability, disaster recovery, and redundancy, ensuring uninterrupted operations even during critical events.

- Collaboration and Integration: Cloud systems facilitate better collaboration between departments and integrate data from multiple sources, providing a unified view of grid operations

- Cybersecurity: Cloud providers deliver advanced security measures, such as threat detection and compliance tools, safeguarding critical infrastructure from cyber threats.

Looking ahead, the adoption of AI-driven analytics, edge computing, and scalable cloud architectures promises to revolutionize data handling in utilities. These technologies can enable real-time decision-making, predictive maintenance, and personalized consumer engagement. However, achieving these benefits requires strategic investments in infrastructure, workforce upskilling, and the development of interoperable platforms to ensure seamless data integration across diverse systems.

Case Study

Consolidated Edison (Con Ed), a major energy provider in New York, has implemented a big data and predictive analytics platform as part of its digital transformation. The platform aggregates vast amounts of data from sensors, enterprise systems, and external sources like weather and social media into a cloud-based system. By utilizing advanced analytics and machine learning, Con Ed gains real-time insights to enhance operations, customer engagement, and service differentiator. The unified platform enables predictive maintenance, tracks installations, identifies faults, prioritize, and expedite resolution to improves network health. With over 100 million sensors and devices under management, the chosen application stack employs self-tuning ML algorithm to accurately identify network issues and drive operational excellence. The platform provides the only development environment for next-gen AI/IoT applications. [29]

4.3 The Internet of Things

The Internet of Things (IoT), a suite of technologies and associated business processes, connects devices to communicate their status and share information, is revolutionizing real-time monitoring and controls in utilities [16]. An IoT-enabled smart grid, at its very basic nature, provides bidirectional communication and distributed computational capabilities. Gartner predicts that by 2025, IoT will be embedded in over 80% of new smart grid infrastructure investments [17]. IoT devices, combined with big data platforms, allow utilities to collect and analyze vast amounts of data, driving smarter decision-making and enhancing operational efficiency.

Some of the IoT technology application are as following:

- Smart Grids: IoT sensors are critical in smart grid systems, providing real-time data on energy consumption, grid health, and fault detection. These insights help utilities balance supply and demand, reduce energy losses, and integrate renewable energy sources effectively. Operational and maintenance processes benefit from autonomous event detection, isolation, and rerouting, significantly reducing downtime and lowering operating costs. Intelligent assets enhance system intelligence by creating autonomous behaviours from the physical edge to the cloud, including orchestrating customer owned assets behind the meter, collected by a data fabric to leverage open energy data.

- Predictive Maintenance: IoT devices embedded in critical infrastructure, such as transformers and pipelines, continuously monitor conditions like temperature, pressure, and vibration. Coupled with edge computing, these systems can predict equipment failures and trigger maintenance before breakdowns occur, reducing downtime and repair costs. IoT devices also provide real-time location and status updates for assets thus improving asset tracking and management.

- Advanced Metering Infrastructure (AMI): Smart meters equipped with IoT technology enable utilities to collect granular data on energy, water, and gas usage. Consumers benefit from greater transparency and control, while utilities can implement dynamic pricing and demand-response strategies. It also allows consumers to monitor and manage their energy consumption more effectively.

- DER Integration: IoT can play a pivotal role in managing growing volume of DERs such as rooftop solar panels, battery storage, and electric vehicles. Enhanced edge processing will allow for localized decision-making, ensuring seamless integration and grid stability.

- Sustainability Analytics: IoT and edge computing can facilitate detailed tracking of carbon footprints and energy efficiency metrics, aiding utilities in meeting regulatory requirements and sustainability goals.

Case Study

i-DE is Iberdrola's entity responsible for the electric distribution grid in Spain and Portugal. i-DE was looking for a solution that can connect to both legacy and modern IoT sensors, as well as derive insights from video to detect and act upon anomalies. Through a web app, Iberdrola's operators need to receive alerts about the events that take place in the substations. In turn, the platform should help them correlate and cross-analyse the data from the systems that are related to the event, and so an incident is reported for on-site operators to solve the problem. The solution helped reduce the number of trips to facilities whenever an incident occurred by 50%. It lowered unauthorized access by 30% to risky areas by using geo-fencing and location tracking solutions. Also, close to zero unauthorized access to facilities with the implementation of smart keys.

4.4 Digital Twins for Grid Simulation and Planning

A Digital Twin is a virtual replica of physical assets, systems, or processes that allows for real-time monitoring, and simulation. In the utility sector, digital twins are playing a transformative role in the modernization of grid operations, enabling more efficient, reliable, and resilient energy systems. By creating a real-time, digital counterpart of the physical grid, utilities can optimize performance, predict failures, and manage the complexities of transitioning to a smart grid.

The advent of digital twins in grid simulation and planning, has been enhanced by the convergence of real time data, edge and cloud computing. Real-time data generated from IoT sensors, smart meters and grid monitoring systems has enabled utilities to simulate and analyse grid behaviour with good accuracy and detail. On-demand processing of large datasets which facilitate the rapid simulation and analysis complex grid scenarios play a crucial role in the success of the digital twin across grid assets. Edge computing and analytics which are closer to the source, reduce latency and bandwidth constraints, enabling more accurate decision-making further fuelling the adoption of an autonomous grid.

The adoption of digital twins is also key from a change management perspective, where grid planners and operators had to move from looking at simple simulations and analyses to today, complex grid scenarios including renewable energy integration and grid resilience are made possible. This too has been made possible due to the scalability and flexibility offered by the Cloud. The integration of physical systems with digital twins allows utilities to simulate, monitor, and optimize their assets and processes more effectively. Current applications of digital twins include:

• **Real-Time Grid Monitoring and Control:** Digital twins allow utilities to mirror the physical grid, continuously updating the virtual model with data from sensors, automation systems, and other IoT devices. This enables operators to monitor the entire grid's health in real time and detect any inefficiencies or potential issues. In cities like Singapore, digital twins of the electricity grid are being used for real-time performance monitoring, which helps operators adjust to supply-demand imbalances quickly and prevent potential failures.

