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Digitalisation and AI for power system transformation

Perspectives for the G7

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About IRENA

The International Renewable Energy Agency (IRENA) is an intergovernmental organisation that supports countries in their transition to a sustainable energy future, and serves as the principal platform for international co-operation, a centre of excellence, and a repository of policy, technology, resource and financial knowledge on renewable energy. IRENA promotes the widespread adoption and sustainable use of all forms of renewable energy, including bioenergy, geothermal, hydropower, ocean, solar and wind energy in the pursuit of sustainable development, energy access, energy security and low-carbon economic growth and prosperity.

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Disclaimer

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ABBREVIATIONS

3DEN	digital demand-driven electricity networks
AI	artificial intelligence
AMI	advanced metering infrastructure
APUA	Association of Power Utilities of Africa
BEMS	building energy management system
BESS	battery energy storage system
BNEF	Bloomberg New Energy Finance
CRA	Cyber Resilience Act
DERs	distributed energy resources
DKK	Danish krone
DLR	dynamic line rating
DR	demand response
DSO	distribution system operator
EAC	Energy Attribute Certificate
ECOWAS	Economic Community of West African States
ECREEE	ECOWAS Centre for Renewable Energy and Energy Efficiency
EDF	Électricité de France
EHRC	Electricity Human Resources Canada
EIF	European Interoperability Framework
EMDEs	emerging and developing economies
EMS	energy management system
ENTSO-E	European Network of Transmission System Operators for Electricity
ESG	environmental, social and governance
EU	European Union
EUR	euro
EV	electric vehicle
FACTS	Flexible Alternating Current Transmission System
FEMS	Factory Energy Management System
FLISR	fault location, isolation, service restoration
FSC	Future Skills Centre
G7	Group of Seven
GO	guarantee of origin
GW	gigawatt
GWh	gigawatt hour
IEA	International Energy Agency
IoT	Internet of Things
IRENA	International Renewable Energy Agency
MASE	Ministry of the Environment and Energy Security
mFRR	manual frequency restoration reserve
O&M	operation and maintenance
PAYGO	pay-as-you-go
PMUs	phasor measurement units
R&D	research and development
RE	renewable energy
REC	Renewable Energy Certificate
RETA	Regulatory Energy Transition Accelerator
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
SCADA	supervisory control and data acquisition
ToU	time-of-use
TWh	terawatt hour
UE	United Energy
UN	United Nations
USD	United States dollar
V2G	vehicle-to-grid
VRE	variable renewable energy
WAMPACS	Wide Area Monitoring Protection and Control Systems
XAI	explainable AI

EXECUTIVE SUMMARY

Digital solutions hold great potential to accelerate the **transformation of power systems** to contribute to **energy security**, **affordability**, **sustainability** and **reliability**, and thereby support the global community on its pathway to **prosperity for everyone**. In this report, the International Renewable Energy Agency (IRENA) explores how digitalisation, using sensors, smart meters and data platforms – and new, artificial intelligence (AI)-based applications, for predictions or automation – can **create value** for actors across the system.

The ongoing transformation of power systems is characterised by increasing complexity. As electricity's share of final energy consumption reaches 52% by 2050, doubling the current electrification rate (as projected by IRENA [IRENA, 2024a]) digitalisation will become essential to manage the unprecedented scale. The variability of the growing demand and generation, and the rising number of distributed energy resources, require a digital transformation of power systems to maintain service reliability without diminishing the cost reductions brought by renewables.

The Group of Seven (G7), representing an informal grouping of advanced economies and the European Union, has an important role to play an important role in addressing the needs for **global power system transformation**. Key steps are to address barriers to the deployment and integration of digital solutions, and to support emerging and developing economies in the use of digital solutions to **improve energy access,** creating socio-economic opportunities worldwide.

A CALL FOR DIGITALISING POWER SYSTEMS

A digitalised power system is no longer a nice option but a **decisive enabler of electrification and decarbonisation**. In fact, the reported need for accelerating the deployment of renewable energy capacities, to meet the UAE Consensus tripling target by 2030, can be catalysed by digitalisation (IRENA *et al.*, 2025). Digital solutions can add value along the entire electricity supply chain, especially through the integration of AI, helping to benefit a diversity of stakeholders. To foster the adoption of digital solutions, including through the needed policy support and investments, it is important to identify their **concrete benefits**.

Many countries recognise digitalisation as a strategic priority in energy planning.[1] This represents a critical **window of opportunity** to shape corresponding efforts such that energy security is strengthened, costs are reduced and broader energy transition goals are supported. The current stage of policy development offers a timely moment to align digitalisation efforts with regulatory and investment frameworks. As this report demonstrates, digitalisation in the power sector demands a holistic approach. For the G7, this moment in time is an opportunity. A **targeted, ambitious action agenda, setting the direction for power system transformation**, would unlock benefits for consumers and businesses (from system operators to data centres) and boost energy security and affordability.

[1] *In stakeholder consultations, 66% of respondents indicated that they are incorporating digitalisation in their national energy strategies. Only 15% indicated that digital solutions are not addressed in the national energy strategy or in planning.*

A QUALITATIVE ASSESSMENT OF THE VALUE ADDED BY DIGITAL SOLUTIONS

IRENA proposes a qualitative framework for assessing the benefits of value-added digitalisation solutions for power system transformation.

Key benefits of digital solutions are:

- **Reduced electricity costs for end users** through optimisation of operation, market participation and integration of low-cost generation assets. AI-enhanced forecasting in Denmark reduced operating reserve costs by 10-15%, yielding annual savings of more than USD 9 million for customers (Bjørn Godske, 2025).
- **Improved security of supply** by ensuring continuous, reliable electricity delivery even under stress conditions, during outages or during extreme events, with faster recovery from disruptions. Compared with traditional grids, grids equipped with automation technologies have been proven to reduce supply interruptions by up to 45% and the duration of outages by over 50% in controlled trials (T&D World, 2019).
- **Greater integration of renewables** through effective management of variability in the generation mix. AI-enhanced forecasting and automation can effectively minimise renewable energy curtailments. AI can enable grids to operate beyond their traditional operational limits (IRENA, 2025a). Examples from Australia, India and the United Kingdom show how AI has enabled up to 45% more accurate forecasts compared with traditional methods, enabling better anticipation of wind and solar variability and reduced curtailment (Solcast, 2025; Sustainable Future Australia, 2025).
- **Added value for end users**, helping them experience greater comfort and have more control and awareness of optimisation opportunities. Beyond cost, comfort plays a significant role in energy-related decision making, especially in demand response programmes, and digitalisation can avoid trade-offs. Smart energy technologies (*e.g.* smart thermostats, electric vehicle chargers, home energy management systems) enabled about 70% of United States consumers to gain greater control of their energy consumption while making their homes more comfortable (Smart Energy Consumer Collaborative, 2025).
- **Improved business performance** of energy companies and in other sectors, which demonstrate greater operational and economic efficiency, higher asset utilisation and more competitiveness. In Germany, 42% of manufacturing companies stated energy savings as the motivation for recent digitalisation projects (ZEW, 2023). AI-driven optimisation can reduce energy consumption by 10-60% across the buildings, manufacturing and logistics sectors (WEF, 2025).

IRENA categorises the **added value of digital solutions** in monitoring, forecasting, operational optimisation, end-use automation and transparency. Even simple measures contributing to these value propositions can lead **to powerful outcomes in a digitally orchestrated system**:

- **Monitoring** is the foundational layer of power system digitalisation; it enables all other solutions by providing the data needed for intelligent decision making, automation and optimisation.
- **Forecasting** is among the prominent applications of AI today. Continuous machine learning anticipates weather and consumption patterns, helping to plan and operate systems more efficiently. Thanks to these advances, short-term forecasts have mean absolute percentage errors under 5% today; the result is more efficient dispatch and reserve planning (GET.transform, GIZ, 2024).
- **Operational optimisation** through digital devices deployed by grid operators reduces losses and congestion, balances the system and increases reliability. These advanced technologies can deliver greater granularity and speed, enabling corrective measures at all system levels beyond traditional operating timelines.

- **End-use automation** – using digital market tools, demand-side management platforms and energy efficiency technologies – reduce consumer costs. At the system level, they promote more efficient utilisation of existing grid assets and help alleviate stress in grids by time shifting peak loads.
- **Transparency** enables visibility across the energy value chain and fosters innovation among all actors in the power system.

