Alliance for AI, IoT and Edge Continuum Innovation

Energy-6G Convergence: a Perspective

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Executive Summary

The energy sector is undergoing a profound transformation driven by decarbonization, electrification, decentralization, and digitalization. In parallel, 6G is emerging as the next-generation communication paradigm, envisioned not merely as a faster network, but as an intelligent, sustainable, and human-centric digital infrastructure.

This white paper examines the convergence of these two transitions and argues that 6G can become a foundational enabler of future energy systems only if its capabilities are aligned with the safety-critical, long-lived, and sustainability-driven nature of energy infrastructures.

In this paper, the following aspects are covered:

- **Introduction**: Introduces 6G's evolutionary and revolutionary features, emphasising its importance for the energy sector.
- **Relevant 6G Features in Energy Systems**: Details critical 6G capabilities like heterogeneous networks from edge to cloud, ultra-low latency, AI-driven automation, real-time control, and secure infrastructure all vital for energy systems, and their role in future energy systems and assets.
- **Application Areas:** Discusses practical applications of 6G in applications such as smart grids, smart buildings, and industrial energy management.
- **KPIs and Requirements:** Summarize quantitative *Key Performance Indicators (KPIs)* and, increasingly, *Key Value Indicators (KVIs)* that capture not only technical performance but also sustainability and resilience ones.
- **Challenges and Future Perspectives:** Examines issues related to energy efficiency, sustainability, cybersecurity, deployment feasibility, and the technical complexities of converging 6G with energy systems.
- **Conclusions and Road Ahead:** Summarises key insights and outlines future steps for leveraging 6G in transforming the energy landscape.

A central conclusion of this paper is that **observability, security, and sustainability are pre-requisites for trust**. Without standardized energy and carbon metrics that link communication services to measurable energy-system outcomes, the contribution of 6G to the energy transition cannot be credibly assessed. Likewise, security-by-design and resilience-by-design are essential as connectivity becomes embedded in critical energy operations. Consequently, 6G must evolve **in coexistence with legacy systems**, through phased deployment and rigorous validation, rather than disruptive replacement.

If energy and digital infrastructures evolve independently, Europe risks inefficiencies, fragility, and loss of technological sovereignty. Conversely, coordinated evolution positions Europe as a global leader in sustainable, trustworthy cyber-physical systems.

Hence, debating and addressing the convergence of 6G and energy systems presents a strategic opportunity for Europe to strengthen leadership in sustainable digital infrastructure, critical energy resilience, and trustworthy AI-enabled automation if research, industry, policy, and standardization communities act in a coordinated manner.

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List of Acronyms

Acronym	Definition
5G	Fifth Generation Mobile Network
5G-Advanced	Advanced Phase of Fifth Generation Mobile Network
6G	Sixth Generation Mobile Network
AC-OPF	Alternating Current Optimal Power Flow
AI	Artificial Intelligence
AIOTI	Alliance for Artificial Intelligence, Internet of Things and Edge Continuum Innovation
API	Application Programming Interface
ASM	Advanced Sleep Mode
B6G	Beyond six generation
BS	Base Station
CEM	Customer Energy Manager
CNF	Cloud-Native Function
CO_2 / CO_2-eq	Carbon Dioxide / Carbon Dioxide Equivalent
DA	Distributed Automation
DER	Distributed Energy Resource
DR	Demand-Response
DSO	Distribution System Operator
EE	Energy Efficiency
EMS	Energy Management System
ESS	Energy Storage System
ETSI	European Telecommunications Standards Institute
EU	European Union
EV	Electric Vehicle
FDIR	Fault Detection, Isolation and Recovery
FR3	Frequency Range 3
GHz	Gigahertz
ICT	Information and Communication Technology
IEC	International Electrotechnical Commission
IIoT	Industrial Internet of Things
IMT	International Mobile Telecommunications
IoT	Internet of Things
IRS	Intelligent Reflecting Surface
ISAC	Integrated Sensing and Communication
ISO	International Organization for Standardization
ITU	International Telecommunication Union
ITU-R	ITU Radiocommunication Sector
ITU-T	ITU Telecommunication Standardization Sector
KPI	Key Performance Indicator
KVI	Key Value Indicator
LCA	Life Cycle Assessment
LoS	Line of Sight
MCO	Monitoring, Control and Optimization
ML	Machine Learning
MmWave / mmWave	Millimetre Wave
MRV	Monitoring, Reporting and Verification
MTBF	Mean Time Between Failures
MTTR	Mean Time To Repair
NDT	Network Digital Twin
NIS2	Network and Information Security Directive 2
NOC	Network Operations Center
OT	Operational Technology
OTC	Over-the-counter
P2P	Peer-to-peer
PET	Privacy Enhancing Technology
PMU	Phasor Measurement Unit
QoE	Quality of Experience
QoS	Quality of Service
RAN	Radio Access Network
RES	Renewable Energy Source
RF	Radio Frequency
RIS	Reconfigurable Intelligent Surface
SCADA	Supervisory Control and Data Acquisition
SEGM	Smart Energy Grid Management
SLA	Service Level Agreement
SNS	Smart Networks and Services
SOC	Security Operations Center
THz	Terahertz
TSO	Transmission System Operator
URLLC	Ultra-Reliable Low-Latency Communication
V2G	Vehicle-to-Grid
VNF	Virtual Network Function
WAMS	Wide-Area Monitoring System
WT	Wind Turbine
ZSM	Zero-Touch Service Management

1. Introduction

The sixth generation of wireless communication (6G) marks a profound transformation in how humans, machines, and environments connect and interact. Building on the technological foundation laid by 5G, 6G is envisioned not just as a faster or more efficient network, but as an intelligent, sustainable, and human-centric ecosystem. It is designed to serve as the digital nervous system of future societies, with deep integration across domains such as Mobility, Manufacturing, Healthcare and critically: the energy sector.

In parallel, energy systems are undergoing their own transformation. The energy transition, driven by decarbonization targets, electrification of mobility and heating, integration of renewable generation, and the rise of *Distributed Energy Resources (DERs)* is shifting the grid from a predictable top-down structure to a **distributed, dynamic, and connected cyber-physical system**. This transition requires new levels of observability, coordination, resilience, and automation across millions of heterogeneous assets: smart meters, inverters, EV chargers, heat pumps, storage systems, microgrids, and industrial energy management systems. The resulting complexity cannot be managed with legacy communication and control paradigms alone.

Communication networks are increasingly part of critical energy operations. They enable monitoring, control, market interactions, and automated response at multiple time scales, from millisecond-level protection functions to hour-ahead flexibility and day-ahead optimization. At the same time, they introduce new dependencies and risks: cybersecurity threats, performance variability, and energy consumption of ICT infrastructure itself. This creates a dual challenge: (i) enabling advanced energy services and automation, while (ii) ensuring that the connectivity layer remains robust, secure, and sustainable.

Throughout this document, the term "**6G**" therefore refers to a continuum from advanced 5G deployments to future IMT-2030 systems, rather than a single disruptive technology leap. While many of the capabilities discussed in this paper will begin to emerge through 5G-Advanced evolution, their full realization at scale requires 6G-class capabilities, particularly with respect to deterministic latency, massive device density, integrated sensing, and sustainability-aware orchestration. Furthermore, energy systems evolve on 20–40-year cycles; telecom on 5–10-year cycles. 6G must bridge this mismatch.

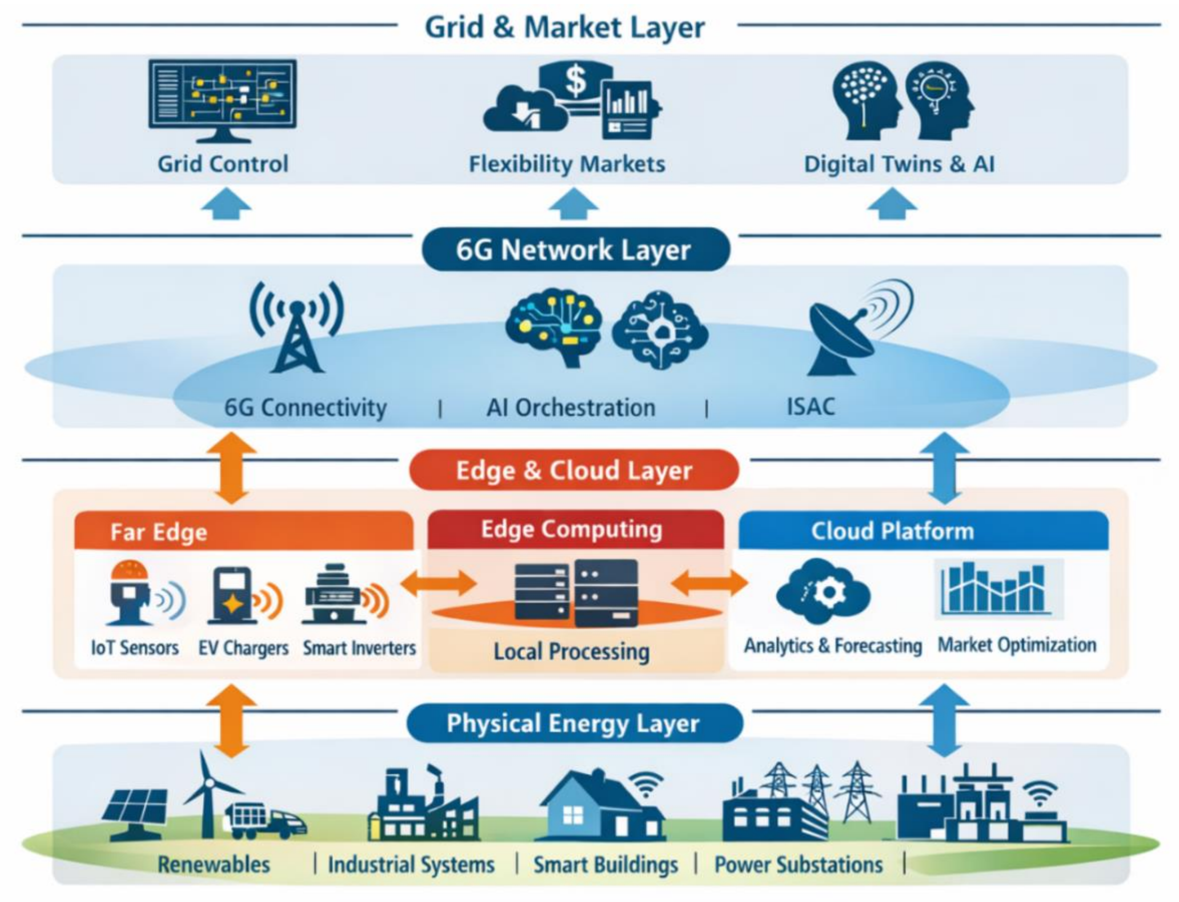

Figure 1: 6G as the spine of future energy systems, integrating data communications, sensing, computation, and control across distributed energy assets.

This white paper addresses that gap. It provides a perspective on how 5G-Advanced and future 6G concepts can support the transformation of energy systems, while acknowledging the constraints, risks, and responsibilities associated with critical infrastructure. The document connects emerging 6G capabilities with concrete energy use cases, outlines key performance and sustainability requirements, and highlights challenges related to security, observability, deployment feasibility, and governance. Rather than promoting 6G as a replacement for existing solutions, it frames 6G as an enabling layer that must coexist with legacy systems and evolve incrementally toward deeper integration as trust, maturity, and regulatory clarity increase.

The paper is structured to progressively connect 6G technological capabilities with the concrete needs of the energy sector. It begins, in this **section** and **section 2,** by outlining the relevant features of 6G and explaining how they map to energy-sector requirements across the full continuum from far-edge devices to edge computing and cloud platforms. It then explores in **section 3** key application areas where this convergence creates tangible value, including smart grids, smart buildings and cities, industrial energy management, and the energy management of the telecommunications infrastructure itself through network digital twins. Building on these use cases, the paper introduces in **section 4** key performance indicator domains and requirement ranges that go beyond traditional communication metrics, explicitly incorporating resilience, security, and sustainability considerations that are essential for critical energy infrastructures. The discussion then turns to the main challenges and future perspectives (**section 5**),addressing issues such as energy observability, cybersecurity and regulatory compliance, and the feasibility of deploying 6G capabilities within the long lifecycles and safety constraints of energy systems, proposing research pathways to overcome, in the short-run, the identified challenges.

Finally, the paper concludes in **section 6** by synthesizing the key insights and outlining a pragmatic road ahead, proposing concrete steps toward pilots, interoperability frameworks, and alignment with ongoing standardization efforts.

1.1. 6G Evolutionary and Revolutionary aspects

At its core, 6G continues the natural evolution of mobile networks:

- **Faster Speeds and Lower Latency:** Building on the performance targets of 5G, 6G aspires to deliver data rates in the hundreds of gigabits per second, with sub-millisecond latency and near-instantaneous responsiveness.

- **Spectrum Expansion:** Evolution will include moving into terahertz (THz) frequency bands (beyond 100 GHz), extending the usable spectrum to accommodate more users and demanding applications.