Predictive Maintenance and Failure Prevention: By using digital twins, utilities can simulate the behaviour of equipment under different conditions and predict potential failures before they occur. This allows for targeted maintenance and repairs, preventing unplanned outages and reducing maintenance costs. Duke Energy has successfully implemented digital twins for transformers and other critical infrastructure, leveraging predictive analytics to optimize maintenance schedules and extend the life of equipment.

Asset Management: Digital twins are used to create a comprehensive virtual inventory of all utility assets, enabling better management of assets across their lifecycle, from installation to decommissioning. This helps utilities maximize asset performance, optimize resource allocation, and reduce operational costs.

<u>Technology adoption prospects:</u>

- **Advanced Grid Simulation and Scenario Analysis:** The use of digital twins will enable utilities to simulate various “what-if” scenarios, such as extreme weather conditions, sudden demand spikes, or grid failures. Utilities can simulate scenarios to test operational strategies without impacting real-world systems. These simulations will allow utilities to optimize grid performance, plan for infrastructure upgrade, and plan for emergencies without risking physical equipment.

- **Integration of DERs and Renewables:** As more renewable energy sources, such as solar and wind, are integrated into the grid, digital twins will help utilities manage the variability of renewable generation. The digital twin will act as a testbed for understanding how renewable energy impacts grid performance, enabling better forecasting and grid balancing. A highly advanced digital twin will allow for seamless integration of DERs, facilitating ESSs, smart appliances, electric vehicle (EV) integration, and microgrids in a way that maximizes the use of clean energy.

- **Enhanced Energy Efficiency and Demand Response:** With further advancements in AI and machine learning, digital twins will be able to not only predict demand but also optimize consumption in real time. By simulating and analysing grid conditions, utilities will be able to better manage demand response and ESSs. This will help balance load, reduce energy waste, and enable more efficient energy distribution across the grid.

- **Smart Grid and Autonomous Operations:** The digital twin’s virtual environment will evolve to integrate with AI-driven systems, enabling smart grid operations that can autonomously adjust energy distribution based on real-time data. The smart grid will be capable of self-healing, rerouting energy during outages, and integrating new technologies such as electric vehicles, solar power, and battery storage.

<u>Case Study</u>

E.ON, a leading private energy company in Europe, implemented "Smartification of Grid Infrastructure" project that involves creating a digital twin, a virtual replica of the grid infrastructure & network. This virtual image contains the topology of the operating equipment used, such as local network stations and transformers. In addition, the status of the grid is visible through the data and can be intelligently controlled. For this purpose, E.ON built state-of-the-art, intelligent equipment that transmits relevant information and receives control commands. Mathematical models enable E.ON to achieve complete monitorability over their medium-voltage level with the recording of just 30 percent of the grid points. It was realized that mere installation of smart meters was not enough. It was crucial that the transmitted information and the data on the operating devices are available in a secure, standardized, and readable form. Only then could it be used develop new solutions for the energy system. For this, E.ON has set up a uniform digital platform for their energy networks. The key benefits real-time insights about asset condition and performance, reduced operational costs and risks, and smarter asset management through improved

4.5 Blockchain for Secure and Transparent Transactions

Blockchain, originally developed for secure digital currency transactions, has found transformative applications in the utilities sector. Its decentralized and transparent nature addresses key challenges, such as inefficiencies, trust issues, and lack of real-time data validation. As integration costs reduce and regulatory frameworks evolve, blockchain adoption is expected to accelerate, fostering a decentralized energy future. Current applications include:

- **Peer-to-Peer (P2P) Energy Trading:** Blockchain enables consumers to trade surplus energy, particularly from renewable sources like rooftop solar panels, directly with peers. Platforms like Power Ledger and LO3 Energy facilitate such transactions, ensuring transparency and reducing intermediaries.

- **Grid Management:** Distributed ledgers provide real-time updates of energy flows, helping utilities optimize load balancing and reduce grid congestion. Blockchain also ensures tamper-proof recording of energy usage, enabling accurate billing.

- **Renewable Energy Certification:** Blockchain simplifies issuing and verifying Renewable Energy Certificates (RECs) or Guarantees of Origin (GO), ensuring traceability and authenticity. Companies like Energy Web Foundation use blockchain to validate clean energy claims.

- **Enhancing security:** Blockchain-based data security provides a secure and transparent platform for sharing threat intelligence among utilities, government agencies, and cybersecurity firms. By enabling a tamper-proof, real-time network, it enhances cyberthreat preparedness and ensures data integrity across the energy sector. In December 2022, a Spanish utility company, Iberdrola implemented a blockchain-based compliance system in 2024. This technology facilitates the exchange of compliance documentation within the company, ensuring a reliable, efficient, and secure process that increases transparency and trust.

<u>Technology adoption prospects:</u>

- **Supply Chain Transparency:** Blockchain enhances traceability in the procurement and delivery of utility assets.

- **Carbon Credits and Sustainability Tracking:** With increasing focus on decarbonization, blockchain can streamline the trading of carbon credits and track sustainability metrics across supply chains. This ensures compliance with global environmental standards.

- **Smart Contracts for Utilities:** Smart contracts, automated agreements executed on the blockchain, can revolutionize utility billing and service agreements. For example, customers could pay based on real-time consumption or specific usage criteria.

- **Electric Vehicle (EV) Integration:** Charging stations utilize blockchain for seamless payment processing and integration with decentralized energy markets, enabling drivers to sell stored energy back to the grid.