To harness the benefits of digital solutions for power systems, the global community will have to overcome a set of barriers to implementation. Based on consultations with IRENA member states and experts from all around the world, IRENA identified four key challenges in both advanced and emerging and developing economies.

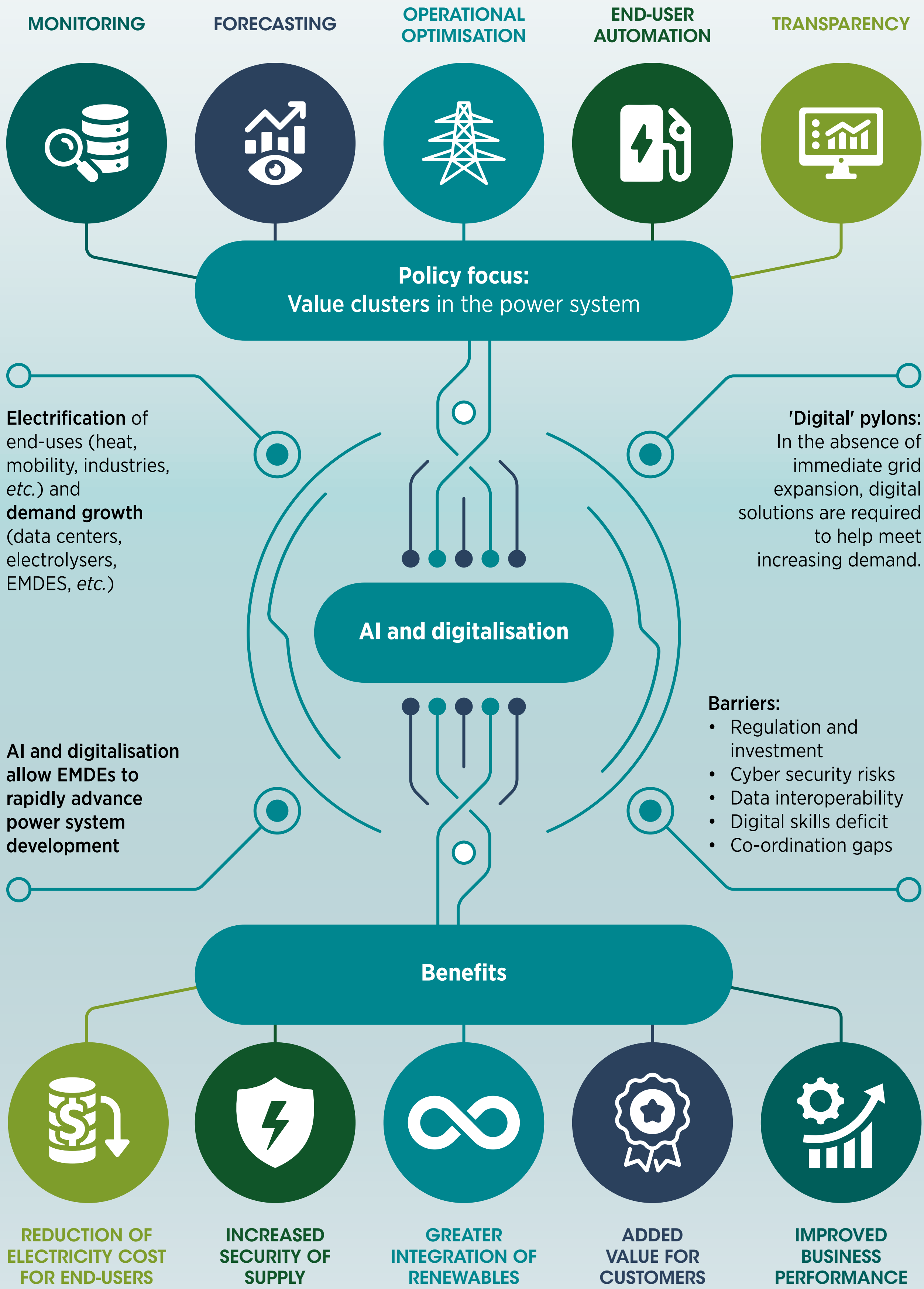
AN ACTION AGENDA FOR G7 AND INTERNATIONAL PARTNERS

IRENA has the following recommendations for a **G7 action agenda** that supports worldwide power system transformation using digital solutions and promotes universal prosperity:

- **Data and interoperability:** Support the improved collection, processing and exchange of data, alongside appropriate cyber security measures, to lay the foundation for digital solutions.
- **Digital skills:** Support measures that train the global workforce in digital skills for everyday application, preparing them for a new age in power systems.
- **Enabling factors:** Encourage the innovative regulations required for digital solutions' integration in power system applications (whose lead times and life cycles vary), even while prioritising energy security. Long-term planning across both the electricity and digital sectors is vital for the cost-effective implementation of digitalisation efforts.
- **Co-ordination:** Improve stakeholder co-ordination supporting specialised local, regional and global initiatives, as many successful initiatives in this report show. Partnerships between grid operators, member states, digital innovators, data centres and regulators are key to accelerating power system transformation in a digital age.

IRENA stands ready to support the G7 and the IRENA membership on this promising pathway to create more affordable, secure and reliable power systems with digital solutions.

DIGITAL ADVANTAGE



Note: AI = artificial intelligence; EMDEs = emerging markets and developing economies.

1. INTRODUCTION

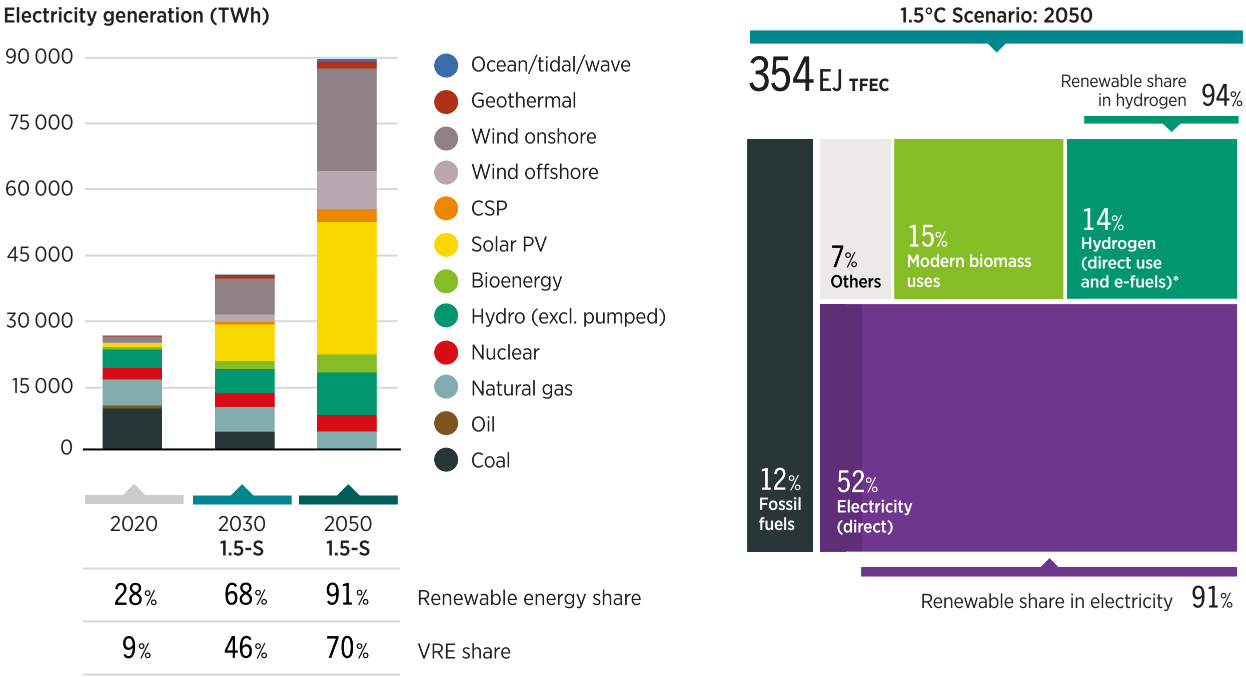
Amid growing global electrification efforts, the efficient management of power systems to deliver affordable, reliable and sustainable energy is becoming ever more important. In this context, both advanced as well as emerging markets and developing economies (EMDEs) can gain from innovative digital solutions – supported by revolutionary advances in artificial intelligence (AI) – that provide new means to achieve affordable, reliable and sustainable supply.