- **More Intelligent Infrastructure:** The core network and radio access components will become more efficient through enhanced AI/ML integration, smarter edge computing, and adaptive resource management.

- **Greener Networking**: Improved energy efficiency at every layer, from the core to end devices, will help make networks more sustainable while maintaining performance.

The evolutionary improvements envisioned for 6G build directly on the foundations established by 5G and earlier generations, particularly in the pursuit of higher energy efficiency and reduced environmental impact. Although these advances are incremental, they are nonetheless essential. A core principle of 6G evolution is **energy efficiency and carbon-awareness by design**, whereby network components across the radio access network, core, and edge are systematically optimized for energy consumption. AI-based scheduling, traffic prediction, and intelligent resource management will enable networks to dynamically adapt to demand, while advanced sleep modes, adaptive transmission power, and flexible resource allocation mechanisms will further reduce unnecessary energy use, extending and refining the energy-saving features already introduced in 5G. Building on the sustainability trajectory initiated in 5G, 6G networks are expected to integrate more tightly with renewable-powered data centers and base stations, potentially enabling energy sharing and trading between network nodes. In addition, standardized application programming interfaces for monitoring carbon footprints may emerge, allowing operators and vendors to measure, compare, and optimize the environmental impact of network services in a transparent and interoperable manner.

In parallel, 6G will address the energy implications of **spectrum and infrastructure expansion**. The use of higher-frequency bands, such as *millimetre-wave (MmWave)* and THz spectrum, introduces new challenges due to increased path loss and more demanding radio conditions. To mitigate these effects, 6G will evolve sophisticated beamforming techniques, leverage intelligent reflecting surfaces, and adopt energy-aware radio protocols that improve spectral efficiency while limiting additional power consumption.

At the device level, 6G will bring further **efficiency improvements in end devices and sensors**. Low-power chipsets, combined with ambient energy harvesting techniques, will extend device lifetimes, and significantly reduce battery replacement and electronic waste. This represents a natural progression beyond the Internet of Things focus of 5G, enabling large-scale deployments of long-lived and maintenance-free devices.

Beyond evolution, 6G introduces a structural, **revolutionary** shift that is important to address the magnitude of the global energy transition and climate challenge. The energy sector requires more profound, structural change driven by digital disruption.

One such area is **systemic decentralization**, as energy systems shift from centralized generation toward distributed energy resources such as rooftop solar, home batteries, and electric vehicles acting as grid assets. Managing this transformation demands real-time, peer-to-peer coordination across millions of distributed resources, far beyond the capabilities of traditional centralized control approaches.

A second area is **autonomous grid intelligence**. Modern power grids are becoming too complex for conventional SCADA-based control systems to manage effectively. What is required instead are AI-driven, self-managing grids, where edge-based intelligence and ultra-reliable, low-latency communication enable fast, localized decision-making while maintaining system-wide stability.

Equally transformative is the need for **ubiquitous, zero-energy monitoring**. Today's energy infrastructure often lacks fine-grained visibility because deploying and maintaining powered sensors at scale is costly and impractical. A disruptive shift toward battery-free, self-powered sensors deployed across transmission lines, substations, and buildings expected to be interconnected through ultra-low-power 6G links would fundamentally change how energy systems are observed and managed.

Beyond operations, the **lifecycle sustainability of telecom infrastructure itself** must be addressed. Communication networks are significant energy consumers and contributors to electronic waste. Meeting climate goals therefore requires fully sustainable telecom infrastructure, including recyclable materials, modular and upgradeable hardware, and clean energy sourcing throughout the supply chain.

Table 1: Evolutionary vs. revolutionary 6G contributions aligned with IMT-2030, Hexa-X. SNS JU, and AIOTI.

Dimension	Evolutionary 6G Improvements (IMT-2030 / Hexa-X)	Revolutionary 6G Disruptions (SNS JU / AIOTI)	Energy-Sector Benefits (Policy-Relevant Outcomes)
Energy Efficiency by Design	Energy efficiency KPIs (energy per bit, bits/Joule), AI-assisted resource management, advanced sleep modes across RAN, core, and edge	Intent-based, sustainability-aware network control with energy and carbon as first-class objectives (KVIs)	Reduced ICT energy footprint; alignment with net-zero energy systems
Spectrum & Infrastructure Optimization	Advanced beamforming, RIS, and spectrum efficiency for FR2/FR3/THz bands	Integrated Sensing and Communication (ISAC) reducing physical infrastructure overhead	Lower deployment cost; improved observability of energy assets
Carbon-Aware Network Operation	Renewable-powered sites; energy efficiency monitoring interfaces	Carbon-aware routing, orchestration, and workload placement (time/location aware)	Measurable CO_2 reduction; coupling telecom operation with grid decarbonization
Device-Level Improvements	mMTC, low-power devices, energy harvesting	Zero-energy / battery-free massive sensing	Reduced maintenance cost; scalable grid and building monitoring
System Architecture	Optimized hierarchical architectures; edge–cloud continuum	Fully decentralized, peer-to-peer coordination of DERs and prosumers	Scalable integration of DERs; increased system flexibility
Grid Intelligence	Enhanced automation and analytics supporting existing SCADA systems	AI-native, autonomous, self-managing energy systems (distributed intelligence)	Faster fault recovery; higher resilience in renewable-rich grids
Lifecycle & Infrastructure Sustainability	Improved operational efficiency of network infrastructure	Circular, modular, low-embodied-carbon telecom infrastructure	Reduced lifecycle emissions; long-term sustainability and cost savings
Design Philosophy	Performance-driven KPIs with energy efficiency optimization	Human-centric, sustainable, and trustworthy-by-design networks	Public trust; regulatory compliance; societal acceptance

1.2. Relevancy of 6G for the Energy Sector

As the world accelerates toward a decarbonized and decentralized energy future, the role of digital infrastructure is becoming increasingly central. The traditional energy sector, once dominated by predictable, top-down power flows, is now transforming into a complex, dynamic, and distributed ecosystem. In this transition, 6G is poised to become a foundational enabler, offering not just faster connectivity, but a paradigm shift in intelligence, coordination, and sustainability.

From Centralized Utilities to Distributed Energy Ecosystems

The energy transition is characterized by a massive proliferation of Distributed Energy Resources (DERs) such as rooftop solar panels, electric vehicles (EVs), home batteries, and microgrids. Managing this fragmented landscape demands real-time, peer-to-peer communication, which existing networks were not designed to support.

6G, with its support for direct device-to-device communication, ultra-low latency, and AI-native architecture, can unlock seamless coordination between millions of decentralized energy assets. This enables not only operational reliability but also the emergence of local energy markets, where prosumers trade electricity in real time with minimal overhead.

Grid Intelligence Through AI-Native Infrastructure

Modern power grids are becoming too complex for traditional supervisory control systems (like SCADA) to manage effectively. Forecasting energy flows, detecting anomalies, or adjusting loads across thousands of devices requires distributed decision-making, a capability central to 6G's design.

By embedding AI at the network edge, 6G empowers energy systems to become autonomous and adaptive, reacting instantly to changing conditions such as weather shifts, demand surges, or equipment faults. This is crucial for balancing renewable generation and ensuring resilience against disruptions.

Pervasive Monitoring with Zero-Energy Devices

Fine-grained visibility is essential for a smart energy system, but powering and maintaining billions of sensors across grids, substations, and buildings remains a logistical and economic challenge. 6G introduces support for ultra-low-power and battery-free communication technologies, enabling the deployment of self-powered sensors that can monitor environmental and operational conditions continuously, without the need for manual maintenance.

This allows utilities to move from reactive maintenance to predictive asset management, reducing downtime and extending equipment lifespans, all while minimizing the system's own energy consumption.

Sustainable Telecom Infrastructure for a Low-Carbon Grid

The digital infrastructure enabling sustainability can itself become an environmental burden. 6G directly addresses this through its green-by-design philosophy: modular, recyclable hardware; energy-efficient radio protocols; and intelligent orchestration that minimizes energy use across network components. By aligning its own operations with clean energy sources, 6G not only enables a smarter grid but becomes part of it.

The integration of carbon-aware networking, where routing decisions are based on renewable availability or energy impact, further connects the telecom and energy sectors in a mutually reinforcing sustainability loop.

1.3. Stakeholders and Roles in Energy-6G Convergence

The convergence of energy systems and 5G-Advanced/6G communication technologies involves a broad and interdependent ecosystem of stakeholders spanning the energy, telecommunications, digital, and policy domains. Unlike traditional sector-specific deployments, the Energy–6G convergence requires coordinated action across multiple value chains, governance models, and innovation cycles. Clear delineation of roles and responsibilities is therefore essential to ensure interoperability, trust, and sustainable deployment, as provided in

Table 2: Groups of stakeholders across the 6G and Energy domains, and their relevancy in Energy-6G convergence.

Stakeholder Group	Primary Roles	Key Requirements from 6G
TSOs & DSOs	Grid stability, protection, control, regulatory compliance	Deterministic latency, ultra-high reliability, security-by-design, observability
Utilities & Aggregators	DER coordination, demand response, market participation	Massive connectivity, edge intelligence, interoperable platforms
Energy Communities & Prosumers	Local generation, storage, flexibility, peer-to-peer coordination	Low-cost connectivity, privacy-preserving data exchange, trust, and transparency
Telecom Operators & Vendors	Connectivity, edge/cloud orchestration, SLAs	Deterministic services, energy-aware operation, resilience
Technology & Platform Providers	Integration, digital twins, AI, cybersecurity	Open interfaces, standard data models, legacy coexistence
Industrial & Large Consumers	Energy optimization, flexibility, resilience	Network slicing, predictable performance, local control
Research & Innovation Actors	Prototyping, validation, pilots	Testbeds, digital twins, cross-domain experimentation
Standardization & Regulators	Interoperability, safety, compliance	Clear requirements, certifiable architectures
Coordination Platforms (e.g. AIOTI)	Alignment, best practices, policy linkage	Cross-sector governance, reference architectures

Energy system stakeholders are central actors in this convergence. *Transmission System Operators (TSOs)* and *Distribution System Operators (DSOs)* are responsible for maintaining grid stability, reliability, and security under increasingly dynamic and decentralized operating conditions. Their role includes defining functional and performance requirements for communication services supporting protection, monitoring, control, and market operations, as well as ensuring compliance with regulatory and safety obligations. Utilities, energy service companies, and aggregators operate as intermediaries that translate flexibility, demand response, and distributed energy resource capabilities into operational and market value, relying on communication infrastructure to coordinate large numbers of assets in real time.

Energy communities and prosumers are emerging as a distinct and increasingly influential stakeholder group. Citizen energy communities, renewable energy communities, cooperatives, and local prosumer collectives actively participate in generation, storage, consumption, and flexibility provision. Their importance lies not only in contributing renewable capacity, but also in enabling local balancing, peer-to-peer coordination, and social acceptance of the energy transition.

6G is uniquely enabling for energy communities by supporting scalable, low-latency coordination among household-level assets (e.g., PV, batteries, EVs, heat pumps), privacy-preserving data exchange, and participation in local or aggregated flexibility markets. For these actors, trust, transparency, affordability, and data sovereignty are critical requirements, making observability, security, and interoperability particularly important.

Telecommunication stakeholders, including mobile network operators, infrastructure providers, and equipment vendors, are responsible for delivering the connectivity, compute, and orchestration capabilities that underpin 6G-enabled energy services. Their role extends beyond providing bandwidth to offering deterministic, secure, and energy-aware communication services tailored to safety-critical applications. In the context of energy systems, telecom stakeholders must support vertical-specific service level agreements, network slicing, edge computing, and security-by-design, while also ensuring that the telecom infrastructure itself aligns with sustainability and resilience objectives.

Technology providers and platform developers play a bridging role between energy and telecom domains. This group includes vendors of IoT devices, sensors, control systems, energy management systems, digital twin platforms, AI and analytics solutions, and cybersecurity technologies. Their responsibility is to ensure interoperability across heterogeneous devices and systems, support open interfaces and standardized data models, and enable phased integration with legacy infrastructure. In Energy–6G convergence, these actors are critical for translating advanced communication capabilities into deployable energy applications.

Industrial stakeholders and end users, such as manufacturing plants, building operators, mobility providers, municipalities, and large energy consumers, increasingly act as active participants in the energy system. Through electrification, local generation, storage, and flexible consumption, they become both users and providers of energy services. Their role includes adopting and operating 6G-enabled solutions for energy efficiency, resilience, and sustainability, while ensuring that operational requirements, safety constraints, and business objectives are met.

Research and innovation actors, including universities, research institutes, and public–private partnerships, play a foundational role in de-risking and shaping the convergence. They contribute by developing architectures, algorithms, and prototypes; validating concepts through pilots and testbeds; and providing independent assessment of performance, security, and sustainability impacts. Initiatives under the SNS Joint Undertaking, IMT-2030 research, and AIOTI working groups are particularly important for aligning technological innovation with societal and policy goals.