Case Study

SP Group, Singapore's leading utilities company, launched a blockchain platform for issuing and trading Renewable Energy Certificates (RECs). RECs are used to track and verify the production and consumption of renewable energy. Blockchain ensures transparency, traceability, and immutability in REC transactions, reducing fraud and administrative costs. The impact was in reduced transaction costs and enhanced trust and traceability in renewable energy markets, encouraging more investment in clean energy. [23]

4.6 Augmented Reality (AR) and Virtual Reality (VR) for Maintenance and Training

By integrating AR and VR, utilities can streamline operations, reduce costs, and enhance both employee and consumer experiences, positioning these technologies as vital components in the digital transformation of the sector. Current applications include:

- **Remote troubleshooting and grid maintenance:** Field technicians use AR-enabled devices to visualize underground infrastructure, such as pipelines and cables, without excavation. This reduces inspection time and minimizes disruptions.

- **Real-Time Collaboration:** VR facilitates real-time collaboration between field staff and remote experts, enabling effective problem-solving for complex technical issues without requiring on-site presence.

- **Training and Simulation:** Immersive VR simulations provide hands-on training for employees, replicating hazardous scenarios like electrical substation repairs. This improves preparedness while ensuring safety.

- **Customer Engagement:** Utilities are leveraging AR to educate consumers on energy usage, helping them visualize consumption patterns and implement energy-saving measures.

<u>Technology adoption prospects:</u>

- **Predictive Maintenance:** Combining AR with IoT sensors and AI algorithms will allow real-time diagnostics and predictive maintenance, preventing failures before they occur. AR could provide real-time overlays of grid performance metrics, aiding in rapid identification and resolution of outages or inefficiencies.

- **Digital Twins:** AR will be integrated with digital twin technology, enabling operators to interact with virtual models of physical assets for enhanced decision-making and scenario planning.

- **Consumer-Centric Services:** Future AR applications may include personalized energy management interfaces, allowing users to visualize their carbon footprint and customize energy solutions interactively.

Case Study

Siemens has AR apps for gas turbines and power generation equipment that guide technicians through maintenance procedures. This is crucial for complex machinery where mistakes can be costly or dangerous. Siemens VE Studio Virtual Training Development Platform utilizes Unity's real-time 3D development platform on which to develop virtual training and field service applications quickly and cost-effectively by using the proven workflow and tools. [24]

GE renewable energy uses AR overlays on wind turbines. Technicians wear tablets or smart glasses, and the AR system shows them step-by-step repair instructions, schematics, and even past maintenance records, directly on the turbine itself. It helps increase productivity, reduce errors and downtime, improve safety, and allows employee skills development to enhance productivity. [25]

4.7 Drones for Grid Maintenance

Robotics and drones have emerged as transformative tools in utility grid maintenance, offering enhanced efficiency, safety, and cost-effectiveness. Drones equipped with high-resolution cameras and thermal imaging sensors are used for inspecting transmission lines, substations, and wind turbines. They detect structural anomalies, overheating, or vegetation encroachment without requiring human crews to scale towers or traverse hazardous terrains. Drones and robotic systems collect data to feed predictive maintenance algorithms, enabling utilities to address potential failures before they occur. This minimizes downtime and reduces repair costs. Also, drones are used for post-disaster assessments. In the aftermath of natural disasters, drones quickly survey damage, providing real-time data for prioritizing repairs and restoring power efficiently.

Case Study

ENGIE is a global energy company that provides services and solutions in the areas of renewable energy, gas, and energy infrastructure. It has been focusing on ground energy activities through various R&D projects led by the Drones & Robots Lab at ENGIE Lab CRIGEN. The Clearance platform provides drone pilots secure access to controlled areas for missions. In wind power, ENGIE has developed an autonomous drone solution for turbine inspections, reducing inspection time by 75%, minimizing downtime, and cutting financial losses. For solar energy, ENGIE Lab CRIGEN supports ENGIE Green in developing offers across all solar project phases, from construction to maintenance. Additionally, the lab partnered with ENGIE Green to assist bird conservationists in locating nests of Montagu's harriers using drones, which sped up the process without damaging crops. Following a successful proof of concept, AI tools will be developed to monitor nest locations, with plans to extend conservation efforts to other species. [26]

Technology adoption prospects:

Automated inspection of power lines and substations: Next-generation sensors, such as LiDAR and multispectral imaging, will improve data accuracy and enable more comprehensive condition monitoring. Swarms of drones working collaboratively with robotic ground units will revolutionize large-scale inspection done automatically and repair tasks, especially in remote or hazardous areas. Solar-powered drones and robots will enhance operational sustainability, aligning with utilities' renewable energy goals.

4.8 Advanced Energy Storage Technologies for Balancing the Grid

Energy storage technologies are revolutionizing the utilities sector by enabling efficient energy management, reducing dependency on fossil fuels, and enhancing grid reliability. With the growing integration of renewable energy sources, advanced storage systems are becoming critical for stabilizing power supply and demand.

- **Next-Generation Battery Storage Systems:**Emerging battery technologies, such as solid-state batteries, offer higher energy density, improved safety, and longer lifespans compared to traditional lithium-ion batteries. These advancements are poised to enhance applications in both residential and industrial energy storage.

- **Grid-Scale Energy Storage Solutions:** Large-scale ESSs are pivotal for balancing energy generation and consumption at the grid level. Round-the-clock (RTC) energy storage ensures uninterrupted power availability by seamlessly integrating renewable generation with advanced storage solutions for consistent energy delivery. Technologies like flow batteries, compressed air energy storage (CAES), and liquid air energy storage (LAES) provide scalable options for long-duration energy storage. Real-world implementations, such as Tesla's Megapack and Form Energy's iron-air batteries, are demonstrating the feasibility of storing energy at the terawatt-hour scale, enabling reliable grid operations even during periods of low renewable generation.

- **Optimized Energy Distribution During Peak Loads:** By deploying batteries at critical nodes in the grid, utilities can store energy during off-peak hours and discharge it during peak demand periods. This approach minimizes the need for peaker plants, reduces operational costs, and enhances energy efficiency.