The Group of Seven (G7) has already highlighted the key role of digitalisation in accelerating the energy transition – particularly in making energy systems more flexible, modernising grids and integrating renewable energy – as reflected in its statements on the digitalisation of power grids, efforts to boost flexibility by integrating demand response and energy storage, and international co-operation on digital energy solutions (G7, 2024). Canada's 2025 presidency is committed to accelerate this development and drive power system transformation, recognising its importance to broader energy, economic and national security imperatives, by advancing a G7 Energy and AI Workplan to address the energy challenges of AI, harness its innovative potential, and drive integration of digital technologies into the energy sector to strengthen affordable, secure, and reliable energy access globally.

Building on an established advisory to the G7 (IRENA, 2024b, 2024c, 2024d, 2024a), work on innovation in energy systems (IRENA, 2019a, 2020, 2023a) and its global tracking work (IRENA, 2024a; IRENA *et al.*, 2025), IRENA, with its membership of 170 countries worldwide, is committed to supporting the G7 in advancing power system transformation for the benefit of the global community.

End use electrification (*e.g.* transport, heating and cooling) is expected to drive the growth of electricity demand in the coming years. Renewable energy holds strong potential in this context. Robust economic drivers are enabling renewable capacity additions. In the year 2024, 91% of all newly commissioned utility-scale renewable energy projects delivered electricity at a lower cost than the cheapest new fossil fuel–fired alternative (IRENA, 2025b). Renewables constituted 92.5% of all capacity additions (against 85.8% in 2023), with Asia hosting 72% of these additions. The G7 countries (excluding the European Union) accounted for 14.3% of new renewable capacity. IRENA's 1.5°C Scenario indicates a 52% share of electricity in final energy by 2050. Power system reliability and cost efficiency are foundational for energy security and affordability in this scenario, implying a larger role for digitalisation to deliver on those outcomes (Figure 1.1) (IRENA, 2024a). In some countries, additional consumption from data centres is expected to surge. For example, Ireland's data centres are forecasted to consume 31% of the country's yearly electricity production by 2030, and those in the United States are estimated to consume 7-12% by 2028 (Berkeley Lab, 2024; EirGrid, SONI, 2024). Other factors such as the electrification of mobility and, in many countries, heating, contribute to global energy efficiency gains and sustainability but also to potential stress on electricity grids. These possibilities further underline the need to harness the benefits of digitalisation and AI across technological, regulatory and operational dimensions.

Figure 1.1 IRENA's 1.5°C Scenario



Note: Renewables dominate the supply side and electricity demand dominates the demand side. Renewables are now clearly driving the global expansion of power supply; solar photovoltaic alone accounts for approximately 73% of all new renewable capacity in 2023. The graph illustrates the projected global electricity generation through 2050, which reaches nearly 90 000 terawatt hours and is increasingly dominated by wind and solar, consistent with the goals of the Paris Agreement. The right-hand figure depicts the rising importance of electricity on the demand side. The share of electricity is expected to grow from around 20% today to 52% by 2050, highlighting the critical role of electrification in a sustainable energy future (IRENA, 2023b, 2024a). CSP = concentrated solar power; EJ = exajoule; PV = photovoltaic; TFEC = total final energy consumption; TWh = terawatt hour; VRE = variable renewable energy.

This report looks to digitalisation as a key enabler of power system transformation. Digitalisation, in the context of power systems, is defined as the integration of digital technologies in system planning, operation and management. This includes the use of sensors, smart meters, communication networks, data platforms and automation tools to make grids more reliable, efficient and flexible and increase customer engagement. AI for energy systems refers to the use of computational models and algorithms that are capable of analysing data from energy environments and monitoring, predicting, optimising and automating operations – with some autonomy – across the energy value chain. The term "digital solutions" encompasses digitalisation as well as AI applications (European Commission, 2018).

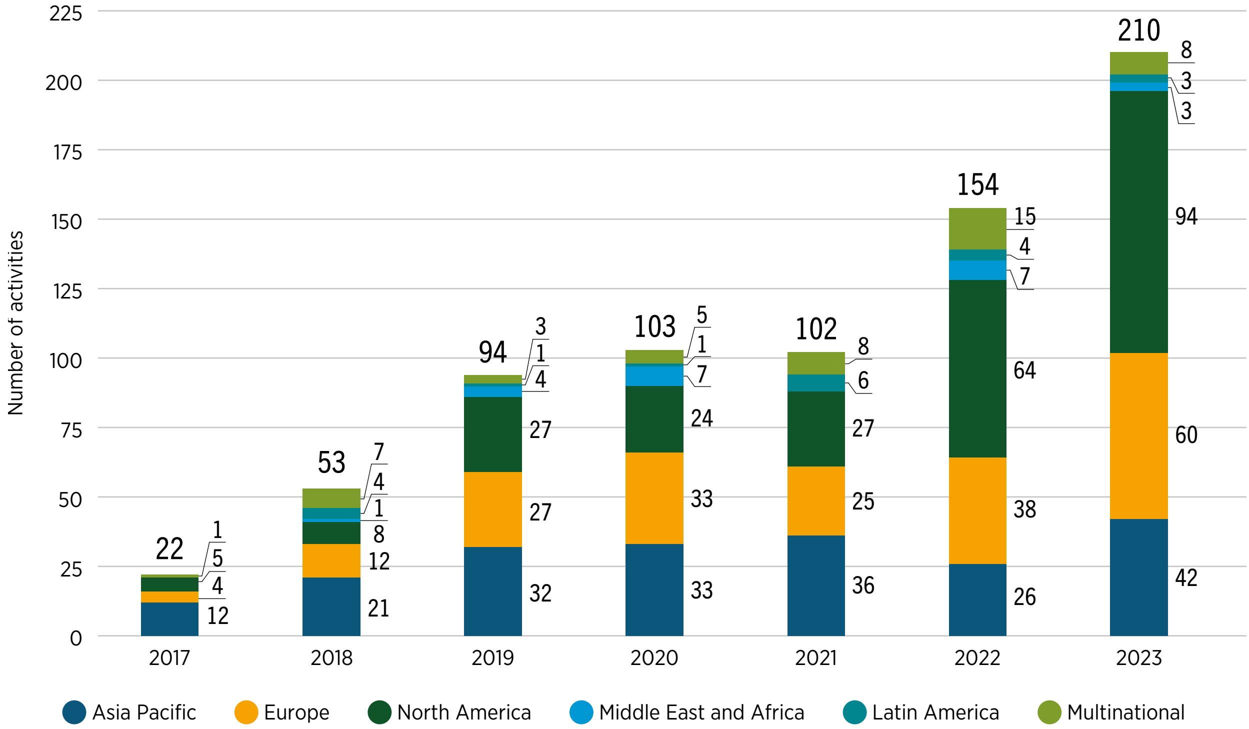
While efficiency gains are inherently desirable for system management, they also help to accommodate the rising deployment of variable renewable energy, thereby amplifying the benefits of low-cost technologies. Digital solutions enable faster, more efficient system response by automating repetitive tasks or tasks that involve large volumes of data. From smart grids and predictive maintenance to real-time data analytics and AI, digitalisation can drive efficiencies, make grids more flexible, improve system planning, increase effective network capacity and optimise energy consumption. At the same time, implementation of a more co-ordinated approach is needed to fully realise the potential of digital solutions to accelerate the energy transition.

The rise of digitalisation in energy also brings its own risks. Increasing reliance on digital infrastructure creates data privacy concerns, exposes infrastructure to cyber attack and might lead to vulnerable populations getting left behind. This report explores the complexity of digitalisation, offering a balanced perspective on a digital transition in the energy sector.

The G7, through its global leadership, can support and accelerate the worldwide adoption of digital solutions in the energy transition. Digital solutions can yield energy efficiency gains and make energy systems more resilient and sustainable. There is significant potential to leverage them for the public good in EMDEs that are working to modernise and expand their energy systems.