Standardization bodies and regulatory authorities provide the governance framework within which Energy–6G convergence can scale. Organizations such as ITU-R, ITU-T, ETSI, IEC, ISO, and 3GPP define technical standards that ensure interoperability, safety, and global alignment, while national and European regulators establish rules related to critical infrastructure protection, spectrum allocation, data protection, cybersecurity, and sustainability reporting. Their role is to enable innovation while safeguarding public interest, system stability, and consumer trust.

Finally, **multi-stakeholder coordination platforms**, such as AIOTI, play a crucial integrative role. They provide neutral forums for dialogue, alignment, and knowledge exchange across sectors, helping to bridge cultural, technical, and regulatory divides. By fostering shared reference architectures, best practices, and policy recommendations, such platforms support a coordinated and trustworthy evolution of energy and digital infrastructures.

In summary, Energy–6G convergence is not driven by a single actor or technology, but by coordinated action across a diverse ecosystem. Success depends on early collaboration, shared understanding of requirements and constraints, and joint responsibility for security, sustainability, and long-term resilience. This multi-stakeholder perspective underpins the remainder of this white paper, which connects technological capabilities with concrete application areas, performance requirements, and deployment challenges.

2. Relevant 6G Features in Energy Systems

The transformation of the energy sector toward decentralization, decarbonization, and digitalization places unprecedented demands on communication networks. In contrast to traditional telecom use cases, energy systems require **deterministic performance**, **extreme reliability**, and **tight integration between physical infrastructure and digital intelligence**. In this context, 6G introduces a set of foundational capabilities that align closely with the emerging needs of future power systems. 6G promises a step-change: not just in speed or latency, but in how energy systems are monitored, coordinated, and optimized in real time.

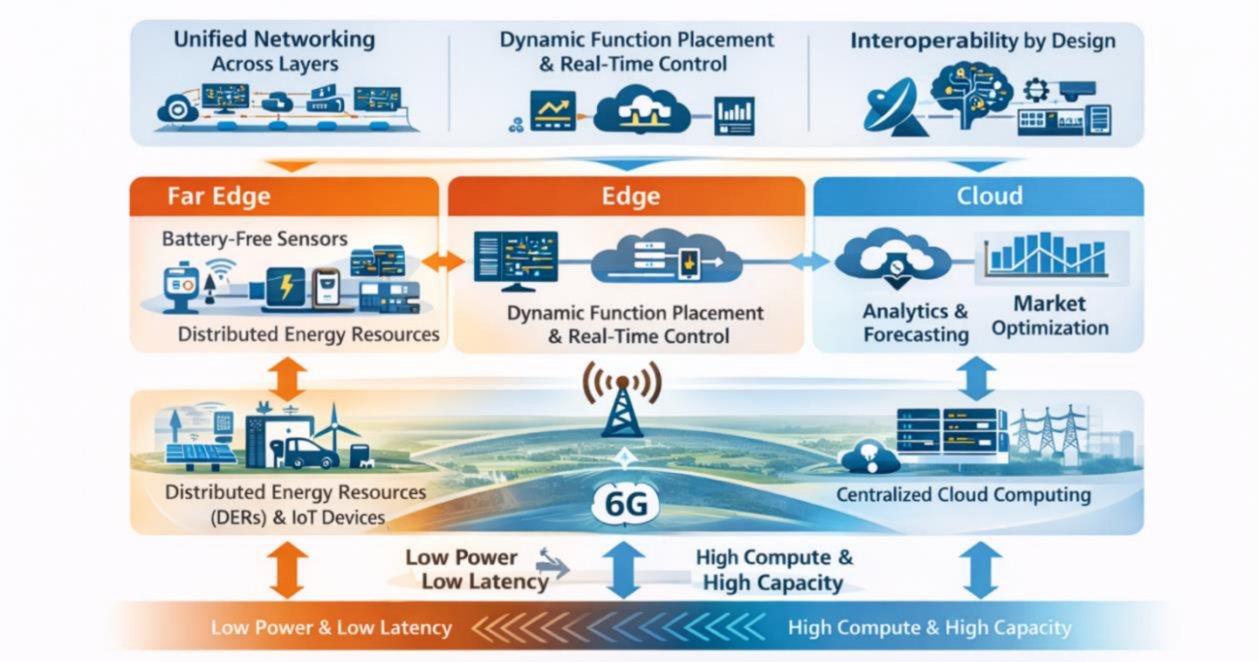

Figure 2: IoT-Edge-Cloud continuum enabled by 6G, supporting interoperable, dynamic, unified energy architectures, covering cyber-physical systems from low-power, far-Edge devices to high-compute centralized cloud environments.

2.1. Heterogeneous Systems, far Edge to Cloud Aspects

Energy systems are heterogeneous in nature. They consist of large, centralized power plants, renewable-powered microgrids, rooftop solar installations, home batteries, electric vehicles, sensors along transmission lines, and more. Managing such a diverse ecosystem requires communication infrastructure that supports a wide variety of devices, from ultra-low-power sensors to high-compute edge servers and centralized cloud analytics.

6G is ideally suited for this challenge. Recent work has shown that beyond-5G/6G networks can support the converged demands of *Industrial IoT (IIoT)* and smart-grid infrastructures through a mix of communication paradigms, including low-power wide-area connectivity, mobile edge computing, and energy harvesting, all within a unified network architecture [29].

Heterogeneous "compute continuum" architectures are emerging: devices at the far edge (e.g., sensors, DER controllers), edge-level nodes (micro-data centers, substations), and centralized cloud backends, expected to be interconnected via 6G and orchestrated intelligently. Such multi-tier architectures enable scalability, flexibility, and resilience, allowing resource-constrained devices to offload heavy computation to edge or cloud layers when necessary, while preserving low-power, low-overhead communication for simple sensing or control tasks [30].

For energy systems especially decentralized ones with large numbers of *distributed energy resources (DERs)*, microgrids, and real-time demand-response, these capabilities are essential. Coordination among DERs, rapid load balancing, fault detection, and autonomous grid reconfiguration all require near-instantaneous communication to maintain stability, avoid blackouts, and manage fluctuations in supply (e.g., from renewables). Moreover, high data rates enable the transfer of richer telemetry, high-resolution sensor data, and even video or image data for remote inspections, predictive maintenance, or anomaly detection across distributed infrastructure. This makes 6G an enabler for both control-plane communication and data-plane analytics.

Such heterogeneous far-edge-to-cloud models are critical for future energy systems that must respond dynamically to supply, demand, and grid conditions without sacrificing scalability, energy efficiency, or reliability. Without deterministic, observable, and trustworthy digital infrastructure, the energy transition will stall, not because of generation limits, but because of coordination limits. Key capabilities of such an architectural model need to include:

- **Unified networking across layers**: Seamless integration of battery-free sensors, embedded controllers, edge AI nodes, and central cloud systems under a single architectural framework.

- **Dynamic function placement**: 6G enables adaptive distribution of computation and control, ensuring that latency-sensitive grid control runs at the edge while large-scale forecasting and optimization execute in the cloud.

- **Interoperability by design**: Support for heterogeneous devices, communication protocols, and energy-sector standards allows legacy infrastructure and next-generation assets (DERs, EVs, microgrids) to coexist and cooperate.

2.2. Ultra-low Latency and High-Speed Communications for Real-time Control

One of the defining promises of 6G is its dramatically improved performance relative to prior generations: orders-of-magnitude higher data rates, massive device density, and sub-millisecond latency in some scenarios [30].

Energy systems increasingly depend on *time-critical communication*, where delays of milliseconds can impact stability, safety, and efficiency. 6G extends beyond 5G's ultra-reliable low-latency communication (URLLC) by targeting sub-millisecond latency with extreme reliability.

Relevance for energy systems includes:

- **Real-time grid protection and control**: Fast fault detection, isolation, and recovery (FDIR) in transmission and distribution networks.

- **Synchronized control of distributed assets**: Coordinated inverter control, frequency stabilization, and voltage regulation across DERs.

- **High-bandwidth data flows**: Support for real-time high-resolution sensing (e.g., waveform-based monitoring, digital twins) and immersive visualization for grid operators.

These features allow energy networks to transition from reactive operation to proactive and predictive control.

2.3. AI-driven automation and Decision making

6G's value goes beyond raw connectivity. Its real power lies in the deep integration of intelligence. A rising set of literature emphasizes that 6G networks will be "*AI-native*": with AI/ML embedded into network management, resource allocation, scheduling, and even at the RAN (Radio Access Network) and edge levels [31][32].

Native AI integration provides the means for energy systems to become autonomous, adaptive, and optimized in near real time. For example, AI-driven 6G smart grids can perform predictive load forecasting, dynamic demand-response, decentralized coordination among DERs, anomaly detection, and even real-time energy trading among peers [33] [35].

However, concerns about the energy cost of AI itself are rising and several research frameworks propose incorporating energy information exposure, leveraging renewable-energy supply, and applying AI/ML-based resource optimization to minimize overall carbon footprint, in a way to balance performance with sustainability. The AI native integration of 6G considers the following key aspects:

- **Edge-based AI for autonomy**: Localized AI agents can make fast decisions on load balancing, fault response, and energy routing without waiting for centralized commands.

- **Collaborative intelligence**: Multiple AI agents running on devices, edge nodes, and cloud platforms can coordinate actions across regions and time scales.

- **Context- and goal-aware networking**: Network behavior adapts based on energy system goals such as grid stability, renewable maximization, or carbon reduction.

2.4. Real-time Monitoring and Control

The smart grid paradigm has transformed the traditional utility-centric power grid into a communication-enabled, distributed, and increasingly autonomous cyber-physical system. Modern smart grids integrate hierarchical power system control with two-way communication networks, enabling coordinated monitoring and control across multiple spatial and temporal scales. This integration is essential to manage DERs, flexible loads, storage systems, and EVs safely and reliably.

Real-time monitoring and control are fundamental to grid stability, particularly in renewable-rich and decentralized power systems. *Distribution automation (DA)* enables distribution networks to detect faults, reconfigure topology, and restore service autonomously, thereby reducing outage duration and improving resilience. At larger scales, *wide-area monitoring systems (WAMS)* combine high-speed communication infrastructure with synchronized measurements from *phasor measurement units (PMUs)* to provide system-wide visibility and support fast, coordinated control actions. These applications impose stringent requirements on communication systems, notably URLLC, which exceed the capabilities of legacy cellular technologies and motivate the adoption of advanced 5G and future 6G solutions [6].

The increasing coupling between smart grids and EV charging infrastructure further amplifies these requirements. EV fleets and associated *energy storage systems (ESSs)* are evolving into flexible, grid-interactive subsystems capable of providing ancillary services, load balancing, and *vehicle-to-grid (V2G)* functionality. Coordinating such systems across multiple substations and heterogeneous assets requires deterministic, large-scale communication and control mechanisms, which remain insufficiently addressed in current deployments [4].

Despite ongoing advances, many grid management systems still lack real-time situational awareness, limiting operators' ability to respond effectively to rapid fluctuations in demand and renewable generation. This often leads to conservative operational strategies that underutilize available flexibility and renewable resources. The advent of 6G networks offers promising solutions by enabling ultra-low latency, high-throughput, and highly reliable data exchange, providing operators with near-instantaneous visibility into grid conditions and supporting faster, more precise control decisions [6].

Beyond connectivity, the integration of artificial intelligence (AI) and machine learning (ML) is central to next-generation grid operation. AI-driven analytics can process large volumes of data from grid sensors and devices to enable predictive maintenance, anomaly detection, demand response, and real-time optimization [7][8]. These capabilities enhance grid reliability, efficiency, and resilience by enabling proactive rather than reactive operation.

In particular, AI and ML techniques support predictive maintenance by identifying early signs of equipment degradation [9], enable advanced demand response through forecasting of consumption patterns and user behavior [10], detect anomalies and abnormal grid behavior [11], optimize dispatch and power flows to maximize renewable energy utilization, and improve energy forecasting by combining weather data, historical trends, and real-time measurements [14]. When combined with high-performance communication, AI-driven forecasting and control allow renewable energy producers and grid operators to anticipate fluctuations in supply and demand and coordinate distributed assets accordingly [28].

Complementing AI, the integration of IoT and intelligent sensing technologies enhances observability across the grid. Smart meters, sensors, and actuators enable real-time data collection and analysis, supporting dynamic load management, efficient integration of renewable energy sources, predictive maintenance, and faster fault detection and recovery [17][19][20][21][22][23]. These technologies are essential for transforming traditional power grids into intelligent and sustainable energy systems, particularly when coupled with reliable, low-latency 6G connectivity.

These developments underscore that real-time monitoring and control in future energy systems depend not only on communication performance, but on the tight integration of sensing, intelligence, and deterministic service guarantees, a theme that recurs across the application areas discussed in Section 3.

2.5. Secure and Resilient Energy Infrastructure

As energy systems become increasingly digital, distributed, and autonomous, **security and resilience** emerge as foundational requirements rather than secondary concerns. The integration of millions of connected assets significantly expands the cyber-physical attack surface of the energy infrastructure. Failures or malicious attacks in this environment can have immediate and large-scale societal impacts [35].