As energy storage technologies evolve, they will play a crucial role in enabling a carbon-neutral future. For instance, battery storage systems, which are technically capable of addressing many grid challenges, are central in providing system flexibility. In 2050, in the International Energy Agency's net-zero emissions scenario, storage could meet 28.3% of flexibility needs in advanced economies and 27.9% in emerging ones [1]. Innovations such as hybrid ESSs (combining batteries with other storage mediums) and second-life battery applications are expected to reduce costs and environmental impact. Additionally, the integration of AI and machine learning in energy storage management systems will further optimize performance, ensuring that utilities can meet the growing demand for clean, reliable, and affordable energy.

Case Study

Tata Power Delhi Distribution Limited (TPDDL) achieved a significant milestone by empowering the energy sector with the first grid-scale battery energy storage system of 10 MW at Rohini, Delhi. BESS was implemented to stabilize the grid, manage peak load demands better, add system flexibility, and enhance the reliability of power supply in the legion. The state-of-the-art BESS offers an array of applications and features including demand side management, frequency regulation, transmission/ distribution system deferral to build new generation/ distribution capacity and reactive power management. Furthermore, BESS aids in energy arbitrage. The solar plant is available during the day and the perfomance of the same is highly weather dependent. [27]

4.9 Smart Microgrids

Microgrids, which operate independently or integrate seamlessly with the main grid, empower communities to manage local energy demand and provide critical backup during outages, potentially boosting grid resilience. Smart microgrids are self-sufficient networks that integrate advanced technologies, representing a transformative shift in energy distribution and management, enabling localized, connected systems to complement traditional utility grids.

Current applications include:

- **Decentralized Grid Management and Energy Distribution:** Smart microgrids decentralize energy management by operating autonomously or in tandem with the main grid. Equipped with real-time monitoring and control systems, they optimize energy flow between generation, storage, and consumption points. Decentralized grids empower local communities by reducing dependency on centralized power systems, enhancing grid reliability, and minimizing transmission losses. Current deployments include industrial campuses and remote areas where centralized infrastructure is impractical.

- **Enhanced Resilience During Outages and Natural Disasters:** : One of the most significant benefits of smart microgrids is their ability to provide localized power during grid failures or natural disasters. With advanced load-balancing algorithms and islanding capabilities, these systems can isolate themselves from broader grid disruptions, ensuring uninterrupted power supply to critical facilities such as hospitals, emergency services, and data centres.

- **Integration with Renewable Energy and Local Storage Solutions:** Smart microgrids seamlessly integrate renewable energy sources like solar and wind with advanced storage technologies, such as lithium-ion batteries. By balancing fluctuating renewable energy supply with local demand, microgrids enhance energy efficiency and reduce carbon emissions.

Case Study

Smarter Grid Solutions developed a community microgrid for Lac-Mégantic, Quebec, to enhance energy resilience and support the town's transition to renewable energy. The microgrid integrates solar power, battery storage, and advanced grid management technologies. The microgrid has increased energy resilience by 40%, reduced carbon emissions by 30%, and lowered energy costs for the community by 15%. [28]

4.10 Real-World Implementation Challenges of Emerging Technologies in Utilities

To effectively implement the transformative technologies discussed above, there are both technical and systemic challenges that must be navigated. Regulatory constraints, integration with legacy systems, cybersecurity concerns, and financial viability are common obstacles. Here's a breakdown of the key issues tied to technology and broader systemic challenges:

- **Grid Integration Complexities:** Many of the technologies (like smart grids, advanced storage, and IoT) require careful coordination with existing power grid systems. Seamless integration with legacy systems can be slow and complex or requires significant investment in infrastructure upgrades, and maintaining this infrastructure can be costly. This can be both technically challenging and financially prohibitive, especially in older, outdated grids.

- **Financial Viability:** The financial barriers to adopting emerging technologies can be high. Initial costs for hardware, infrastructure, and specialized talent can be prohibitive, especially for smaller utilities or businesses. Furthermore, proving the ROI (Return on Investment) of new technologies can be difficult, especially in complex and capital-intensive sectors like energy. For example, cloud migration can lead to higher-than-expected costs due to the scale of data transfer, storage needs, and the complexity of cloud-native architecture.

- **Standardization:** There's a lack of common standards across IoT and edge devices, communication protocols, data types, etc. which complicates interoperability and integration with existing systems.