Advanced economies and EMDEs face mostly similar challenges to deploying digital solutions – skills, investment, regulatory gaps and a lack of co-ordination are the major barriers, as IRENA finds. Yet, the number of digital projects deployed and the implementation rates are higher in the North American and European energy sectors than elsewhere in the world. BloombergNEF's analysis of publicly available project information suggests that, in 2023, more than 3.5 times as many digital projects were deployed in North America and Europe as in the Asia-Pacific, and more than 10 times as many as in the rest of the world (Figure 1.2).

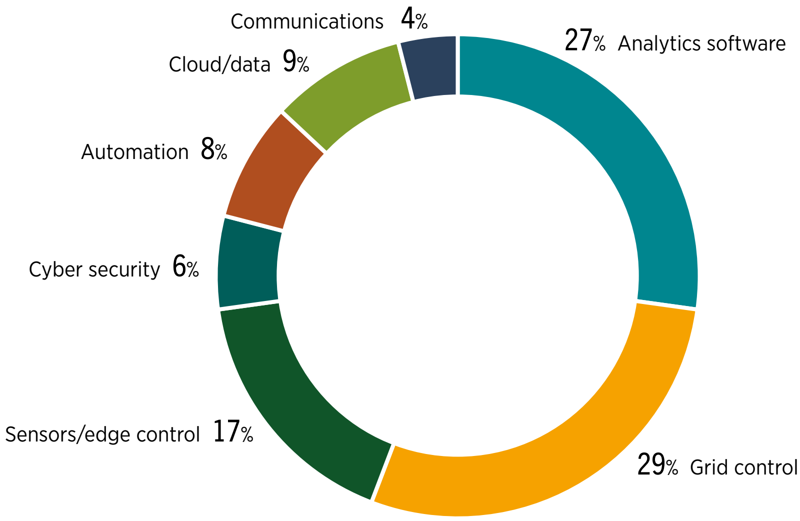
Figure 1.2 Number of digital projects and partnerships tracked by BNEF in the power sector, 2017-2023



Source: (BNEF, 2024).

Apart from the regional differences and the global trend, an assessment of the focus of the projects can give a sense of the fields that are concentrating higher attention (Figure 1.3).

Figure 1.3 Power sector digitalisation by technology area, 2023 and 2024



Source: (BNEF, 2024).

Note: BNEF tracked 353 projects, in 2023 and 2024, in the areas of grid control, automation, analytics software, cloud/data, communications, sensors/edge control and cyber security. Overall, grid control activities accounted for almost a third of the total activities, due to distributed energy resource management systems, virtual power plants, advanced distribution management systems, vehicle-to-grid, demand response and digital substations.

Beyond the regional differences, in EMDEs, challenges differ in scale and can be exacerbated by a weak ecosystem that does not fully support those technologies. Infrastructure coverage is poor (*i.e.* Sub-Saharan Africa accounted for 85% of the global population without electricity as of 2023 [IEA *et al.*, 2025]), as well as spending on research and development (R&D). Although R&D spending in Northern Africa and Western Asia slightly increased in 2023, they received only 4% of global R&D spending that year (Bonaglia *et al.*, 2024). Low-income countries are 2.5 times as likely to default on private investments as high-income countries (Galizia and Lund, 2024). IRENA finds that, in 2024, the weighted average cost of capital for generation projects was roughly 3.8% in Europe, versus 12% in Africa (IRENA, 2025b). Overall, these challenges slow the adoption of digital solutions.

Meanwhile, IRENA recognises that EMDEs are a diverse group of countries with very different structures and challenges. Some of these countries are realising digital achievements in many areas of society, not just energy, and have much deeper digital penetration than more advanced economies. For example, the Democratic Republic of Congo, Sierra Leone and Bangladesh have implemented innovative pay-as-you-go business models and integrated digital solutions, such as Internet of Things (IoT), smart meters and mobile payments to increase access to clean electricity (IRENA, forthcoming). As this report addresses the challenges facing EMDEs, it does not imply that those challenges apply to all EMDEs, or that a particular pathway could benefit all of them equally. Instead, it showcases several successful, innovative initiatives towards power system transformation in EMDEs and encourages the global sharing of best practices, learning and innovation.

The report begins with a discussion of five value clusters of digital solutions in power systems transformation, – monitoring, forecasting, operational optimisation, end-use automation and transparency. It then explores the concrete benefits of digital solutions and lists use cases related to each cluster (Chapter 2). In Chapter 3, the report will identify and discuss the barriers to implementing digital solutions and discuss innovative initiatives to overcome them. Building on IRENA's innovation work stream, stakeholder surveys and multiple interviews, the report seeks to outline an action-oriented roadmap to accelerate the deployment of digital solutions – in the G7 and international community – to enable a power system transformation that delivers energy security, affordability and reliability.

2. THE DIGITAL VANTAGE: ADDED VALUE OF DIGITALISING POWER SYSTEMS

Digitalisation is a broad concept that extends beyond a mere analogue-digital substitution to encompass diverse and evolving applications that enable automation and smart systems by harnessing computational capabilities. Digitalisation, therefore, is not a closed-end task but the transformational process that leverages innovations in information technologies to enhance the systems where they are applied.

Digitalisation initiatives in power systems are not new. Examples such as supervisory control and data acquisition (SCADA) systems and phasor measurements have been used by utilities for decades. However, the scale (millions of endpoints), needs (managing growing complexities from variability to congestion to flexibility) and tools (advanced and ubiquitous sensors/meters, revolutionary computational capabilities as AI and quantum) that extend and advance these legacy capabilities are more relevant today than ever before.

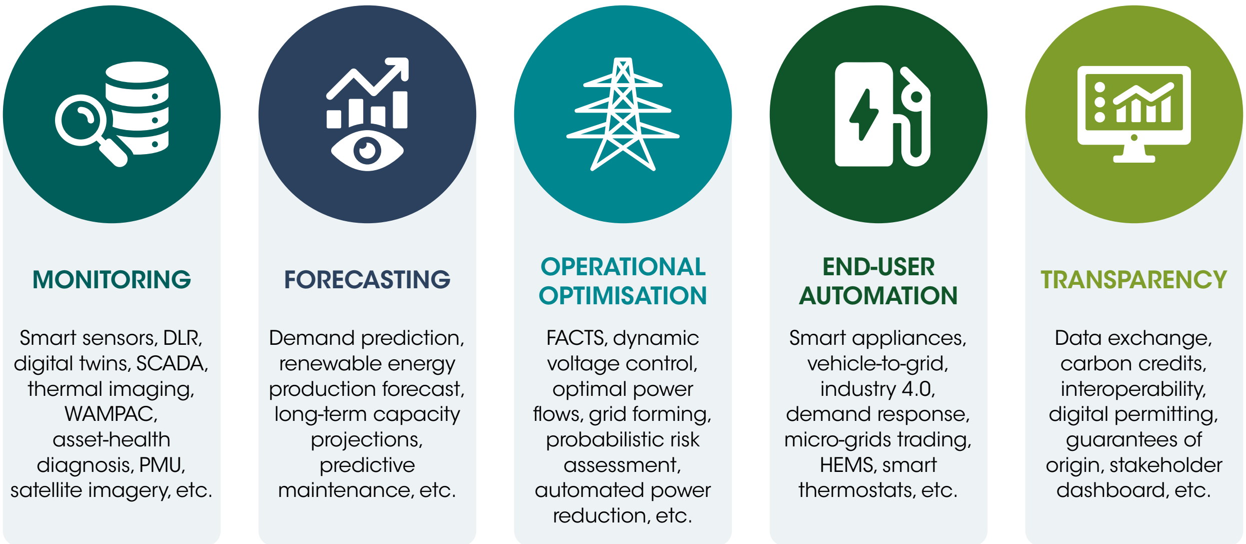
Digital technologies can support the operation of energy systems with complex and diverse assets; they can do so using optimised forecasting, operation and maintenance, among other approaches. This is expected to boost efficiency and support energy security by making systems more reliable and resilient (IRENA, 2025a).

Categorisation is a needed step to sort the ever-growing and evolving initiatives and solutions that digitalisation entails for the power system. The following sections categorise digital solutions by added value and benefits. Selected use cases are described based on short-term implementation potential, highlighting the solutions that can be delivered soon, especially with the right stakeholder support.