6G is being designed with **security-by-design and resilience-by-design principles**, addressing limitations observed in earlier generations. Recent research highlights that future 6G architectures will integrate security mechanisms natively across all layers, including the radio interface, edge computing, and cloud services. This includes zero-trust networking models, AI-driven threat detection, and decentralized trust management frameworks tailored for massive, heterogeneous device ecosystems.

For the energy sector, these capabilities are particularly relevant. AI-enabled intrusion detection and anomaly detection systems operating at the network edge can identify abnormal behavior in grid devices in real time, supporting early fault detection and cyberattack mitigation. Surveys on AI-powered smart grids in the 6G era emphasize that such distributed intelligence is essential for ensuring both cyber resilience and operational continuity in decentralized energy systems.

Resilience also extends beyond cybersecurity. Climate-driven extreme weather events, equipment failures, and cascading outages pose increasing risks to energy infrastructure. Research on resilient 6G-enabled systems points to self-healing network capabilities, multi-connectivity, and cooperative device communication as mechanisms for maintaining service continuity under adverse conditions. In energy systems, this enables adaptive grid reconfiguration, islanding of microgrids, and graceful degradation rather than catastrophic failure.

2.6. SLA Aspects for the Energy Sector

Energy systems impose fundamentally different service requirements compared to traditional consumer or enterprise telecom services. While commercial networks have historically focused on throughput and best-effort availability, energy applications demand deterministic, mission-critical performance. This shift necessitates a rethinking of *Service Level Agreements (SLAs)* in the context of 6G.

Emerging research on vertical-specific SLAs for beyond-5G and 6G networks highlights the need for **multi-dimensional and context-aware SLA frameworks**, particularly for critical infrastructures such as energy. Relevant SLA parameters extend beyond latency and bandwidth to include reliability, availability, jitter, security assurance, geographic coverage, and even energy efficiency and carbon impact.

For energy operators, SLAs must support:

- **Deterministic latency and reliability guarantee** for grid protection, control loops, and safety-critical operations.
- **Priority-aware service differentiation**, ensuring that grid stability traffic is preserved even during network congestion.
- **Geographically localized guarantees**, essential for distributed substations, microgrids, and rural energy assets.
- **Resilience and survivability metrics**, defining acceptable degradation modes during faults or attacks.

Research on network slicing and intent-based networking in 6G shows how such SLAs can be enforced dynamically. By mapping energy-system intents (e.g., "*maintain voltage stability*" or "*maximize renewable utilization*") to network policies, 6G enables automated SLA negotiation, monitoring, and adaptation throughout the network lifecycle [36].

A particularly novel dimension emerging in recent literature is the integration of energy-aware and carbon-aware SLAs, where service guarantees are optimized not only for performance, but also for sustainability objectives. For example, latency-sensitive energy control traffic may be preferentially routed through network segments powered by renewable energy sources, aligning telecom operations with broader decarbonization goals.

Through these mechanisms, 6G moves SLAs from static contractual constructs to real-time, adaptive performance agreements, tightly coupled to the operational needs of the energy, by building on earlier energy-aware SLA concepts [37].

3. Application Areas

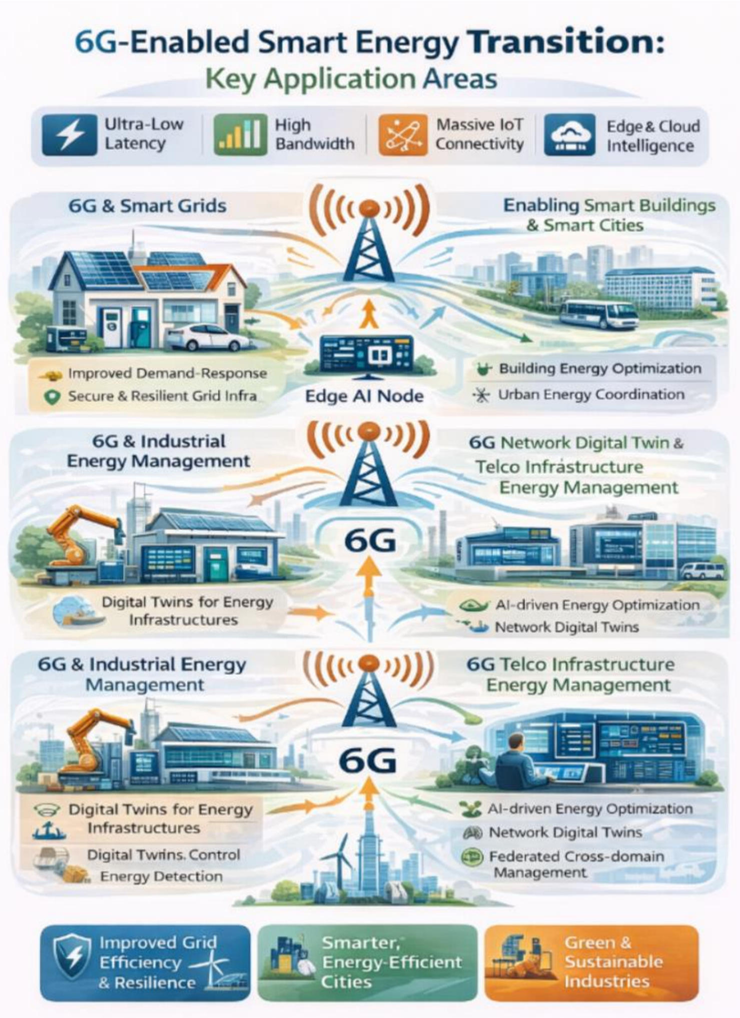

Figure 3: application areas where 6G shall improve demand-response.

This section examines key application areas illustrated in **Figure 3** where 6G capabilities align most strongly with emerging energy-sector requirements and where early deployment can deliver tangible benefits. These application areas reflect priorities identified in **IMT-2030 use-case families**, **Hexa-X vertical integration studies**, and **AIOTI recommendations** on green and trustworthy digital transformation. They also correspond to domains where phased adoption starting from monitoring and optimization and progressively extending toward control can be realistically achieved within existing regulatory and operational frameworks.

The discussion spans the full energy ecosystem, from transmission and distribution grids to buildings, cities, industrial facilities, and the telecommunications infrastructure itself. Across these domains, 6G enables a shift from centralized, reactive operation toward distributed, predictive, and intent-driven energy management, supported by ultra-low latency communication, massive device connectivity, edge intelligence, and integrated sensing. Importantly, the section highlights not only technical feasibility but also operational and policy relevance, emphasizing interoperability, security, and sustainability as prerequisites for large-scale adoption.

3.1. 6G and Smart Grids

Smart grids are the backbone of the energy transition, as they must accommodate the rapid growth of renewable generation, distributed energy resources, electrified mobility, and flexible demand while maintaining system stability and security. The shift from centralized, predictable power flows toward decentralized, variable, and bidirectional operation fundamentally increases system complexity. Achieving decarbonization, resilience, and affordability therefore depends on the ability to observe, coordinate, and control grid assets in near real time across transmission and distribution levels.

6G is uniquely enabling for smart grids because it offers deterministic communication, massive scalability, integrated sensing, and AI-native orchestration tailored to safety-critical cyber-physical systems. Beyond incremental improvements over existing networks, 6G enables fast, reliable coordination among distributed energy resources, supports real-time protection and control functions, and provides the observability required for autonomous and self-healing grid operation. These capabilities position 6G as a key enabler for the next generation of smart grids, where digital intelligence and physical infrastructure operate as a tightly coupled system.

3.1.1. Improved Demand-Response Management

DR is evolving from manually coordinated programs toward fully automated, data-driven, and decentralized control mechanisms. The support of 6G communication technologies can accelerate this shift by enabling reliable, low-latency, and high-bandwidth connectivity that supports distributed intelligence and real-time decision-making.

The ultra-low latency capabilities from 6G yield faster interactions between grid operators, market operators and consumers to engage in dynamic pricing schemes and real-time load shifting, significantly reducing peak demand stress and enhancing grid flexibility. This is even more beneficial when real-time data acquisition from smart meters, electric vehicles, industrial loads, and other smart appliances, can be combined with AI and computational power for automated decision-making and optimization. Distributed intelligent agents can respond to grid signals or market incentives with minimal latency, improving both energy efficiency and grid stability. Those intelligent agents can interact with the grid by controlling energy storage systems, managing flexible loads, and participating in *peer-to-peer (P2P)* or *over-the-counter (OTC)* energy trading markets contributing to a more resilient and self-healing grid.

The heterogeneous computing infrastructure enabled by 6G, from edge to cloud, can dynamically allocate computational resources to nodes that lack local processing power. This supports real-time decision-making for optimizing energy consumption, mitigating congestion risks, and maximizing economic or ecological outcomes for prosumers.

To maximize the integration of renewable energy sources, DR systems can incorporate predictive analytics forecasting demand, modelling user behaviour, and making autonomous decisions to balance supply and demand without manual intervention and making informed decisions. Here, beside model predictive control, reinforcement learning agents have emerged as powerful tools for adaptive DR management. However, bridging the gap between simulation environments and real-world deployments remains a challenge. Techniques such as system identification, fine-tuning, and domain adaptation can benefit from federated learning architectures, where distributed energy systems collaboratively train models without sharing raw data.

Furthermore, a highly interconnected and automated energy ecosystem allows for the deployment of multi-agent systems that could use game-theoretical strategies to optimize for diverse objectives at different layers, namely, financial, environmental, or ethical. These agents can negotiate, cooperate, or compete in decentralized markets, enhancing the overall efficiency and adaptability of the grid[1]

Recent European research initiatives[2,3] illustrate how 6G can enhance DR capabilities in practice:

- **Seamless integration of energy assets** such as developing a plug-and-play *Customer Energy Manager (CEM)* that connects household, building, and industrial devices into a common framework. In a 6G context, this would allow distributed energy assets (EVs, heat pumps, and solar panels) to be coordinated in near real-time.

[1] https://doi.org/10.1109/MSP.2012.2186410
[2] https://independent-energyproject.eu
[3] https://independent-energyproject.eu

- **Smarter forecasting and control through AI-driven models** that combine physics-based and data-driven approaches to forecast energy use and flexibility. 6G's ultra-low latency makes it possible to turn these forecasts into instant control actions, improving responsiveness to fluctuations in demand or renewable generation.
- **Participation in multiple markets by creating an aggregator platform** that enables flexible assets to contribute not only to local grid stability but also to wholesale and balancing markets. With 6G connectivity, these assets could seamlessly interact across markets, making flexibility more valuable and widely accessible.
- **Real-world pilots demonstrating how buildings can adjust consumption** based on grid operator signals and renewable availability. 6G could strengthen such scenarios by enabling faster, more secure communication between operators and energy assets.
- **Scalability and interoperability** ensuring that the developed solutions can scale across countries and sectors. 6G can act as the trusted communication layer that ties these heterogeneous systems together securely and efficiently.

Beyond technical enablement, 6G-supported demand-response systems must operate within regulatory and market frameworks governed by DSOs and TSOs, requiring trusted communication, verifiable data exchange, and auditable control actions to support settlement, compliance, and consumer protection.

3.1.2. Secure and Resilient Grid Infrastructure

Smart grids must be robust against failures, cyberattacks, and unpredictable demand. Besides allowing the inclusion of distributed diverse energy sources and increasing variable loads, the transition to a modern decentralized, flexible and intelligent energy grid must be built on secure, adaptive, and fault-tolerant infrastructure. 6G has the potential to enhance resilience, safety and security on the energy infrastructure by a variety of means.

Resilience in smart grids refers to the system's ability to anticipate, absorb, recover from, and adapt to disruptive events ranging from equipment failures and natural disasters to cyberattacks and market volatility. 6G's ultra-reliable low-latency communication, and integrated sensing capabilities provide the foundation for real-time situational awareness, predictive maintenance, and automated fault response. Nodes equipped with AI models can detect anomalies, forecast failures [16], and initiate corrective actions enhancing operational continuity. Integrating different type of distributed data for ML [16]. To further enhance resilience, digital twins of grid infrastructure can be maintained and synchronized in real time using 6G's high-throughput capabilities. These virtual replicas allow operators to simulate scenarios, test responses, and optimize configurations before deploying changes to the physical grid.

Distributed energy resources, microgrids, and intelligent agents can leverage 6G to coordinate responses across the grid, enabling self-healing mechanisms that isolate faults, reroute power, and restore services autonomously. Distributed Ledger technologies and localized decision-making leveraged by 6G features would play a role increasing scalability, transparency, reliability, customer centricity and reducing computational costs in a transactive energy system [17].

However, increased observability and control also raise privacy and cybersecurity concerns. Studies have demonstrated how easily load disaggregation techniques can infer detailed behavioural patterns from energy data, even when measurements are coarsely aggregated or anonymized [19][20]. As sensor density increases, so does the risk of data breaches and manipulation attacks. This underscores the need for privacy-enhancing technologies such as differential privacy and secure multi-party computation, as well as 6G-native security frameworks, to safeguard sensitive information and ensure the integrity of DR systems.