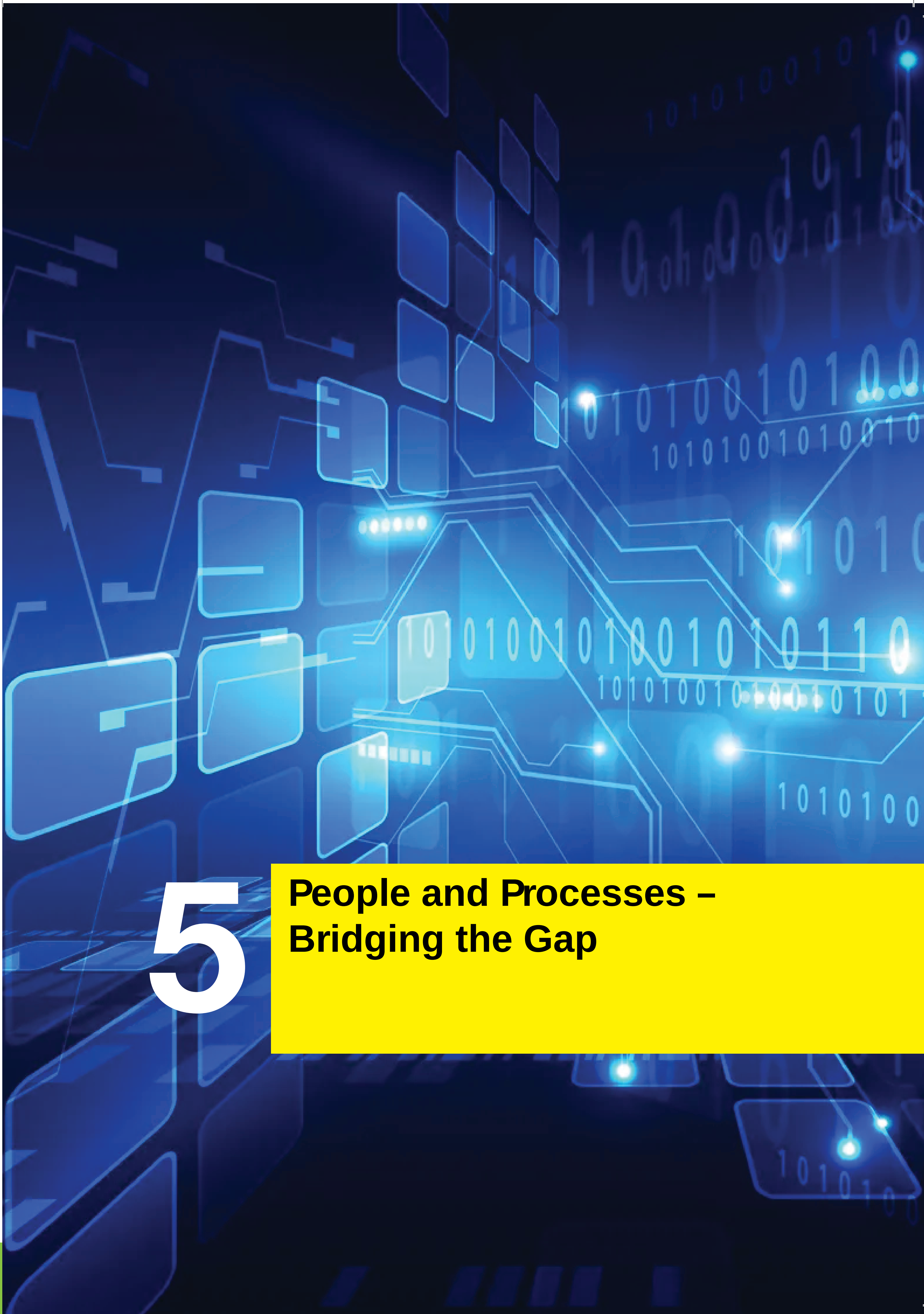
- **Data Privacy and Cyber Security:** IoT and edge devices are vulnerable to hacking, and the vast amount of data they generate raises privacy concerns and cybersecurity risks. Storing sensitive data on the cloud requires compliance with local regulations, which introduces complexity across geographies.

- **Data Quality and Accuracy:** AI/ML systems require high-quality, clean data for effective training. Gathering, maintaining, and curating this data can be resource intensive. To create accurate digital twins, continuous data feeds from physical assets are necessary. Maintaining high-quality, real-time data can be a logistical and financial challenge.

- **Scalability:** The computational power required for AI/ML-based analytics and simulating large-scale digital twins is high, leading to both hardware and operational cost concerns. Processing large volumes of data demands high computational power, which in turn requires energy-intensive data centres. Also, it may overwhelm existing systems and lead to network congestion, necessitating robust data management and analytics infrastructure. Deploying AR/VR technologies at scale requires specialized hardware (e.g., headsets, sensors), which can be expensive.

- **Regulatory Constraints:** Many emerging technologies face regulatory uncertainty. Governments may be slow to create new frameworks or adjust existing ones to accommodate innovations, especially in critical infrastructure like utilities. Some industries may also encounter regulatory fragmentation, where rules differ across regions or countries, making global rollouts difficult. For example, there are limited frameworks to govern AI and ML, especially for critical information infrastructure (CII), leading to uncertainties in how these technologies will be controlled. On the other hand, drone operations in many countries are subject to strict regulations regarding airspace, privacy, and safety, which can delay deployments.

- **User Adoption:** The adoption of new technologies is often slow, particularly when employees need to be trained to use the technology effectively. Public perception and acceptance also play a critical role in technology adoption, especially with concerns around privacy (in case of connected devices) and job displacement (in the case of automation or AI).



5 People and Processes – Bridging the Gap

Utilities are navigating a new era of growth and transformation as they address emerging challenges and rising demand. However, this transformation is not just about technology. It also requires a paradigm shift in how utilities engage with their workforce, customers, and stakeholders. To fully capitalize on the benefits of digitalization, it is essential for people and processes to align, ensuring that digital tools are used effectively, and the workforce is equipped to thrive in new operational environments. For successful implementation and scaling of these technological transformations, utilities must prioritize managing organizational change, upskilling employees, encouraging cross-functional collaboration, while adhering to new processes and ethical guidelines.

5.1 Workforce Upskilling and Training

For technology to be useful, a company needs employees that can use the technology [16]. The rapid pace of technological change in the utility sector requires continuous workforce upskilling and training programs. The integration of AI, IoT, machine learning, and other cutting-edge technologies necessitates a workforce that can leverage these tools effectively. Effectively and efficiently working with these advanced applications will help employees in making informed decisions, getting better and faster outcomes making a positive impact. Hence, resulting in better and faster return on investment made on the technology advancements.

Digital skills have a disproportionately large footprint in core power sector job openings. IT jobs constitute 35% of all utility job openings, the second-highest share of any non-tech industry. More broadly, our data analysis shows that digital skills, which include both IT and analytical skills, are in highest demand in the power sector. On average, each power sector job posting requires two digital skills, one business skill, and less than one of any other type of skill.

Another increasing trend is the use of connected devices and sensors. By improving asset infrastructure and equipping field workers with devices, utilities can help in reducing downtime and improving productivity and safety. Additionally, virtual reality and augmented reality-based trainings and safety procedures will help in simulating high-risk scenarios for training purposes and can help get ready for any issues which may arise in the field. The real-time guidance and data overlays would in turn help field workers improving their safety further.