2.1 VALUE CLUSTERS

Initiatives or solutions included under power system digitalisation can be categorised following multiple approaches. This report considers the value proposition as the originator of specific use cases. Such an understanding implies that digital technologies, policy measures and business models can be classified into the value clusters of **monitoring**, **forecasting**, **operational optimisation**, **end-user automation** and **transparency**. These are selected under the rationale that even the simplest value proposition of a digitalisation business model or policy action can address specifically one of these clusters. Together, these clusters lead to the digital orchestration of power systems towards the diverse benefits described later in this chapter. Figure 2.1 illustrates the value clusters of power system digitalisation.

Figure 2.1 Value clusters



Notes: DLR = dynamic line rating; FACTS = flexible alternating current transmission system; HEMS = home energy management system; PMU = phasor measurement unit; SCADA = Supervisory Control and Data Acquisition; WAMPAC = wide area monitoring protection and control systems.

2.1.1 Monitoring

Monitoring is the foundational layer of power system digitalisation. All other digital solutions rely on monitoring, which supplies the raw, structured and contextual data necessary for intelligent decisions, automation and optimisation. Without robust monitoring, effective implementation of forecasting, operational optimisation, end-user automation and transparency are not possible.

Monitoring encompasses acquiring, transmitting and handling data from across the entire energy supply chain, from generation systems and transmission to distribution networks to end users. It relies on real-time and historical data on electrical parameters, asset conditions, environmental factors and user behaviour, among other data.

Several basic technologies come under this value cluster:

- **Sensors:** These are the primary data acquisition tools. They gather data on physical and environmental parameters, such as voltage, current, temperature, vibration and humidity. Advanced sensors, including nanoscale and AI-enhanced variants, enable high-resolution, context-aware monitoring.

- **Smart meters:** Installed at consumer endpoints, smart meters provide granular consumption data and support two-way communication with utilities. They form the backbone of advanced metering infrastructure (AMI) and help produce insights on demand and respond appropriately to flexible pricing schemes (EPICO, Guidehouse, 2025).
- **SCADA systems:** They integrate field devices, communication networks and central processors to monitor and control grid operations, as well as generators and power assets in general. They are essential for real-time situational awareness and remote asset management.
- **Phasor measurement units (PMUs) and wide area monitoring protection and control systems (WAMPACS)** provide synchronised, high-frequency measurements across large grid areas. They increase visibility and enable fast response to disruptions.
- **Digital twins:** These virtual replicas of physical assets continuously ingest sensor data to simulate behaviour, detect anomalies and forecast degradation. They are increasingly used for testing digital systems in the design phase, conducting predictive maintenance and optimising asset life cycles, as well as for system surveillance and assisted operation.

Monitoring is the foremost step in the digital transformation of power systems. Monitoring based on comprehensive, high-quality data (acquired and managed) enables the development and implementation of the solutions envisioned in the other value clusters. It is the basis for smarter, and thus more resilient, and more sustainable, energy systems.

Specific use cases under monitoring include highly granular monitoring of system parameters, real-time monitoring of asset health, wide-area situational awareness (WAMPACSs/PMUs), system communications and cyber security anomaly detection, and monitoring of the environment and weather conditions.

2.1.2 Forecasting

Advanced digital solutions and technologies (*e.g.* AI) strengthen power systems through their enhanced forecasting capabilities that produce meaningful insights by combining highly accurate data with ever-evolving analytics. Multidimensional predictive modelling and continuous machine learning, which are among the best-known areas of AI application, anticipate weather and consumption patterns. With these applications, generation and demand, as well as their scale-ups, among other aspects, can be efficiently scheduled and managed. Better forecasting enables better system planning and operation. It relies on advanced algorithms for the handling of specialised datasets.

Forecasts are crucial in performing unit commitment (*i.e.* scheduling the power generators to be connected in each time period) and in managing reserves (*i.e.* scheduling the amount of stand-by power to handle variations in generation demand) and grid congestion. As the shares of variable renewable energy (VRE) and other distributed energy resources grow, power systems are having to adapt to rapid variability; this may incur additional costs to ensure reliability. Better forecasts effectively cut system costs by reducing the need for reserves, and reducing renewable energy curtailments and imbalances. A pilot project across the United States and Canada shows that integrating probabilistic solar forecasts could save 10-25% in regulation (*i.e.* reserves) procurement, exemplifying the significant potential of advanced forecasting in reducing costs and increasing reliability (The Johns Hopkins University, 2022).

Specific use cases can be categorised as follows:

- **AI-enhanced demand forecasting:** Advanced analytics (machine learning, neural networks) leverage weather data, historical usage data, data on social events and patterns, and real-time data to generate more accurate predictions of electricity demand than conventional methods. Advanced analytics models continuously retrain on new data to capture evolving patterns (*e.g.* electric vehicle [EV] charging, prosumer behaviours, industrial loads, heating or cooling inertias, or even cooking times). Better forecasts allow generators, grid operators and aggregators to plan dispatch and reserves optimally. Studies show that AI can markedly improve load prediction and demand-response planning; for instance, linear regression and machine learning algorithms can effectively predict power demand at both system and regional levels.

- **AI-enhanced forecasting of variable renewable generation:** AI and statistical models analyse weather forecasts and historical output to predict wind and solar generation. Advanced AI techniques known as *ensemble learning* or *convolutional neural networks* can now produce highly accurate short-term forecasts (minutes to hours ahead). Better VRE forecasts allow operators to ramp up other resources and manage reserves correctly. On the other hand, highly accurate weather-based forecasts, with high temporal and geographical granularity, improve load balancing and renewable integration, making operations more reliable and cost-effective.
- **Short-term market price forecasting:** AI models can predict short-term electricity prices by combining demand and generation forecasts. This enables dynamic pricing, supports market operations and empowers consumers to make cost-effective decisions – either through behind-the-meter automations that leverage arbitrage opportunities, or by selecting a provider that implements these advanced forecasts to offer lower prices.
- **Predictive maintenance:** AI and machine learning algorithms process real-time data on the state and condition of power system assets, resulting in predictive maintenance that reduces equipment downtime, maximises system reliability and extends asset life.

2.1.3 Operational optimisation

Operating existing assets more efficiently (and more securely) minimises losses and congestion, helps balance the system, contributes to reliability and increases effective grid capacity. Modern digital solutions add granularity to and speed up established practices (state estimation, optimal power flows, stochastic planning) followed at the transmission and distribution levels and enable fault correction in less than the time needed by human operators. In addition, digitally enabled operational optimisation supports the development of reliable off-grid solutions. While monitoring helps detect losses, digital loss reduction solutions focus on specific actions to reconfigure the grid based on real-time analysis, smart management of power flow and voltage, and operational reserves' optimisation.

- **Power flow optimisation:** Advanced optimisation tools (real-time optimal power flow, flexible alternating current transmission system [FACTS] controllers, distributed algorithms) adjust voltage and currents to minimise losses and maximise grid usage. Controlling capacitor banks, tap-changers and phase shifters smartly keep power factors near unity. State estimators and machine learning continually refine power flow models. In distribution, smart inverters and controllable devices rebalance phase loads. In the last decade, diverse studies of the US Department of Energy have proven that using real-time control of reactive power and balancing can reduce distribution losses by up to 30% (US DOE, 2015, 2024).
- **Probabilistic assessment:** Digitalisation empowers stochastic planning solutions. Stochastic planning is particularly relevant for systems with large hydropower reservoirs, such as in Canada and Brazil, where water inflows and storage levels introduce significant uncertainty. Digitalisation also makes it possible to quantify disruptive events (equipment failure, demand surges, weather volatility). Instead of using worst-case deterministic rules, operators leveraging advanced AI solutions can run multiple simulations of uncertain scenarios using data-driven forecasts of renewables and loads. Extended simulation capacity increases operators' ability to identify vulnerable lines and set reserves more flexibly; this reduces power

losses. Further, such analytics let planners weigh a small probability of failure against cost and help find more cost-optimal approaches to operate.