Finally, as more distributed nodes gain autonomous control capabilities, the threat landscape expands. Cyberattacks could target not just data, but the physical infrastructure itself coordinating attacks across multiple control points to destabilize the grid. To counteract those threats, 6G can support zero-trust architectures, secure device onboarding, and end-to-end encryption to protect communication channels and control signals. Additionally, network slicing enables the isolation of critical grid functions from less sensitive operations, reducing the risk of cascading failures. Ensuring resilience-by-design through secure communication protocols, anomaly detection, and distributed fault tolerance becomes essential in this new era of intelligent energy systems.

Recent German research initiatives, illustrate how 6G can enhance grid reliability and resilience in practice:

- **Developing AI/ML methods that use distributed sensor data to detect faults** in low-voltage grids. 6G enables dense, reliable data collection and edge-based inference, reducing fault localization time and improving operational safety[4].
- **Developing a blockchain-based energy trading platform that enables secure, decentralized electricity markets**. 6G supports real-time transactions and user privacy, improving responsiveness and trust in distributed energy systems[5].
- **Implementing energy digital twins to help municipalities model and optimize** local energy systems. With 6G, these twins can be updated in real time, enabling faster planning, fault detection, and sector coupling across thermal and electrical grids[6].

While autonomy increases responsiveness, 6G-enabled systems must preserve human-in-the-loop control and fail-safe mechanisms for safety-critical interventions.

In addition to communication-enabled resilience, operational resilience also depends on how flexibly the grid can utilize its existing assets during disruptions. For instance, some studies demonstrate that using demand response programs enabled beyond connectivity services of 6G i.e. AI, can significantly enhance a grid's ability to withstand contingencies without requiring major infrastructure upgrades [59]. By coordinating flexible demand, local DERs, and storage resources through hierarchical optimization frameworks operators can minimize load shedding, maintain critical services, and reduce operational costs even during high-impact, low-probability disruptions. When coupled with 6G-enabled distributed sensing and real-time data flows, such predictive intelligence allows system operators to pre-position flexibility, schedule demand response proactively, and reconfigure network flows before critical thresholds are reached. This synergy between AI-driven forecasting, demand response-based flexibility, and ultra-reliable low-latency 6G communication forms a foundation for autonomous resilience, where the grid can not only respond to disruptions but prepare for them in advance, thereby reducing the severity and duration of outages and improving overall system robustness.

Digitalization is becoming a foundational layer of resilience, enabling continuous monitoring, adaptive control, and knowledge-driven decision-making across heterogeneous energy assets. Digital tools ranging from IoT-based sensing and edge–cloud intelligence to interoperable platforms and advanced forecasting create a unified operational picture essential for managing renewable-rich, highly distributed grids. When these digitalization frameworks are enhanced with 6G connectivity, their capabilities expand dramatically: sensors can stream high-fidelity data in real time, Digital Twins can be updated continuously, and decentralized agents can coordinate securely at millisecond timescales.

[4] https://www.fortiss.org/en/research/projects/detail/grid-ml
[5] https://www.fortiss.org/forschung/projekte/detail/best
[6] https://www.fortiss.org/en/research/projects/detail/etwinby

This convergence of digitalization and next-generation communication not only enhances everyday system efficiency but fundamentally strengthens the grid's ability to anticipate, absorb, and recover from disruptions, embedding resilience-by-design into future energy systems [51].

3.2. Enabling Smart Buildings and Smart Cities

Smart buildings and smart cities represent a critical convergence point between the energy, mobility, and digital infrastructure domains. Buildings alone account for a significant share of global energy consumption, and their electrification through heat pumps, EV charging, and smart appliances, for instance, introduces both flexibility and complexity into urban energy systems. Cities, meanwhile, must orchestrate energy flows across buildings, transportation systems, public infrastructure, and distributed renewable generation.

6G provides a unifying communication and intelligence layer enabling real-time coordination across these heterogeneous urban systems. Compared to current connectivity solutions, 6G supports higher device density, deterministic latency, *integrated sensing and communication (ISAC)*, and AI-native management, capabilities that are fundamental for energy-aware urban environments.

At the building level, 6G enables high-resolution monitoring of consumption, occupancy, thermal conditions, and device states, while edge intelligence allows local optimization of heating, cooling, lighting, and EV charging. At the city scale, these buildings become active participants in grid-aware control strategies, demand-response programs, and flexibility markets. Research on 6G-enabled smart cities emphasizes that such tight coupling between communication, computation, and energy systems is key to reducing peak loads, increasing renewable consumption, and improving resilience during extreme events [40].

The increasing penetration of renewable energy sources such as solar and wind fundamentally changes grid dynamics due to their intermittent and location-dependent nature. Effective integration of renewables requires fast communication, adaptive control, and accurate forecasting, areas where 6G offers decisive advantages. With its support for massive machine-type communications and ultra-reliable low-latency links, 6G enables continuous monitoring and fine-grained control of renewable assets across buildings, campuses, and cities. Distributed photovoltaic systems, wind turbines, and community energy storage units can exchange real-time status information and react collectively to grid conditions.

Recent research highlights that 6G's edge intelligence allows local renewable generation to be optimized in coordination with consumption and storage, reducing curtailment and improving self-consumption. Furthermore, integrated sensing capabilities can support environmental monitoring (e.g., solar irradiance, wind conditions), improving short-term generation forecasts and enabling faster corrective actions.

In urban contexts, 6G can support sector coupling by coordinating electrical energy with heating, cooling, and mobility infrastructures. This holistic view is increasingly seen as essential to fully exploit renewable energy potential at scale.

3.2.1. Smart Buildings as Active Energy Nodes

At the building level, 6G enables high-resolution, real-time monitoring of energy consumption, thermal state, occupancy, indoor environment, and device operation. Edge intelligence allows local optimization of heating, ventilation, air conditioning, lighting, storage charging, and EV charging while respecting comfort, safety, and user preferences. Compared to current best-effort connectivity, 6G supports deterministic control loops and predictable performance, which are essential for automation beyond simple monitoring.

Buildings equipped with 6G connectivity can expose standardized, secure interfaces to grid operators, aggregators, or community-level controllers. This allows them to participate in demand-response programs, provide flexibility services, and coordinate with local renewable generation without compromising privacy or autonomy. Importantly, control can remain hierarchical and human-supervised, aligning with safety and regulatory requirements.

3.2.2. Smart Cities and Cross-Domain Coordination

At the city scale, energy systems must be coordinated with mobility, public infrastructure, and urban services. EV charging, public transport electrification, street lighting, water systems, and district heating increasingly interact with the electrical grid. 6G enables this **cross-domain orchestration** by supporting ultra-reliable communication, edge–cloud coordination, and shared situational awareness across municipal systems.

Integrated sensing capabilities allow the communication infrastructure itself to contribute to environmental monitoring (e.g., weather conditions, solar irradiance, wind patterns), improving short-term forecasting and enabling faster corrective actions. Combined with AI-driven analytics, cities can reduce peak loads, increase renewable utilization, and improve resilience during extreme events such as heatwaves or storms.

3.2.3. Energy Communities as a Bridge Layer

Energy communities including citizen energy communities, renewable energy communities, cooperatives, and local prosumer collectives are emerging as a **bridging layer between individual buildings and the wider energy system**. They play a crucial role in the energy transition by enabling local generation, shared storage, collective self-consumption, and peer-to-peer coordination.

6G is particularly relevant for energy communities because it enables:

- **Scalable coordination** of household-level assets (PV, batteries, EVs, heat pumps) with low latency and high reliability.
- **Privacy-preserving data exchange**, allowing community-level optimization without exposing fine-grained individual consumption patterns.
- **Local flexibility markets**, where assets can be aggregated and traded within neighbourhoods or districts before interacting with wholesale markets or DSOs.
- **Resilience and autonomy**, enabling islanded or semi-islanded operation during grid disturbances.

Through 6G-enabled platforms, energy communities can operate as semi-autonomous subsystems that support grid stability while empowering citizens to actively participate in the energy transition. This contributes not only to technical efficiency but also to **social acceptance, trust, and democratic participation**, which are increasingly recognized as critical success factors.

3.3. 6G and Industrial Energy Management

Industrial facilities are among the largest and most complex energy consumers, with stringent requirements for reliability, safety, and predictability. Electrification, flexible manufacturing, and the integration of local generation are driving a shift toward more intelligent and adaptive energy management approaches [41].

6G enables industrial energy systems to move beyond centralized monitoring toward distributed, real-time optimization. Factories, logistics hubs, industrial parks can coordinate energy consumption, storage, and on-site generation with millisecond-level responsiveness, while ensuring strict service guarantees through network slicing and deterministic communication. 6G network slicing further supports deterministic isolation of mission-critical industrial energy traffic.

3.3.1. Supporting Digital Twins for Energy Infrastructures

Digital twins, i.e., virtual representations of physical systems continuously updated with real-world data, are becoming a cornerstone of industrial energy management. In energy-intensive industries, digital twins are used to optimize process energy efficiency, evaluate operational scenarios, and predict the impact of equipment or production changes [41][44][45][46]. Their effectiveness, however, is fundamentally dependent on the timeliness, accuracy, and richness of data exchanged between the physical and virtual domains [44].

6G enhances digital twins by enabling **continuous, high-resolution synchronization** between physical assets and their virtual counterparts. Beyond conventional communication advances, 6G ISAC is a native capability, allowing the radio interface itself to act as a distributed sensor. ISAC enables precise localization, motion detection, and environmental sensing directly through the communication infrastructure, reducing reliance on dedicated sensing hardware while improving observability of industrial equipment and processes. This is particularly relevant in harsh or complex industrial environments where deploying and maintaining extensive sensor networks is costly or impractical.

In combination with massive device connectivity and extreme data rates, ISAC allows digital twins to ingest rich, real-time state information from machines, production lines, and energy assets. These capabilities support near–real-time updates of asset conditions, power flows, thermal states, and operational dynamics, enabling twins to move from static or periodic models toward truly living representations of industrial systems.

Ultra-low latency and edge intelligence, also intrinsic to 6G, ensure that analytics and control loops can be executed close to the physical process. Edge-based AI models can perform fast inference, anomaly detection, and control optimization, while cloud platforms host computationally intensive simulations, long-term optimization, and cross-site coordination. This hierarchical architecture allows digital twins to scale across entire factories or industrial campuses, while still supporting time-critical local decision-making.

In industrial energy systems, 6G-enabled digital twins can therefore assess energy flows across machines, production lines, and utilities; identify inefficiencies in real time; and recommend or trigger control actions that balance production objectives with energy efficiency and emissions reduction goals [55]. Over time, learning-based twins can adapt to evolving operational conditions, improving predictive accuracy and supporting data-driven investment, maintenance, and decarbonization strategies.

3.3.2. Predictive Maintenance and Fault Detection

Unexpected equipment failures not only disrupt industrial operations but also lead to energy inefficiencies and costly downtime. Predictive maintenance addresses this challenge by detecting early signs of degradation and enabling intervention before failures occur.

6G strengthens predictive maintenance by enabling dense sensing, low-latency data transmission, and edge-based analytics. Vibration, temperature, acoustic, and electrical signatures from industrial assets can be continuously monitored and analysed using AI models deployed close to the equipment.

Such real-time diagnostics are especially valuable for energy-critical components such as transformers, converters, motors, and power electronics. By reducing reaction time and enabling distributed anomaly detection, 6G-supported predictive maintenance improves reliability, extends asset lifetimes, and reduces energy waste across industrial systems.

3.4. 6G Network Digital Twin and Telco Infrastructure Energy Management

6G networks are expected to deliver much more data at faster rates than today's networks, which makes building a sustainable network infrastructure extremely challenging. On the other hand, sustainability is one of the guiding aspects of the upcoming 6G era [52]. AI-driven solutions have high potential to overcome the defect of network complexity and find a path toward a sustainable ecosystem. However, direct development of these solutions in the operational network can have negative performance impacts due to unpredictable operational effects and conflicts with other running optimization procedures [53]. Since the network is a critical infrastructure, it is of extreme importance that the AI models can be trained and evaluated in a virtual sandbox environment before the actions in the physical network are taken. *Network Digital Twin (NDT),* i.e., the digital twin of the 6G network itself, can serve as such a sandbox. The ITU has provided a first, high-level approach for standardising this concept, through the recommendation ITU-T y.309031, where a conceptual architecture providing specific functions to be implemented is proposed. Since then, more specific proposals have been made for NDT's functional architecture, such as [54] encompassing data collection, zero-touch service and network management, federated management and orchestration and simulation frameworks.