Utilities should consider ways to further adapt their workforce strategies with a focus on technology empowerment, modular skills development, and cultivating a culture of innovation [9]. Utilities must invest in both technical and soft skill development, ensuring their employees are equipped with knowledge in areas such as automation, cloud, cybersecurity, data analysis, data management, connected technologies, and software development. The shift to Industry 4.0 is also necessitating a workforce evolution which is requiring new skill sets and roles to bridge the gap between traditional operations and the digital landscape. To effectively leverage data-driven insights and implement advanced technologies, the industry needs to gear up for roles including data evangelists and data catalysts. These roles will play a crucial role in championing data literacy, driving adoption of new technologies and helping with transitioning to a more agile and mature utility sector.

Tech-empowered professionals are the need of the hour. Partnering with universities, industry groups, and online education providers can help utilities create programs that support ongoing learning. National Power Training Institute (NPTI) in India has been actively involved in promoting and incorporating AI and ML technologies within the Indian power sector. Specifically, around predictive maintenance and developing AI-powered models to anticipate equipment failures in power plants, reducing downtime and maintenance costs. NPTI actively disseminates knowledge and best practices related to AI and ML through publications, conferences, and industry forums. Such customized learning paths ensures that the workforce remains agile and capable of managing the increasing complexity of systems and technologies

5.2 Talent Acquisition and Retention

As the utility sector embraces new technologies, attracting and retaining skilled talent becomes a priority. The global power industry is grappling with a workforce shortage of 3.9 million, further compounded by a skills gap and heightened competition for talent from both within and outside the energy sector. This talent shortages across different skillset are hindering their ability to quickly adapt and implement advanced solutions (Figure 9). Simultaneously, the industry is contending with career stagnation and an increasing wave of retirements

Figure 9: Talent Shortages Across Seven Clusters

The demand for professionals with expertise in cybersecurity, data analytics, AI, and machine learning is at an all-time high. Leadership development is another key aspect for front-line supervisors. In the energy sector, many leaders are developed internally. Therefore, assessing leadership potential during the recruitment process can help create a strong pool of future leaders from the outset. This approach makes it less likely for leadership gaps to emerge and easier to address as talent is promoted from within.

Utilities need to position themselves as innovative and purpose-driven organizations to attract top talent. They must compete for top talent by offering attractive compensation packages, career development opportunities, and a supportive work culture. Building relationships with universities and industry associations can also help utilities tap into emerging talent pools, while mentorship and internal development programs can ensure long-term employee engagement and satisfaction. To attract and retain employees, utilities should foster an environment that values innovation, collaboration, and professional growth.

- Upgrade workforce analytics to properly anticipate and plug skill gaps.
- Anchor talent strategy on their purpose.
- Collaborate to build sector-wide talent pools.
- Transition from role-based to skill-based talent management.

5.3 Change Management

The integration of emerging technologies within utilities demands a robust change management strategy. As organizations adopt digital transformation, employees must navigate shifts in job roles, workflows, and even corporate culture. A well-defined change management framework ensures that stakeholders—from leadership to field personnel—are adequately prepared and supported throughout the transition. This includes:

- **Communication strategies:** Engaging stakeholders early and often to build trust and ensure alignment with organizational goals.

- **Iterative Rollouts:** Implementing technologies in phases and adjustments to workflows to minimize disruptions, coupled with feedback loops to allow continuous improvement and manage resistance.

- **Leadership Advocacy:** Senior leadership must champion digital initiatives, reinforcing the vision and demonstrating commitment..

5.4 Cross-Functional Collaboration

The successful implementation of emerging technologies requires the breaking down of traditional silos within organizations. Cross-functional collaboration is critical as utilities adopt new technologies that span multiple departments, from IT and operations to customer service and compliance. Facilitating communication and collaboration between these departments enables a holistic approach to problem-solving, design, and implementation. Forming agile teams comprising engineers, data scientists, and business analysts promote collective ownership and accountability towards aligned objectives.

5.5 Field Force Management

Effective field force management is critical for utilities to ensure the smooth and efficient operation of infrastructure. Technologies such as GPS, mobile applications, and asset management systems allow field workers to receive real-time updates, prioritize tasks, and navigate to locations with greater efficiency. Additionally, remote diagnostics and troubleshooting capabilities enable field staff to resolve issues more quickly, reducing the need for return visits. Some examples include mobile tools integrated into ERP systems to create digital work orders to automate task assignments, Geospatial analytics via GIS is used for optimized routing and real-time tracking of field personnel, equipping workers with AR-enabled wearable tech devices enhance safety and productivity. Optimizing field force operations using emerging technologies leads to improved service delivery, lower operational costs, and enhanced customer satisfaction.

5.6 Agile Processes and Methodologies to Leverage Emerging Technologies

As utilities integrate modern technologies, adopting agile processes becomes essential for flexibility and efficiency. Agile methodologies allow for iterative development, continuous feedback, and fast adaptation to changing needs. In the context of emerging technologies, this approach ensures that utilities can quickly respond to shifts in the energy landscape, such as the rise of renewable energy sources, ESSs, or changes in regulatory requirements. Agile processes allow utilities to test and refine solutions in real-time, ensuring that new technologies can be integrated smoothly without disrupting operations or customer service.