- **Quantum computing** is explored as a means to solve complex optimisation problems in power systems (*e.g.* load flow analysis and grid reconfiguration), which require increasingly more computation as distributed renewable energy sources and flexible loads are integrated. By performing system-scale simulations at unprecedented speeds, quantum algorithms can efficiently identify optimal solutions for power flows and for preventing and mitigating contingencies, in turn enabling real-time action to, for example, boost supply security and renewables integration (Thomas Morstyn, 2022; TNO, Quantum Delta, 2025).
- **Co-ordination/aggregation of distributed energy resources (DERs):** Aggregation services aggregate multiple small resources as one resource. For instance, aggregators or virtual power plants bundle DERs like rooftop photovoltaic, batteries, controllable loads and EV chargers and then optimise their combined output or consumption via cloud-based control. Aggregation means multiple distributed resources can be observed and eventually controlled collectively; this enables maximum visibility for system operators, to maintain efficiency and security of supply, and enables smarter system operation.

2.1.4 End-use automation

This cluster includes digital market tools, demand-side management platforms and energy-efficiency technologies that help reduce costs for consumers. At the system level, demand-side automation can flatten peaks, shifting demand to minimise the curtailment of renewable energy sources, and relieves congestion, improving the utilisation of existing grid assets and preserving grid reliability, until it is reinforced.

These are user-facing or market-integrated solutions that translate system efficiencies from demand response into direct financial benefits for end users, often through smart pricing or utilising energy usage insights. But although the kind of devices capable of providing these services are effective, they often have long replacement cycles (*e.g.* a decade or more). Therefore, this requires timely implementation of related policies and regulations to support the replacement of legacy devices lacking demand response capabilities, with these smart alternatives.

- **Adaptive demand from appliances and devices:** Digital home/building systems (smart thermostats, IoT appliances) can automatically – on their own or via an aggregator – shift loads to periods of low wholesale market prices or high renewables. For example, a smart dishwasher may delay washing until electricity prices drop (*e.g.* when solar photovoltaic [PV] generation is abundant). This is because smart appliances (*e.g.* a smart fridge) can smartly adjust their functioning time or thermal hysteresis to these factors, without any impact in performance. This demand response, enabled by real-time pricing signals, can considerably reduce bills. Among other devices, heat pumps can help achieve relevant peak demand cuts even just with their smart behaviour, as research shows. A wide implementation of these peak load shifting measures can help not only residential consumers but all users save up to 25% on bills, by avoiding the need to run extremely costly peaker power plants (IRENA, 2024e).
- **Adaptive behaviour from battery energy storage systems (BESSs) and EVs:** Smart charging and discharging of batteries and EVs make them active participants in balancing the grid. An EV can charge during off-peak periods or when solar is plentiful, and even feed power back into the grid during peak periods (vehicle to grid). Home batteries can store cheap overnight power for daytime use. These devices decide charging rates based on digital signals (real-time prices or aggregator commands). Given that smart charging avoids adding to peak loads and enables smart appliances to act as distributed storage resources, its application beyond standard uses significantly boosts flexibility.
- **Adaptive demand from industries:** Industry 4.0 is defined as the integration of intelligent digital technologies (*e.g.* IoT, AI and big data analytics) into manufacturing and other industrial processes,

enabling the smart operation of machines (*e.g.* electric motors). For example, companies can use short-time pricing and signals to adjust operations (*e.g.* slowing non-critical processes during peaks or adapting parallel workstreams in factories into batches that leverage dynamic tariffs while not impacting delivery times, or using thermal storage systems for processes utilising heat). Several opportunities lie in industrial hardware digitalisation. For example, only a handful of large industrial motors use variable speed drives, which can, however, reduce motor energy by up to 60% and respond to price signals. Such smart control yields significant savings: studies estimate that using efficient motors and drives on a price-response basis could help US industry save 85 gigawatt hours/year (GWh) (Fraunhofer ICT, 2023).

2.1.5 Transparency

Transparency solutions do not directly impact technical performance but are essential for governance. They are crucial for building trust among stakeholders and making informed decisions. They enable visibility across the energy value chain and foster innovation. Because electricity networks and most electricity markets are regulated, transparency and access to information are design principles that promote fair competition and enable improved outcomes for consumers.

Digital platforms (*e.g.* open data platforms, visualisation dashboards, traceability tools for renewable energy certificates) offer regulators, planners, developers and investors access to actionable information. For users, access to clear metrics (*e.g.* electricity hourly consumption data) – through a web platform or a digital display panel on meters – along with recommendations for efficient consumption, significantly influences a shift in their behaviour towards energy efficiency. Tailored automation on these platforms can help produce user-friendly insights and enable transparency, making this information accessible and understandable for non-technical stakeholders also.

Transparency solutions do not directly optimise energy flows or technical performance; rather they improve governance, induce trust and enhance decision making by increasing visibility, which also triggers innovation and fosters evolution along the energy value chain.

Energy attribute certificates (EACs), known as renewable energy certificates (RECs) or guarantees of origin (GOs) depending on the region, are another instrument that increases transparency. They are unique digital certificates that verify the source of electricity generation, particularly from renewable sources. EACs make energy markets more transparent by allowing consumers and businesses trace the origins of their energy and make informed choices. Digital platforms streamline the issuance, tracking and trading of EACs, supporting voluntary green procurement, helping consumers make informed choices and ensuring regulatory compliance. However, EACs today typically lack the exact time of generation. This is a key upgrade needed as power systems move towards real-time green power balancing, that can be enabled by digital technologies such as blockchain.

Digital permitting refers to the use of digital tools to streamline and automate the permitting process for energy infrastructure projects. By digitising workflows, integrating geospatial data and enabling real-time stakeholder collaboration, digital permitting reduces administrative bottlenecks and accelerates project timelines. For example, AI can ease administrative bottlenecks by accelerating the evaluation of environmental impact assessments – a common case where duplicities cause inefficiencies, but assisted systematic analysis can considerably accelerate processes. Digital permitting also boosts transparency by allowing developers and the public greater access to permitting criteria, progress and decisions.

Market transactions and retail: Digital platforms improve bidding and make settlement and billing transparent. In turn, they reduce disputes and costs for retailers and market operators (G7 Communiqué, 2024).

Further, Explainable AI (XAI) techniques make AI models more interpretable and transparent. In turn, stakeholders are better able to understand the rationale behind AI-driven decisions in renewable energy systems (*e.g.* generation dispatch, maintenance scheduling, storage charging and discharging patterns). This fosters trust and accountability, especially in areas like grid planning, market forecasting and asset management (Ukoba *et al.*, 2024).

2.1.6 Quantifying value for the power system

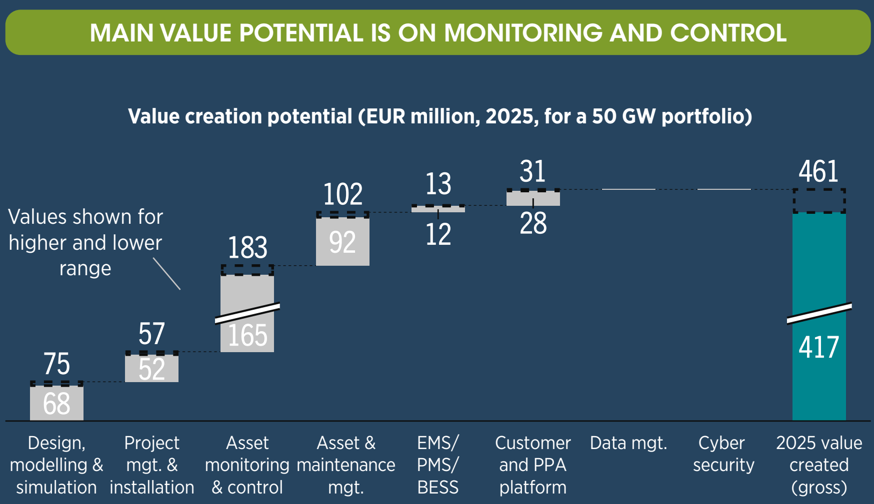
IRENA's proposal of five value clusters qualifies how implementing digital solutions in different areas can add value at the system level. Quantifying value forecasts across these clusters, however, is inherently complex. It depends on the perspective of the stakeholder – whether a utility, developer, consumer or regulator – as well as on market structures, regulatory frameworks and the maturity of digital adoption. Metrics such as operational and capital expenditure savings, reliability improvements, revenue growth, avoided outages (continuity of supply) or consumer cost reductions vary widely across contexts.