3.4.1. 6G Radio Access Network Optimization

High frequency bands

One of the important technological enablers of high data rates is the usage of high frequency bands. Such bands, such as mmWave, sub-Terahertz and Terahertz, offer significantly higher bandwidth at an expense of worse propagation properties due to vulnerability to blockages, higher path loss, and oxygen absorption. To meet the coverage requirements, these technologies rely on beamforming, i.e., focusing of emitted signal with a multi-antenna array. A low wavelength gives an advantage, as the size of the antenna becomes smaller, thus leading to smaller physical size of the array. The performance of the network at high frequencies crucially depends on the beam management, i.e., the functionality that establishes and retains a suitable beam pair, the transmitter-side beam direction and a corresponding receiver-side beam direction. The procedure of finding an optimal beam usually incorporates beam sweeping, i.e., sweeping of all beams from a predefined codebook to find the best one. In the complex environment with multiple obstacles, the directions of these beams can be different from the line-of-sight direction. Since high-frequency bands are extremely vulnerable to blockages, *Reconfigurable Intelligent Surfaces (RIS)* are considered as a powerful and energy-efficient technology to achieve robust transmissions. RIS is a passive meta-surface that adds a different phase shift to the signal to change the direction of the reflected signal and focus it on the direction of the receiver. Since RIS is passive, it does not require energy-hungry RF chains for active radio. However, it adds to the complexity of the beam sweeping, as the beamforming configurations at transmitter and receiver should be selected jointly with the RIS's phase shifts.

The effect on the energy consumption is two-fold: 1) the procedure of the beam sweeping itself leads to high overhead due to transmission of multiple reference signals using different beams to find the best one; 2) the total number of beams that can be tested is limited, leading to non-optimal beamforming, and thus resulting in the need for higher transmission power to provide the required signal strength to the user. To overcome the complexity of the problem, NDT that matches the real channel characteristics can be used for training the AI model aiming at predicting the optimal beam. The model can use both channel measurements from the physical network and measurements of beam trials performed at the NDT. To narrow down the beam search, geometry-based approaches can be used, where an approximate user position obtained from the network telemetry helps to initialize the initial beam guess.

Network management

Growing densification of the networks together with emerging demanding applications, such as extended reality and smart industry, require high network capabilities. However, due to dynamicity of network load and user demands, it is important to efficiently manage the network so that its configuration matches the demand. A common deployment approach is the usage of two types of base stations: one provides high coverage at the expense of lower performance, while the other provides high capacity at lower communication range. For each of these types a different communication frequency can be used. For example, capacity base stations can leverage high frequency bands or FR3, while coverage base stations can rely on classical sub-6GHz bands, such as C-band. Different users can be dynamically assigned to different frequencies depending on the application they use, channel conditions, and availability of resources. Additionally, when some of the BSs are significantly underloaded, they can save energy using power saving mechanisms, such as *Advance Sleep Modes (ASMs)* or even by being completely turned off. NDT is seen as a tool for trial of different management decisions to verify how those decisions affect the satisfaction of service level agreements (SLAs) and the network energy efficiency.

3.4.2. Energy-aware Cross-domain Optimization using Federated NDTs

Decisions made at the RAN domain, such as turning off an underloaded base station, affect traffic patterns, which are also reflected in the aggregated traffic observed at the user plane function, impacting applications running at the edge. Accurately identifying these changes is crucial to maintaining user quality of service. Additionally, power-aware orchestration of the edge applications can be further optimized to enhance energy efficiency without compromising service performance. RAN and the computing platform operate as distinct administrative domains, requiring a federation mechanism to achieve holistic energy efficiency. To proactively adapt to traffic variations, the computing domain can request traffic traces from a RAN NDT as part of its internal optimization loop, enabling “what-if” analyses. For instance, the RAN NDT may provide traces for bursty traffic, on-off traffic patterns, or scenarios involving the addition (e.g., capacity planning) or removal (e.g., resilience to failures) of base stations. The computing platform also collects infrastructure-level data to model the impact of traffic patterns on QoS metrics such as latency and energy consumption. By combining these insights, a Computing NDT can be constructed to evaluate management strategies, including scaling policies that incorporate energy efficiency objectives. Using these models and traffic traces, the system can simulate multiple scenarios and assess alternative scaling strategies. Ultimately, the Computing NDT recommends the most suitable approach for each traffic pattern, ensuring optimal performance during real-world operation.

4. KPIs and Requirements

4.1.1. KPI Domains for 6G-enabled Energy Systems

Across smart grids, smart cities, and industrial environments, 6G emerges not merely as a connectivity upgrade, but as a systemic enabler for intelligent, autonomous, and sustainable energy systems. The common thread is the tight integration of communication, sensing, computation, and control, allowing energy systems to evolve from reactive operation toward predictive, adaptive, and value-driven behavior.

To make this convergence operational, each application area must be mapped to a set of quantitative *Key Performance Indicators (KPIs)* and, increasingly, *Key Value Indicators (KVIs)* that capture not only technical performance but also sustainability and resilience. Current 6G research and pre-standardization activities (e.g., ITU-R's IMT-2030 framework, 5G-PPP/Hexa-X KPI/KVI work, 6G-IA white papers) converge on a core set of KPI domains:

- Communication performance
- Sensing and context awareness
- Computation and intelligence
- Reliability, resilience, and security
- Service-level and operational guarantees
- Energy efficiency and sustainability (KVIs)

These domains provide the organizing structure for the KPI overview summarized in Table 1 and for the detailed interpretation discussed in Sections 4.1.3-4.1.7.

The KPIs and KVIs presented in this section should be interpreted as **representative ranges and domains**, rather than fixed targets. Actual requirements depend on application criticality, regulatory constraints, and deployment context. The purpose of this section is to illustrate how 6G-enabled capabilities translate into measurable performance, resilience, and sustainability outcomes for energy systems.

4.1.2. KPI Overview for the Energy Sector

For energy-sector use cases, these KPIs must be instantiated with **domain-specific targets**: e.g., sub-10 ms latency for grid protection, "*five-nines*" reliability for industrial control, and explicit energy-efficiency and carbon-intensity metrics for telecom infrastructure that supports decarbonization goals. Recent work on 6G-enabled power systems and smart grids provides example requirement ranges for such applications. Table 1 summarizes representative KPIs, their role in energy-sector applications, and references to relevant standardization and research activities.

Table 3: Example of KPIs and their application in the context of the Energy sector.

KPI	Definition	Typical requirements in energy sector	Standards and Research References
Latency	End-to-end delay (ms)	**Protection & fast control:** ~1–10 ms (fault isolation, microgrid protection) **DR & automation:** 10–100 ms; **Monitoring & metering:** 100 ms–seconds. (ETSI TR 103 401 [48])	**ITU-R**: IMT-2030 Framework & Objectives, Rec. *M.2160* (latency as core capability). **3GPP/ETSI**: TS 22.104 cyber-physical control latency requirements; ETSI TR 103 401 for smart-grid real-time needs. Emerging 6G/B6G wireless for the power grid, 2023[49]
Reliability & Availability	Packet error rate; service availability (%)	**Critical protection / industrial control:** ≥ 99.999% service availability, very low loss (10^{-5}–10^{-6} per packet) **DR & city-scale management:** 99.9–99.99% typical, IETF RFC 8655	**ITU-R**: IMT-2030 capabilities for high reliability. **IETF DetNet**: RFC 8655 (Deterministic Networking Architecture) and scaling requirements drafts define bounded loss and high reliability for deterministic flows.

KPI	Definition	Typical requirements in energy sector	Standards and Research References
			ETSI: Smart-grid TR 103 401; URLLC use-case TR 103 515.
Throughput & Capacity	User-experienced data rate; area traffic capacity	**Grid & industrial telemetry:** kbps–Mbps/device. **High-resolution sensing / video inspection:** tens–hundreds of Mbps; high area capacity in dense urban / industrial sites.	**ITU-R IMT-2030**: peak data rate, user-experienced data rate, area traffic capacity, connection density. **5G-PPP / SNS**: Beyond-5G/6G KPI white paper; ADROIT-6G KPI definitions. Sustainable 6G-enabled Digital Transformation of the Energy Sector (TechRxiv, 2023 How Beyond-5G and 6G Makes IIoT and the Smart Grid Green (Varga et al., 2025).
Connection Density & Scalability	Devices per km²; sessions per node	**Smart cities / buildings:** up to 10^6 devices/km² (sensors, meters, EV chargers) **Industrial sites:** 10^3–10^5 devices/site, including machines and sensors, many with periodic small payloads.	**ITU-R IMT-2030**: connection density and scalability capabilities. **Hexa-X / SNS KVI/KPI work**: consolidated KPI/KVI sets for 6G platform. 6G Opportunities from IoT Use Cases (Barakat et al., 2021 KPI sets for massive IoT; Emerging 6G/B6G Wireless Communication for the Power Grid
Time Synchronization & Jitter	Time sync accuracy; jitter (µs / ns)	**Protection / synchro phasors / industrial drives:** sub-1 ms jitter; in some industrial motion control, sub-100 µs or ns-level jitter. **DR / building control:** more relaxed (10–100 ms).	**3GPP/ETSI**: TS 22.104 (cyber-physical control); ETSI TR 103 401 (mission-critical smart-grid timing). IETF DetNet WG requirements on bounded jitter. 6G Vision, Requirements and Challenges (vivo, 2020) – jitter requirements for industrial and smart-grid control
Energy Efficiency (Network)	Energy per bit (J/bit)	Target continuous improvement: x-fold reduction in energy per bit vs 5G; base-station EE KPIs linked to delivered bits per Joule and carbon footprint per service. Critical for aligning telecom with net-zero energy goals.	**ETSI TS 103 786**: base-station energy efficiency KPI. **ISO 50001**: energy-management systems and continuous improvement framework. **6G sustainability white papers** (Fraunhofer IIS, SUSTAIN-6G). Energy-Aware 6G Network Design: A Survey (Kamran et al., 2025); Sustainable 6G-enabled Digital Transformation of the Energy Sector
Energy & Carbon (Service-level)	kWh per delivered service; CO_2-eq per bit or per function	**Smart-grid / industry:** KPIs that link communication services to plant-wide energy efficiency and emissions (e.g. kWh saved / ton CO_2 avoided through optimized control). Still emerging but central to KVIs in 6G.	**ISO 50001**: organisational energy-performance indicators. **SNS KVI/KPI white papers**: integrating environmental KVIs (energy reduction, emissions) alongside technical KPIs. Sustainable 6G-enabled Digital Transformation of the Energy Sector; 6G Energy Efficiency and Sustainability (Fraunhofer IIS
Security & Privacy	Zero-trust properties, privacy loss (ε), etc.	**Smart-grid / industrial:** strong integrity and availability (resilience to coordinated physical–cyber-attacks), low probability of compromise; privacy-preserving DR and consumption data handling (e.g. differential privacy budgets).	**IETF DetNet**: secure deterministic networking architecture. **ETSI**: ENI and ZSM specs for AI-assisted, closed-loop and intent-based management (security-relevant KPIs, closed-loop governance). **ITU-T / ITU-R**: IMT-2030 security capabilities. Security Requirements and Challenges of 6G Technologies (Hakeem et al., 2022); AI-Powered Smart Grids in the 6G Er
Resilience & Fault Tolerance	MTBF, MTTR, service continuity under faults	Targets: graceful degradation and fast recovery for grid-critical and industrial services; self-healing via re-routing, slicing isolation, and digital-twin-driven what-if analysis.	**ETSI TR 103 401**: future requirements for mission-critical real-time systems (e.g. smart grids). **ETSI ZSM & ENI**: closed-loop automation and AI-driven management, including KPIs for service resilience and intent satisfaction. Digital Twin for 6G: Taxonomy and KPIs (Masaracchia et al., 2022); What-if Analysis Framework for Digital Twins in 6G Networks
Localization & ISAC	Positioning accuracy; sensing resolution	**Urban / industrial energy:** sub-meter to cm-level accuracy for asset tracking, indoor equipment localization, and safety; high-resolution RF sensing for anomaly detection (e.g. arc faults, vibration patterns) via ISAC.	**ITU-R IMT-2030**: localization accuracy as part of enhanced capabilities. **6G-IA European Vision**: highlights ISAC and positioning as key differentiators for 6G.

4.1.3. Network Performance KPIs

Network performance KPIs such as latency, reliability, jitter, and connection density are fundamental for enabling time-critical grid protection, demand-response control, and industrial automation. Ultra-low and deterministic latency supports closed-loop control, while five-nines reliability and bounded jitter ensure safety and stability even under congestion or fault conditions. Energy-system functions depend on time-critical coordination and deterministic behavior as discussed. Typical requirements include:

- **Ultra-low latency:** Sub-millisecond to few-millisecond end-to-end latency for protection, grid control, and industrial automation [47].
- **High reliability:** Packet delivery reliability above 99.999% (five nines) for safety- and stability-critical communications[7].
- **Deterministic jitter:** Bounded latency variation to support closed-loop control and synchronized operations across distributed assets.
- **Massive connectivity:** Support for extremely dense deployments of sensors, actuators, DERs, and industrial devices without performance degradation.

These KPIs are particularly critical for demand-response control, grid protection mechanisms, and real-time industrial energy optimization.