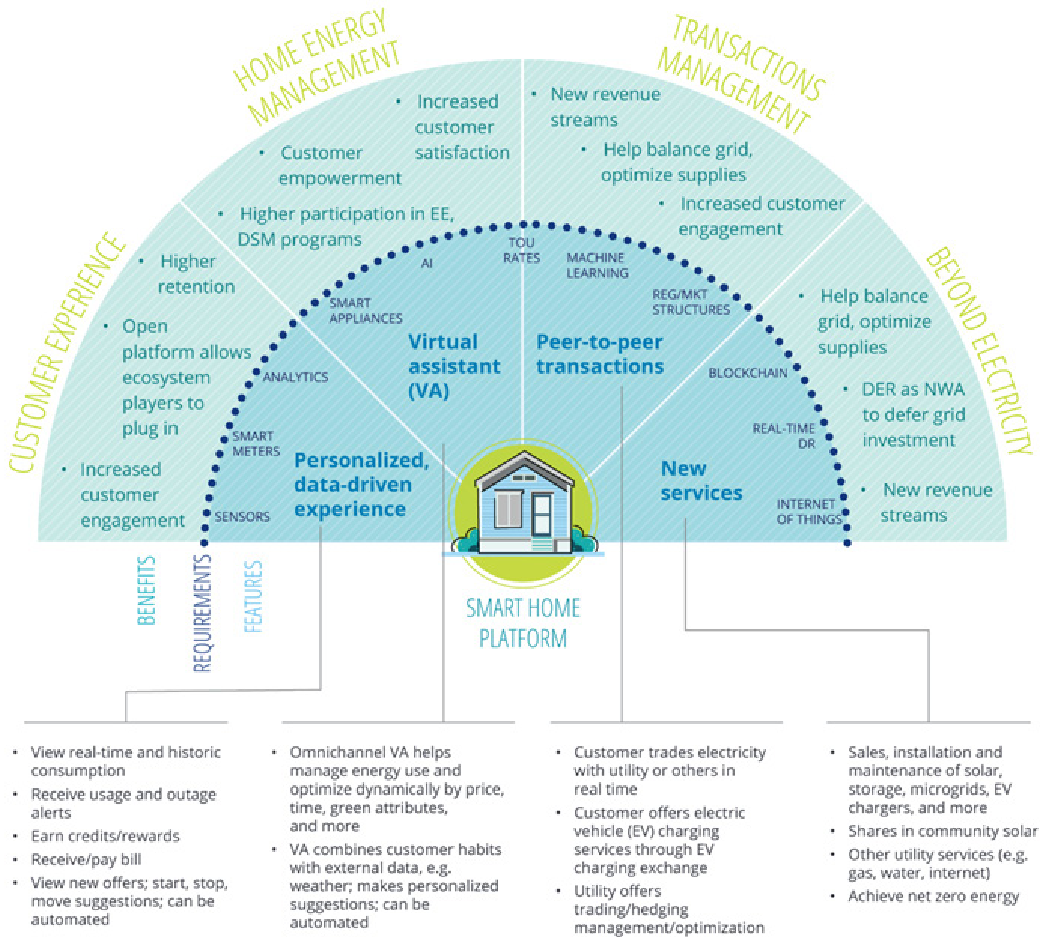
5.7 Consumer-Centric Ecosystem

As utilities move toward more digital-first operations, customer engagement becomes an essential component. Interactive portals, mobile apps, and websites can significantly enhance the customer experience by providing real-time data, personalized notifications, and interactive communication channels. Data intelligence paves the way for a more personalized consumer experience (Figure 10). Utilities can analyze consumption patterns to offer tailored energy solutions, helping customers reduce their carbon footprint and achieve energy savings. Through user-friendly dashboards, consumers are gaining greater control over their energy usage, fostering a more collaborative relationship between utilities and their customers.

The rise of smart technologies and digital platforms has empowered consumers in the energy sector, giving them greater control over their energy usage, costs, and sources. The adoption of smart meters, home energy management systems (HEMS), and mobile apps allows consumers to monitor real-time energy consumption, get outage notifications, pay their bills, adjust usage patterns, and participate in demand response programs. Additionally, the adoption of renewable energy systems like solar PV panels, along with battery storage and smart grids, enables consumers to generate, store, and sell excess energy back to the grid.

Dynamic pricing models, supported by AMI, give consumers more flexibility in choosing when to use energy based on market prices. Programs like dynamic pricing, which adjusts electricity costs based on demand, have been shown to reduce peak load by 15% to 20%, alleviating strain on the grid and potentially saving consumers money during off-peak hours [1]. Utilities are increasingly analyzing consumer behavior to offer tailored services and pricing models, gradually incorporating personalized engagement through digital channels. AI-driven customer support systems and chatbots are improving communication by providing instant responses to inquiries and resolving issues quickly. Moreover, self-service tools are empowering consumers to manage billing, update preferences, and report outages through online platforms or apps. These advancements are creating a more transparent, user-friendly, and responsive energy ecosystem, where customers are better able to manage their energy needs and engage with utility providers efficiently.

Figure 10: Utility Customer of the Future



Note: DER: Distributed energy resources such as rooftop solar, storage batteries, and EV chargers; NWA: Non-wires alternatives; DSM: Demand side management; EE: Energy efficiency; DR: Demand response. Requirements listed are not comprehensive.

Source: Deloitte analysis.

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In the journey from megawatts to megabytes, people and processes form the bedrock of success. By embracing change, fostering collaboration, and prioritizing both workforce development and customer engagement, utilities can harness emerging technologies to create resilient, efficient, and future-ready organizations.