To illustrate how value can be quantified from a specific stakeholder's perspective, Figure 2.2 presents aggregated data from mature renewable energy developers mainly from Europe, the United States and the Middle East. The figure presents consolidated minimum and maximum savings for each type of digital platform. In turn it shows potential cost reductions via efficiency in operational cost (and annualised capital costs), but also potential for additional revenue, summing up to EUR 417-461 million for this exemplary portfolio (*e.g.* by maximising the energy output thanks to reducing the maintenance time). Across area ranges, the difference from the mean for most areas (excluding energy management systems [EMSs]/power management systems [PMSs]/BESSs) is 4.6%-5.2% (5% for the overall portfolio), giving mature developers a good indication of what to expect. According to Guidehouse, these figures are more conservative and based on projects of established developers that have formalised and implemented operation and maintenance (O&M) processes and organised O&M structures, but have potentially more significant effects on less mature utilities or emerging markets and developing economies (EMDEs) (Guidehouse, 2025). The value of data management and analytics is not shown here but is foundational for digital solutions to operate.

Box 2.1 Creating value through digitalisation

Figure 2.2 depicts an aggregated portfolio (of 50 gigawatts [GW]; solar [60%] and wind [40%, onshore and offshore]) of multiple developers. The total value creation potential varies widely across portfolio areas; it is rather moderate in energy management systems, power management systems and battery energy storage systems (EUR 12-13 million) and grows to become quite significant in asset monitoring and control (EUR 165-183 million). Data management and cyber security are not accounted for, but especially cyber security is seen as "insurance" against value losses resulting from non-compliance or cyberattack.

Figure 2.2 Quantifying the value creation of digitalisation for renewable developers (in a 50 GW portfolio)



COMMENTS

Value creation shown includes **solar and wind assets** (onshore/offshore) and includes reductions in OPEX & annualised CAPEX and increases in revenue (electricity outputs)

Value of data management and analytics not quantified but expected to add high-value (building the foundations via integrated database and AI and analytics for many of the functions)

Cyber security seen as **'insurance'** against significant losses of value due to non-compliance or cyber attacks

Source: (Guidehouse, 2025).

Notes: As per the copyright holder, this content is for general informational purposes only and should not be used as a substitute for consultation with professional advisors. AI = artificial intelligence; BESS = battery energy storage system; CAPEX = capital expenditure; EMS = energy management system; GW = gigawatt; mgt = management; OPEX = operational expenditure; PMS = power management system; PPA = power purchase agreement.

In an example of value creation, the Danish system operator Energinet reduced costs as of 2025, shifting its traditional procurement of operational reserves by implementing an AI-enhanced weather forecast. The model leverages weather data for improved forecasts and informs the procurement of the day-ahead reserve. In its test phase in early 2025, Energinet reported savings of 10-15% in operational reserves for the first week in comparison with conventional procurement, corresponding to savings of DKK 1.1 million weekly or approximately DKK 60 million annually (above USD 9 million); further improvements are expected (Bjørn Godske, 2025). The Belgian Elia Group started a dynamic dimensioning test phase as early as 2020 and served as an inspiration for the Energinet project (described further in Box 2.2). Elia Group's test phase showcased how successful development of innovative solutions can be spread via peer learning (Elia Group, 2023).

Box 2.2 Energinet project

Energinet's new approach to the procurement of the manual frequency restoration reserve (mFRR) leverages AI-based weather forecasting. Before it introduced this approach, Energinet purchased a day-ahead reserve of 900 megawatts (MW) every day (distributed between the two major grids Great Belt [DK2] with 600 MW in the east and Great Belt [DK1] with 300 MW in the west). Improved weather forecasting can help Energinet limit its day-ahead mFRR purchase. During the test phase, no purchases under 800 MW were allowed, regardless of the forecast, although effectively, the threshold of 800 MW was met across all the test-phase days. The expectation is that savings can further increase relative to the test-phase results.

The examples provided illustrate how added value from digitalisation can translate into tangible financial benefits for a specific stakeholder. While extrapolation to other contexts may require caution, it serves as a compelling conclusion to the value cluster framework, highlighting the real-world impact of digital solutions.

2.2 POWER SYSTEM DIGITALISATION: A BENEFITS-ORIENTED APPROACH

While the different areas of digitalisation's added value for power systems need to be understood to evaluate digital solutions' true potential, unlocking investment decisions requires identifying final benefits. Any energy value chain stakeholder needs to be able to conduct a qualitative and quantitative cost-benefit analysis.

Power system digitalisation can bring many benefits, including socio-economic benefits, which are beyond the scope of this report. In the context of the present analysis, IRENA, focusing on direct implications for power systems, has identified several key benefits that digitalisation can effectively deliver:

Reduction of electricity costs for end users: Decreasing the final cost of electricity for consumers and businesses through improved operational efficiency, optimised market participation of distributed resources and integration of low-cost generation based on renewables.

Greater security of supply: Ensuring continuous, reliable electricity delivery even under stress conditions, during outages or during extreme events, with faster recovery from disruptions.

Greater integration of renewables: Increasing the share of renewable energy in the generation mix by enabling flexible integration and managing variability effectively.

Added value for customers: Providing end users with greater control of their consumption, greater comfort, and greater awareness and knowledge of the opportunities they have for optimising costs and cutting emissions.

Improved business performance: Improving the operational and economic efficiency of companies in the energy sector or directly linked to it, increasing asset utilisation and strengthening competitiveness.

To map the degree to which the different digital solutions included in each value cluster deliver these benefits, additional sub-categorisation is needed; use cases derive from the value clusters and touch upon their technical specificities.

The use cases identified by IRENA are as follows.

In the **monitoring** value cluster:

- **Highly granular monitoring of system parameters:** High-resolution, real-time measurement of voltage, current, frequency and other critical grid parameters. This includes smart metering infrastructure for granular billing, outage detection and flexibility signals.
- **Real-time asset health monitoring:** Continuous monitoring of grid assets (*e.g.* transformers, lines and substations) using advanced sensors to detect early signs of failure and to optimise maintenance.
- **Wide-area situational awareness (WAMPACS/PMUs):** Co-ordinated real-time monitoring across large grid areas using the so-called synchrophasor technology, enabling WAMPACSs, which help co-ordinate security along regions.
- **System communications and cyber security anomaly detection:** Continuous digital surveillance to detect, analyse and respond to cyber threats in critical energy systems.
- **Monitoring of environmental and weather conditions:** Monitoring meteorological and environmental conditions that affect grid operation and asset performance, using advanced weather and climate sensors, drone-based sensors and satellite imagery.

In the **forecasting** value cluster:

- **AI-enhanced demand forecasting:** Using machine learning for more accurate electricity demand predictions over different time horizons.
- **AI-enhanced forecasting of variable renewable generation:** Predicting wind and solar output with AI to better match generation to demand.
- **Predictive maintenance:** Anticipating equipment failure and scheduling preventive interventions to reduce downtime and costs, using big data and AI-based recommendations for organising maintenance actions, considering not only asset status but also the availability of resources and optimal grid conditions to efficiently plan outages.
- **Short-term market price forecasting:** Optimising power market trading strategies based on wholesale electricity price predictions, utilising machine learning models, fed with granular input of hours to days from cross-sector datasets (*e.g.* grid outages, weather, behavioural demand patterns).
- **Early awareness of grid constraints:** Early detection of potential network bottlenecks and violations of stability parameters, leveraging advanced and constant power flow calculations based on multifactorial algorithms, to prevent overloads and inefficient remedial actions.

In the **operational optimisation** value cluster:

- **Power flow optimisation:** Adjusting electrical flows to minimise losses, avoid congestion and boost system efficiency.
- **Probabilistic risk assessment:** Using probability-based models to evaluate operational risks and prioritise mitigations.

- **Virtual power plants:** Aggregating distributed generation, storage and flexible loads to operate as a single dispatchable unit.
- **Control centre of the future and automated fault location, isolation and service restoration (FLISR):** Fault detection, isolation and service restoration enabling remedial actions in less than the time needed by human operators, minimising outage duration and cascading effects.
- **Dynamic line rating (DLR):** Calculating transmission line capacity in real time based on temperature, wind and other factors, allowing system operators to determine the continuously changing thermal limits of each conductor. This, in contrast to annual or seasonal ratings, implies that each line can be safely operated at higher-than-usual capacities, preventing unnecessary limitations, such as renewable energy curtailments, or other costly measures related to grid congestion.