4.1.4. Sensing, Intelligence, Context-awareness, and Control KPIs

Integrated sensing and communication (ISAC) enable a new class of KPIs related to observability and environmental awareness. These KPIs capture the cyber-physical intelligence layer of 6G-enabled energy systems, beyond traditional communication performance:

- **Sensing accuracy:** High-resolution localization, timing, and state estimation of assets such as machines, EVs, and grid components.
- **Update frequency:** Near real-time sensing updates to support dynamic digital twins and adaptive control.
- **Coverage and robustness:** Reliable sensing under harsh industrial conditions and across geographically dispersed energy assets.
- **Inference latency:** Fast AI inference at the edge for real-time decision-making and control.
- **Scalability:** Ability to manage and coordinate thousands to millions of intelligent agents.
- **Learning efficiency:** Support for federated and distributed learning with limited communication overhead.
- **Model adaptability:** Continuous updating of models to reflect evolving system dynamics and user behavior.

[7] https://digitalregulation.org/overview-of-6g-imt-2030/

4.1.5. Reliability, Resilience and Secure KPIs

Given the critical nature of energy systems, resilience and security must be measurable and enforceable. These KPIs are particularly relevant for energy systems classified as critical infrastructure under national and EU regulations:

- **Service availability:** Extremely high availability even during network congestion, faults, or attacks.
- **Fault recovery time:** Rapid detection and isolation of failures, with graceful degradation rather than system-wide collapse.
- **Security assurance:** End-to-end encryption, secure device onboarding, and protection against data tampering or spoofing.
- **Isolation guarantees:** Strong separation of critical control traffic via network slicing to prevent cascading failures.

These requirements apply across cyber and physical domains and are essential for public trust and regulatory acceptance.

4.1.6. SLA and Operational KPIs

Energy systems require *application-aware Service Level Agreements (SLAs)* that reflect operational priorities. Such SLAs enable telecom providers, TSOs, DSOs, and industrial operators to coordinate responsibilities and enforce predictable system behavior.

- **Intent-based SLAs:** Network behavior aligned with energy objectives (e.g., grid stability, renewable maximization).
- **Geographic guarantees:** Localized performance assurances for substations, microgrids, or industrial sites.
- **Resilience SLAs:** Defined performance under degraded conditions or during extreme events.
- **Auditability:** Transparent monitoring and reporting for compliance and market settlement.

Such SLAs enable telecom and energy stakeholders to coordinate responsibilities and ensure predictable system behavior.

4.1.7. Energy and Sustainability KPIs

Finally, since 6G is both an enabler and a consumer of energy, sustainability metrics must be intrinsic. These indicators go beyond traditional performance KPIs and quantify the value contribution of 6G to the energy transition:

- **Energy efficiency:** Energy per bit and per inference task minimized across the network.
- **Carbon awareness:** Preferential routing and computation placement based on renewable availability.
- **Lifecycle efficiency:** Support for low-power devices, long asset lifetimes, and reduced maintenance overhead.

These KPIs ensure that the digital infrastructure supporting the energy transition does not undermine its sustainability goals.

5. Challenges and Future Perspectives

The convergence of energy systems with 5G-Advanced and future 6G capabilities creates a powerful foundation for autonomy, resilience, and new market structures but it also introduces a set of challenges that must be addressed early to ensure that the resulting infrastructure is trustworthy, sustainable, and deployable at scale. Unlike many "classic" telecom verticals, the energy domain is safety-relevant and time-critical, subject to strict regulatory obligations, and increasingly exposed to cyber-physical risks. In addition, 6G itself must meet ambitious sustainability targets while supporting the digitalization of the energy transition.

This section summarizes the key challenges and highlights future perspectives and solution directions.

Beyond technical considerations, organizational and skills-related challenges may slow adoption. Energy operators and telecom providers operate under different cultures, procurement models, and regulatory regimes. Bridging this gap requires joint training, shared operational models, and cross-sector governance structures is an aspect increasingly emphasized in AIOTI and EU digital-transition initiatives.

5.1. Energy Efficiency and Sustainability

The energy sector will adopt 6G only if its net system-level impact is positive: the digital infrastructure must enable measurable energy savings, grid stability, and emissions reduction *without* introducing disproportionate energy consumption, embodied carbon, or electronic waste. A major risk is that ultra-dense connectivity, high data rates, AI-native operations, and large-scale edge computing increase the overall footprint of ICT systems. The sustainability challenge therefore spans three layers: (i) **network-level energy efficiency**, (ii) **sustainable infrastructure (software and physical) and lifecycle practices**, and (iii) "**green services**" that ensure that 6G-enabled solutions *contribute* to the energy transition.

5.1.1. Green Networking

Green networking for 6G extends beyond incremental power savings: it seeks *energy-aware network operation* with deterministic performance. Techniques like adaptive cell activation, dynamic scaling of virtualized network functions, and AI-driven traffic and resource forecasting are critical for achieving low baseline consumption without compromising mission-critical behavior in the energy domain. Research on energy-aware 6G design highlights the need to balance ultra-reliability and low latency with minimized energy per delivered value, reflecting both network and energy sector priorities [1][2]. Additionally, sustainable orchestration across RAN, edge, and cloud resources is essential to reduce energy waste and align computation with renewables.

A summary of key challenges with proposed future research pathways is as follows:

- **Energy metric and observability definition**
  - **Challenge**: A fundamental challenge for green services in 6G-enabled energy systems is the **lack of standardized, fine-grained, and end-to-end energy observability** across communication, computation, and energy domains. While energy efficiency is frequently discussed at component or network level (e.g., energy per bit, base-station efficiency), these metrics are insufficient to capture the *system-level impact* of 6G-enabled services on energy systems.

- **Pathway**: Agree on core metrics such as energy per bit, energy per inference, energy per control action, and associated carbon intensity (e.g., CO_2); Align telecom metrics (e.g., ETSI base-station energy KPIs) with energy-sector indicators (e.g., kWh saved, peak reduction, flexibility delivered); Define metric semantics and boundaries (what is included/excluded, temporal granularity, spatial scope).

- **Energy proportionality across the network**

  - **Challenge***:* Future 6G networks must reduce baseline power consumption and scale energy use dynamically with traffic demand. Techniques such as deep sleep modes, adaptive cell activation, AI-driven traffic prediction, and elastic scaling of virtualized network functions are essential to avoid over-provisioning and idle energy waste [1]

  - ***Pathway:*** Energy-proportional designs with deep sleep modes, micro-sleep scheduling, elastic scaling of VNFs/CNFs, and intelligent activation of small cells, RIS, and edge nodes only when required.

- **AI-for-energy vs. energy-for-AI trade-offs**

  - ***Challenge:*** AI-native networks may increase energy consumption via model training, continuous inference, and telemetry processing.

  - ***Pathway:*** Energy-aware ML pipelines (model compression, distillation, sparse inference), event-triggered inference, split learning across device/edge/cloud, and carbon-aware training windows aligned with renewable availability.

- **Cross-layer optimization with energy-sector objectives**

  - ***Challenge:*** RAN and core optimizations traditionally focus on throughput/QoE; energy systems require deterministic control and reliability.

  - ***Pathway:*** Multi-objective optimization that jointly considers latency, reliability, and energy; "intent-based" control where energy-sector intents (grid stability, renewable maximization) are translated into network policies that also minimize network energy.

- **Carbon-aware networking and compute placement**

  - ***Challenge:*** Optimizing energy is not equivalent to optimizing emissions; grid carbon intensity is time- and location-dependent.

  - ***Pathway:*** Carbon-aware routing and workload placement across edge–cloud, selecting sites powered by renewables or low-carbon grids for non-time-critical analytics; defining "green slices" with sustainability constraints.

- **Energy harvesting and ultra-low-power communications at the far edge**

  - ***Challenge***: Battery maintenance and replacement at scale (billions of sensors) becomes economically and environmentally prohibitive.

  - ***Pathway:*** Ambient energy harvesting (RF, vibration, thermal, solar) and battery-free communication modes; wake-up radio concepts; ISAC-enabled sensing that reduces the need for dedicated sensor hardware.

Future perspective: *the energy sector can become both a user and a controller of network energy behavior, e.g., flexible network loads participating in demand response, or network sites interacting with local microgrids and storage to smooth consumption peaks.*

5.1.2. Sustainable Infrastructures

Sustainability is not only operational energy; it includes embodied carbon, supply-chain constraints, and end-of-life management. As 6G densifies deployments and introduces new hardware (advanced antenna arrays, edge servers, RIS panels, sensing-capable radio units), the lifecycle footprint becomes decisive.

Key challenges and technical directions include:

- **Embodied carbon and materials footprint**
    - ***Challenge***: High-performance semiconductors, rare earth materials, and advanced packaging increase embodied emissions and supply risks.
    - ***Pathway:*** Lifecycle assessment (LCA) requirements for telecom equipment; low-carbon procurement; design-for-reuse and modular upgrades rather than full replacements.
- **Circularity and right-to-repair**
    - ***Challenge***: Rapid innovation cycles can drive e-waste and premature decommissioning.
    - ***Pathway:*** Modular hardware architectures (replaceable radio units, upgradeable compute modules), standardized interfaces for disaggregation (Open RAN / cloud-native components), repairability targets, and certified refurbishment ecosystems.
- **Sustainable densification**
    - ***Challenge***: Urban densification (small cells, indoor systems) may improve performance but increases the number of physical assets.
    - ***Pathway:*** Hybrid architectures that combine macro coverage with on-demand capacity, RIS where beneficial, shared neutral-host infrastructures, and careful site planning aligned with municipal sustainability goals.
- **Resilient power supply for telecom sites**
    - ***Challenge***: Telecom availability during grid events becomes more important as energy systems rely on connectivity.
    - ***Pathway:*** Local backup power using low-emission solutions (batteries, fuel cells where appropriate), integration with site-level renewables, and coordinated operation with DSOs for critical site prioritization.

Future perspective: 6G infrastructure may be treated as a *critical energy participant* with telemetry, controllability, and contractual mechanisms enabling telecom to contribute to grid stability while meeting its own availability requirements.

5.1.3. Green Services and Impact Measurements

Green services ensure that the operational benefits of 6G connectivity translate into measurable sustainability outcomes in energy systems. Establishing standardized measurement and verification (M&V) frameworks that link communication-enabled optimization to quantifiable energy and carbon savings is crucial. Otherwise, rebound effects can negate apparent efficiency gains. Embedding sustainability metrics into service-level objectives, and extending SLAs to cover energy and carbon KPIs, encourages transparent contribution to decarbonization while enabling accountability across ecosystem partners [37]. Key challenges and technical directions include:

- **Measurability and verification of sustainability impact**
  - ***Challenge***: Quantifying "energy saved" due to connectivity-enabled optimization is complex and can be confounded by external factors (weather, occupancy, industrial production).
  - ***Pathway***: Standardized measurement and verification (M&V) methodologies; digital MRV (Monitoring, Reporting, Verification) pipelines; auditable "sustainability KPIs/KVIs" tied to services and slices.
- **Green-by-default service design**
  - ***Challenge***: Many services are designed for peak performance rather than "right-sized" operation.
  - ***Pathway***: Energy-aware application design patterns: edge-first control loops, cloud-only for long-horizon optimization, adaptive compression, and event-based messaging.
- **Sustainability-aware SLAs and QoS**
  - ***Challenge***: Traditional SLAs omit environmental performance.
  - ***Pathways***: Introduce sustainability clauses: carbon intensity thresholds for non-critical processing, energy-per-function targets, and reporting obligations; align with emerging KPI/KVI frameworks.

Future perspective: "green services" will become a competitive differentiator. Market actors (utilities, aggregators, industrial operators, telcos) can co-design services with explicit energy and carbon budgets, enabling both compliance and value creation.

5.2. Cybersecurity and Data Privacy in Energy Networks

As energy systems become more distributed and autonomous, their threat surface expands dramatically. In 6G-enabled environments, cyber incidents can propagate faster and have physical consequences (load manipulation, protection bypass, unsafe switching), making cybersecurity a safety requirement. At the same time, fine-grained energy data can reveal sensitive information about individuals and organizations, raising privacy concerns and legal obligations. With 6G enabling real-time control of grid assets, cybersecurity is a **safety-critical requirement**, not an IT add-on.

5.2.1. Protecting Critical Energy Infrastructures

Critical energy assets require defence-in-depth strategies that cover identity management, zero-trust architectures, and segmented network slices for critical control traffic. AI-based anomaly detection and hybrid defence mechanisms are essential for identifying sophisticated threats across heterogeneous devices and communication layers [35].