6 Conclusion and Future Outlook

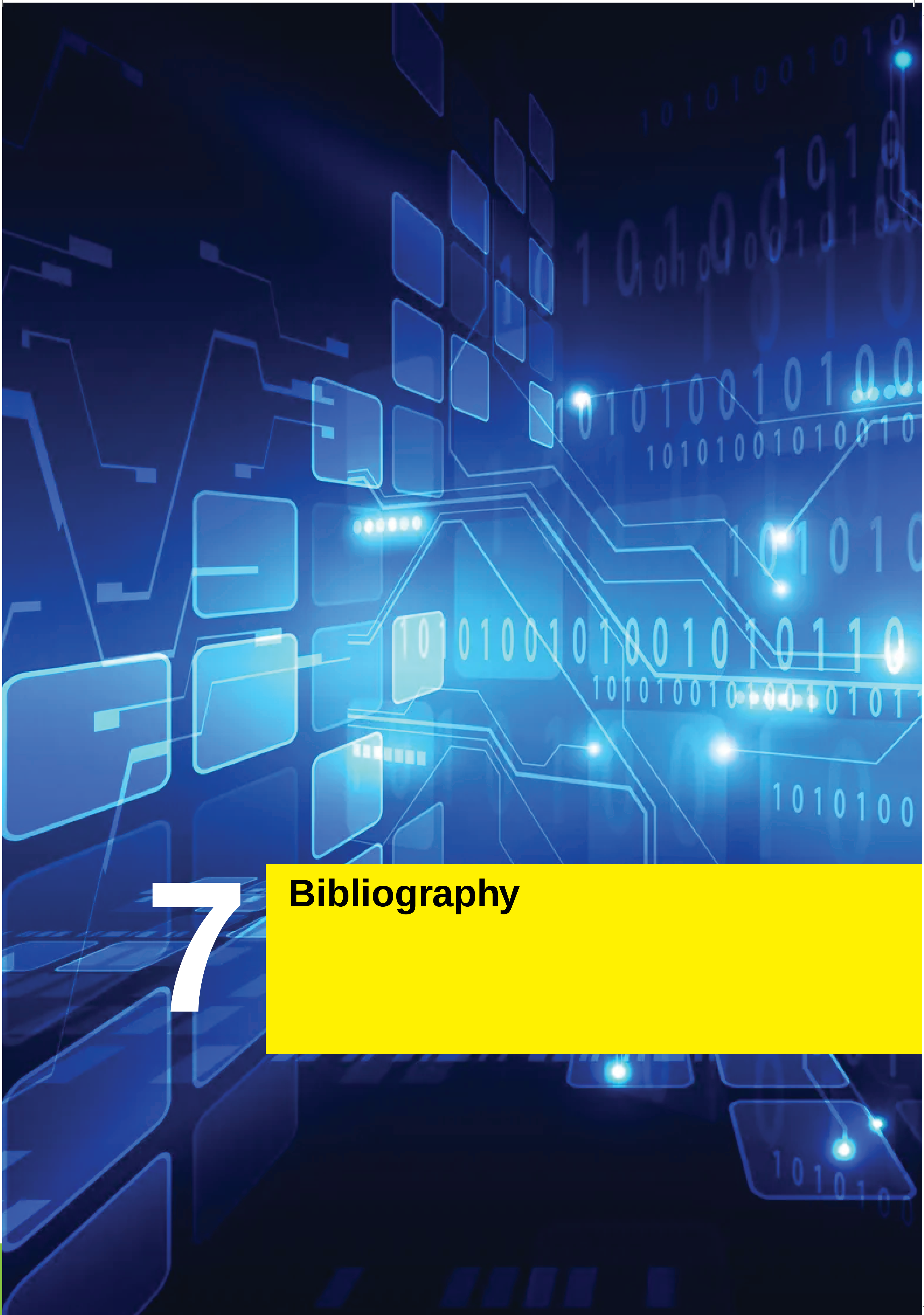
The utility sector is undergoing a paradigm shift, where traditional systems of centralized energy generation and distribution are evolving into dynamic, decentralized, and data-driven ecosystems. The confluence of advanced technologies, such as AI, IoT, and blockchain, with smart infrastructure, is driving this transformation and is central to unlocking new efficiencies, business models, and service offerings. This white paper has outlined the key pillars of this transformation —Smart Infrastructure, Data and Intelligence, People and processes—highlighting how these forces are reshaping the utility sector. bringing about

The continued evolution of this digital landscape, coupled with a strategic focus on cybersecurity, workforce empowerment, and change management, will be critical to ensuring that utilities can thrive in a future defined by innovation, sustainability, and resilience. The transition from “MegaWatts to MegaBytes” signifies a profound transformation where infrastructure, data, technology, and intelligence play pivotal roles in reshaping operations, customer engagement, and sustainability efforts. Enhancing the capabilities of existing OT and IT solutions beyond their core functionalities using emerging technologies like AI/ML, cloud computing, and big data analytics not only enhancing operational efficiency but also enable predictive and proactive capabilities. The focus has expanded from energy generation and distribution to leveraging data for smarter, more personalized solutions. As utilities embrace this digital evolution, the landscape is becoming increasingly complex, interconnected, and dynamic, requiring a concrete framework defining a holistic approach to integrate emerging technologies, data-analytics, and human capital.

Looking ahead, the future of utilities will be defined by continued advancements in digitalization, where smart infrastructure along with AI/ML-driven intelligence, cloud and edge computing, digital twin platforms, blockchain and other emerging technologies become central to utility operations. Energy systems will become more decentralized and flexible, with greater reliance on DERs, renewable sources, smart grids, and advanced energy storage technologies. This will require utilities to adopt new business models, enhance cross-functional collaboration, and prioritize workforce development to keep pace with the evolving ecosystem. In addition, the integration and interoperability of disparate systems and applications will be crucial to ensure seamless data flow and actionable intelligence. Utilities must focus on breaking down silos and fostering a culture of collaboration across departments and organizations to unlock the full potential of their technological investments.

One of the most critical aspects of this future is cybersecurity. As utilities become more reliant on digital tools, the protection of their infrastructure, data, and consumer privacy will become even more vital. A robust cybersecurity strategy, underpinned by proactive threat detection and a zero-trust architecture, will be a non-negotiable necessity to safeguard against growing cyber risks.

In conclusion, the future of utilities lies in leveraging the vast volume of data to create intelligent actionable insights for a resilient, adaptive, innovative, and sustainable energy systems. The journey from “MegaWatts to MegaBytes” is just a beginning, and the possibilities are vast.



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