Key challenges and technical directions include:

- **Expanded cyber-physical attack surface**
  - ***Challenge****:* Millions of DER controllers, EV chargers, sensors, and building EMS devices introduce heterogeneous vulnerabilities; supply-chain risk increases.
  - ***Pathway****:* Security-by-design at onboarding (hardware roots of trust, secure boot, attestation), continuous posture monitoring, and strong identity and credential lifecycle management.
- **Zero-trust architectures for multi-stakeholder environments**
  - ***Challenge****:* Energy ecosystems include TSOs, DSOs, aggregators, prosumers, telcos, municipalities, and vendors. Therefore, interoperability and trust boundaries are complex.
  - ***Pathway****:* Zero-trust networking: authenticate and authorize every device, service, and transaction; least-privilege access; micro-segmentation; and policy-driven enforcement.
- **Isolation and containment through network slicing**
  - ***Challenge****:* Mixed traffic types (critical protection vs. consumer IoT) must not interfere; attacks should not cascade.
  - ***Pathway****:* Slice isolation with strict QoS and security profiles for grid-critical functions; separate management planes; controlled inter-slice gateways; continuous validation of isolation properties.
- **AI-driven threats and AI-driven defence**
  - ***Challenge****:* Attackers can exploit AI models (data poisoning, adversarial inputs) and use AI to automate attacks; defenders increasingly rely on AI for detection.
  - **Pathway***:* Robust ML practices (secure data pipelines, adversarial training where relevant), explainable alerts for operators, and hybrid detection that combines rule-based and learning-based methods.
- **Operational resilience under attack**
  - ***Challenge****:* Even with strong prevention, some attacks will succeed; the system must fail safely.
  - ***Pathway****:* Graceful degradation modes, local fallback control, islanding support, "manual override" capabilities, and well-rehearsed incident response across telecom–energy interfaces.

Future perspective: energy operators and telcos will need joint security operations concepts (shared telemetry, coordinated response playbooks, and cross-domain risk assessments), especially where 6G provides mission-critical control connectivity.

5.2.2. Regulatory and Compliance Considerations

Future energy communication services must incorporate **compliance-by-design** architectures that are auditable, traceable, and aligned with critical infrastructure protection frameworks. Privacy concerns are paramount where fine-grained consumption and telemetry data reveal sensitive patterns; therefore, privacy-enhancing technologies like differential privacy and secure multi-party computation must become operational norms. Transparent governance and human-in-the-loop assurance for AI systems in safety-critical operations are also emerging as regulatory expectations.

5.2.3. Secure, Interoperable Energy Transactions

Decentralized flexibility markets, peer-to-peer trading, and automated settlement depend on trusted data exchange and verifiable actions across stakeholders. The challenge is to ensure interoperability and security without creating excessive overhead or central bottlenecks.

Key challenges and technical directions include:

- **Trust and integrity for measurement and control**
  - *Challenge:* Settlement relies on accurate metering, time synchronization, and proof that control actions were executed as claimed.
  - *Direction:* Trusted measurement pipelines (secure metering, attestation), tamper-evident logging, synchronized timestamps, and cryptographic signing of actions and measurements.
- **Interoperability across domains and standards**
  - *Challenge:* Energy protocols, telecom management, and IoT ecosystems are fragmented; integration costs are high.
  - *Direction:* Harmonized data models and interfaces; translation layers at the edge; standardized APIs for flexibility, asset capability descriptors, and service intents; profile-based interoperability to support phased rollout.
- **Privacy-preserving market participation**
  - *Challenge:* Participation in markets should not require disclosing sensitive user behavior or industrial production patterns.
  - *Direction:* Aggregation mechanisms, PETs for bids/settlement, selective disclosure credentials, and role-based access control for market data.
- **Scalable transaction mechanisms**
  - *Challenge:* If millions of assets transact frequently, centralized settlement may not scale.
  - *Direction:* Hierarchical market designs (local aggregation → regional settlement), event-triggered transactions, and where appropriate, distributed ledger components with careful performance and governance evaluation.

Future perspective: secure transaction infrastructure becomes a cornerstone for flexibility at scale. 6G can provide the deterministic connectivity and distributed compute needed for real-time operation, while governance and interoperability decide whether such markets become practical.

5.3. 6G Deployment Timeline and Feasibility Challenges

6G is expected to emerge gradually, with pre-6G capabilities appearing through 5G-Advanced evolution and early 6G trials before broad commercial rollout. The energy sector, however, operates with long asset lifetimes (10–40 years for grid equipment) and conservative safety processes. The feasibility challenge is therefore not only technical maturity, but also alignment of timelines, investment cycles, and operational risk tolerance. Therefore, energy systems operate on long lifecycles and rigorous safety standards, while 6G development and testing cycles are accelerating toward early deployments.

Bridging this tempo mismatch requires phased approaches that allow 6G capabilities to coexist with legacy systems and evolve from non-critical monitoring to more demanding control functions as maturity and trust grow. Incremental adoption strategies, hybrid architectures, and joint telco–utilities investment models are practical paths forward. Additionally, sandbox environments such as digital twins provide safe spaces for validating AI-driven optimizations and control strategies before live deployment, reducing operational and regulatory risk.

Key challenges and future perspectives include:

- **Phased adoption and coexistence with legacy systems**
  - ***Challenge***: Energy control and protection systems cannot be replaced quickly; utilities require coexistence with SCADA, IEC-based automation, and existing private radio.
  - ***Pathway***: Hybrid architectures where 6G complements (not replaces) wired and legacy wireless; gateways and interoperability layers; migration plans that prioritize non-critical monitoring first, then progressively expand toward control loops where justified.
- **Business case and shared investment models**
  - ***Challenge***: 6G-grade deterministic connectivity may require dedicated infrastructure or premium network capabilities, who pays and who benefits can be misaligned.
  - ***Pathway***: Joint telco–utility investment models, neutral-host deployments for campuses/industrial parks, and "network-as-critical-infrastructure" agreements with clear SLAs and liability frameworks.
- **Coverage, rural feasibility, and extreme environments**
  - ***Challenge***: Many grid assets are in remote areas; harsh environments degrade hardware and radio conditions.
  - ***Pathway***: Multi-connectivity and multi-bearer strategies (terrestrial + non-terrestrial where relevant), edge compute at substations, and robust device and antenna designs; focus on deterministic service rather than peak throughput.

- **Operational complexity and skills gap**
  - ***Challenge**:* 6G introduces AI-native management, slicing, distributed edge intelligence, and security controls raising operational complexity.
  - ***Pathway**:* Automation with human governance (closed-loop control with guardrails), standardized operational tooling, joint training programs, and shared best practices between telecom NOC and energy SOC/OT operations.
- **Validation, certification, and safety assurance**
  - ***Challenge**:* Safety-critical energy functions require rigorous validation; black-box AI and dynamic networks are difficult to certify.
  - ***Pathway**:* Digital twins for "what-if" testing; formal verification where feasible; controlled pilots with clear safety envelopes; and certification frameworks for both connectivity services and AI-driven control components.
- **Dependence risk and resilience requirements**
  - ***Challenge**:* If energy systems depend on connectivity, telecom outages become power-system risks.
  - ***Pathway**:* Redundancy by design: fail-safe local control, fallback channels, multi-operator roaming for critical slices, and clear prioritization policies during emergencies.

Future perspective: the most successful deployments will likely be *incremental and value-driven*, starting with use cases that deliver clear operational benefits (asset monitoring, predictive maintenance, localized flexibility coordination), while building the trust, operational maturity, and regulatory clarity needed for deeper integration into protection and control loops.

6. Conclusions and Road Ahead

6.1. Key Insights

This white paper demonstrates that the convergence of energy systems with 5G-Advanced and future 6G capabilities represents a structural transformation rather than a simple upgrade of connectivity. As energy systems become increasingly decentralized, digitalized, and automated, communication networks evolve into an integral part of energy operations, influencing system stability, resilience, and sustainability. In this context, 6G offers a set of capabilities such as deterministic performance, massive scalability, AI-native operation, and integrated sensing that closely align with the emerging needs of modern energy systems.

A key insight is that 6G enables a shift from reactive and centrally managed energy operations toward predictive, adaptive, and distributed control. Through ultra-reliable low-latency communication and edge intelligence, 6G supports real-time coordination among distributed energy resources, flexible loads, storage systems, and market actors. This capability is essential for managing variability from renewable generation and for enabling self-healing behavior in increasingly complex grids.

The analysis also highlights that observability is a foundational requirement for trust and adoption. Without standardized, end-to-end metrics that link communication, computation, and energy-system outcomes, it remains difficult to assess the true impact of 6G-enabled services on energy efficiency and emissions reduction. Energy and carbon observability must therefore become intrinsic properties of future networks and services, extending beyond component-level efficiency toward system-level accountability.

Security and resilience emerge as equally critical insights. As connectivity becomes embedded in safety-relevant energy functions, cyber incidents can translate directly into physical consequences. The energy domain therefore requires security-by-design and resilience-by-design approaches, including zero-trust architectures, strong isolation of critical services, and fail-safe operational modes that preserve local control under degraded connectivity. These requirements position 6G not merely as a communication technology, but as part of the critical infrastructure itself.

Finally, the white paper underscores that sustainability is not optional. 6G must demonstrably contribute to the energy transition rather than undermine it through increased energy consumption or electronic waste. This requires energy-proportional network operation, lifecycle-aware infrastructure design, and service models that explicitly account for energy and carbon impacts.

6.2. Road Ahead

The path toward 6G-enabled energy systems should be incremental, evidence-based, and policy-aligned, recognizing **energy infrastructures as a safety-critical and regulated domain**. Each step outlined below directly maps to AIOTI recommendations and existing or emerging EU policy instruments, ensuring that technical progress translates into deployable and regulated solutions.

From pilots to validated use cases

Early deployment should prioritize low-risk, high-value applications such as asset monitoring, predictive maintenance, digital twins, and localized flexibility coordination. These use cases build operational confidence while generating quantitative evidence for performance, security, and sustainability KPIs. This approach directly aligns with AIOTI recommendations on large-scale pilots and cross-domain experimentation, as well as with the EU's **Smart Networks and Services (SNS) Joint Undertaking**, which emphasizes vertical-driven validation of 6G technologies before wide-scale adoption.

Establishing shared reference architectures and interoperability

Scalable adoption requires common architectural principles spanning communication, computation, and energy domains. Hybrid architectures where 6G complements existing wired and wireless solutions—are essential for critical infrastructure. This direction is consistent with AIOTI' s long-standing emphasis on interoperability and open ecosystems, and with EU priorities under the **New Legislative Framework** and **Digital Single Market**, which promote interoperability, vendor diversity, and avoidance of technological lock-in. Reference architectures should also align with IEC/ETSI/3GPP work to ensure compatibility with existing energy standards.

Operationalizing energy and carbon observability

A decisive step is the transition from component-level efficiency metrics to service-level energy and carbon observability. This includes standardized metrics, auditable monitoring, and sustainability-aware SLAs. This direction strongly supports EU policy objectives under the **European Green Deal**[8] and the **Fit for 55**[9] packages, which require measurable and verifiable emissions reductions. It also aligns with AIOTI recommendations to integrate sustainability as a first-class design objective for IoT and digital infrastructures, rather than as an after-the-fact reporting exercise.

Security, resilience, and trust by design

As 6G becomes embedded in energy operations, security and resilience must be demonstrable and certifiable. Zero-trust architectures, slice isolation for critical functions, and fail-safe operation modes are essential. This directly supports the **NIS2 Directive**[10] and the **EU Cybersecurity Act**[11], which strengthen requirements for critical infrastructure protection and supply-chain security. AIOTI has repeatedly emphasized the need for security-by-design and cross-sector coordination, a principle that becomes even more critical when telecom networks underpin safety-relevant energy functions.

Governance, accountability, and AI assurance

The increasing role of AI in 6G-enabled energy systems requires transparent governance and human oversight. Digital twins, explainable AI, and controlled sandbox environments should be used to validate AI-driven decisions before deployment. This approach aligns with the forthcoming **EU AI Act**[12], particularly its requirements for high-risk AI systems in critical infrastructure, and with AIOTI guidance on trustworthy AI and human-centric system design.

Long-term integration into mission-critical control

[8] https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en
[9] https://www.consilium.europa.eu/en/policies/fit-for-55/
[10] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32022L2555
[11] https://www.bsi.bund.de/EN/Das-BSI/Auftrag/Gesetze-und-Verordnungen/Cyber-Security-Act/cyber-security-act_node.html
[12] https://artificialintelligenceact.eu/

Only after performance, security, and observability are proven should 6G be integrated into tighter energy control loops. This phased progression supports AIOTI' s recommendation for evolutionary deployment paths and is consistent with EU critical-infrastructure policy, which prioritizes continuity of service, redundancy, and accountability. In the long term, such integration can enable autonomous yet supervised energy systems that balance efficiency, resilience, and sustainability.

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AIOTI is the multi-stakeholder platform for stimulating AI, IoT and Edge Continuum Innovation in Europe, bringing together small and large companies, academia, researchers, policy makers, end-users and representatives of society in an end-to-end approach. We strive to leverage, share and promote best practices in the AI, IoT and Edge Continuum ecosystems, be a one-stop point of information to our members while proactively addressing key issues and roadblocks for economic growth, acceptance and adoption of the AI, IoT and Edge Continuum Innovation in society. AIOTI contributions goes beyond technology and addresses horizontal elements across application domains, such as matchmaking and stimulating cooperation by creating joint research roadmaps, defining policies and driving convergence of standards and interoperability.