In the **end user automation** value cluster:

- **Adaptive demand from appliances/devices:** Automatically adjusting appliance usage timing to shift power consumption in response to price or grid signals.
- **Adaptive behaviour from BESSs and EVs:** Using BESSs and EVs to charge or discharge energy dynamically, benefitting from their role as providers of grid flexibility services.
- **Adaptive demand from industries:** Shifting industrial energy usage to reduce costs and support grid stability and enabling to offer flexibility services to the grid automatically.
- **Energy management systems for end users (*i.e.* HEMSs [home], BEMS [commercial buildings] and FEMS [factories]):** Smart systems optimising energy consumption and production for a household or commercial facility.

In the **transparency** value cluster:

- **Improved information flow among stakeholders:** Improving data exchange and co-ordination between grid operators, generators, suppliers and consumers.
- **Granular renewable energy certificates:** Secure and traceable renewable electricity certificates issued via digital platforms and implementing technology such as blockchain for traceability.
- **Digital permitting:** Streamlining licensing and permitting processes through digital platforms.
- **Consumer-friendly dashboards:** Intuitive interfaces helping consumers understand and manage their energy consumption.
- **Open data platforms:** Publicly accessible data hubs providing transparent information on energy systems, supporting interoperability.

Looking at the presented use cases and the defined benefits, a comprehensive link can be drawn showing which use cases excel at delivering which targeted benefits.

In table 2.1, IRENA labels each digitalisation use case according to its relevance as a major catalyst of (full circle) or a relevant contributor towards (half circle) the five benefits listed. The table is a result of extensive research, including expert surveys and interviews of stakeholders around the world. While some of the use cases identified may be at a mature stage of adoption in some regions, they could be game-changers for other regions, especially EMDEs or small island developing states, or deserve renewed attention for their increased potential brought by AI integration.

Table 2.1 Value cluster use cases and digitalisation benefits

Value Clusters	Use case/digitalisation benefit	Reduction of electricity costs for end users	Greater security of supply	Higher renewables penetration	Added value for customers (e.g. comfort, control)	Improved business performance
MONITORING	Highly granular monitoring of system parameters	○	●	○	◒	●
	Real-time asset health monitoring	○	●	○	○	●
	Wide-area situational awareness (WAMPACS/PMUs)	○	●	◒	○	○
	System communications and cyber security anomaly detection	○	●	○	○	○
	Monitoring of environment and weather conditions	◒	◒	●	○	○
FORECASTING	AI-enhanced demand forecasting	◒	◒	○	◒	◒
	AI-enhanced forecasting of variable renewable generation	◒	○	●	○	◒
	Predictive maintenance	◒	●	○	○	◒
	Short-term market price forecasting	●	○	◒	◒	◒
	Early awareness of grid constraints	○	●	○	○	◒
OPERATIONAL OPTIMISATION	Power flow optimisation	◒	◒	◒	○	◒
	Probabilistic risk assessment	◒	○	●	○	●
	Virtual power plants	◒	◒	◒	○	○
	Control centre of the future and automated FLISR	○	●	○	○	●
	Dynamic line rating	●	○	●	○	○
END USER AUTOMATION	Adaptative demand patterns from appliances/devices	●	○	◒	●	○
	Adaptative behaviour from BESSs and EVs	●	○	●	○	○
	Adaptative demand from industries	◒	◒	●	○	◒
	Energy management systems for end users (HEMS/BEMS/FEMS)	◒	○	○	●	○
TRANSPARENCY	Improved information flow among energy stakeholders	◒	○	◒	◒	●
	Granular renewable energy certificates	○	○	◒	●	○
	Digital permitting	○	○	●	○	●
	Customer-friendly dashboards	○	○	○	●	○
	Open data platforms	○	○	○	◒	●

Note: ● Excels at delivering that benefit directly. ◒ Relevant in achieving this benefit. ○ Its contribution to it is a side effect.

AI = artificial intelligence; BEMS = building energy management system; BESS = battery energy storage system; EV = electric vehicle; FEMS = factory energy management system; FLISR = fault location, isolation and service restoration; HEMS = home energy management system; PMU = phasor measurement unit; WAMPACS = Wide Area Monitoring Protection and Control Systems.

This analysis of digitalisation use cases across value clusters and benefits provides actionable insights for diverse stakeholders. Policy makers can identify which value clusters to prioritise depending on the national or regional context.

For instance, regions targeting greater security of supply should focus on foundational monitoring solutions, which also enable the other value clusters. The rollout of monitoring systems, especially smart meters, is a pre-condition for capturing the benefits associated with demand-side management and other demand optimisation strategies for customers, with delays jeopardising progress in other areas.

Meanwhile, regions with mature monitoring systems, for example, regions where smart meters and advanced grid observability have already been massively deployed, could focus on reducing electricity costs via enhanced forecasting and end user automation.

Added value for customers comes primarily from digital solutions as smart appliances/devices delivering adaptive demand, energy management systems, and traceable and granular energy attribute certificates. These are specially relevant to build trust among stakeholders and give visibility to energy policies.

Companies in the power sector can achieve internal efficiencies by implementing real-time asset health monitoring and control centre of the future and FLISR, while diverse industries can greatly benefit from digital permitting and take advantage of short term price market price forecasting.

Use cases that boost renewables penetration include, among others, monitoring of environment and weather conditions, AI-enhanced forecasting of variable renewable generation, probabilistic risk assessment and digital permitting. Digitalisation initiatives resulting in higher renewables penetration are present in all the value clusters, and they tend to have a secondary positive impact on the other benefits pursued.

An illustrative set of case studies helps identify how these digitalisation benefits are realised.

2.3 HIGH PERFORMERS IN DELIVERING BENEFITS – CASE STUDIES

Digitalisation in the power sector is already delivering tangible benefits across diverse contexts. This section presents use cases of high performance that exemplify how digital solutions contribute to the five core benefits outlined – reducing electricity costs for end users, increasing security of supply, enabling higher renewables penetration, enhancing added value for the customer and boosting business performance.

Each subsection explores a specific use case, by detailing its architecture and operational mechanisms, explaining how the use case delivers the targeted benefits and offering a forward-looking perspective on its evolution between 2026 and 2030. These examples serve not only to illustrate impact but also to guide policy makers, regulators and market actors in identifying scalable, replicable digitalisation pathways.

In addition, one example is selected from each value cluster but monitoring – which is the primary step for all the other value clusters.

2.3.1 Reduction of electricity costs for end users: adaptative behaviour of plugged-in EVs (smart charging)

Smart charging refers to adapting the charging cycle of EVs to both the conditions of the power system and the needs of vehicle users. Thus, smart charging is optimised based on real-time data such as data on grid constraints, local renewable energy production, price signals and user preferences.

Digital technologies – including but not limited to AMI and smart meters, cloud-based platforms and IoT, communication infrastructure, and machine learning algorithms for projecting energy demand and forecasting VRE generation – form the basis of smart charging of end-user loads like EVs. Meanwhile, interoperability between EVs, chargers and grid systems remains a challenge. Standardised communication protocols and open application programming interfaces (APIs) are essential for seamless integration across manufacturers and platforms.

Applications of smart charging include automatically shifting charging to when energy costs are low, minimising the wholesale cost of energy (customers can be on a fixed low-cost tariff for the device) or charging during off-peak hours when electricity prices are generally lower (by leveraging time-of-use tariffs). Automated load shifting and peak shaving to participate in ancillary services markets (for instance, balancing) or local flexibility markets are also common existing applications.

How smart charging via digitalisation helps reduce electricity costs for the end user

There are a variety of approaches to smart charging. In unbundled markets, where suppliers/retailers are managing EVs, they can offer a very low per kilowatt hour price for the power consumed by the device; this significantly lowers the cost of vehicle ownership. In power systems where utilities offer time-of-use prices, smart charging systems could automatically schedule charging during off-peak hours, when prices are lower. End users are thus able to benefit from reduced prices overall, while still charging their EVs and maintaining the required mobility.

End-user costs would reduce also if EVs participate in demand response markets or ancillary services markets as flexibility providers for third parties in exchange for revenue (ICCT, 2025).

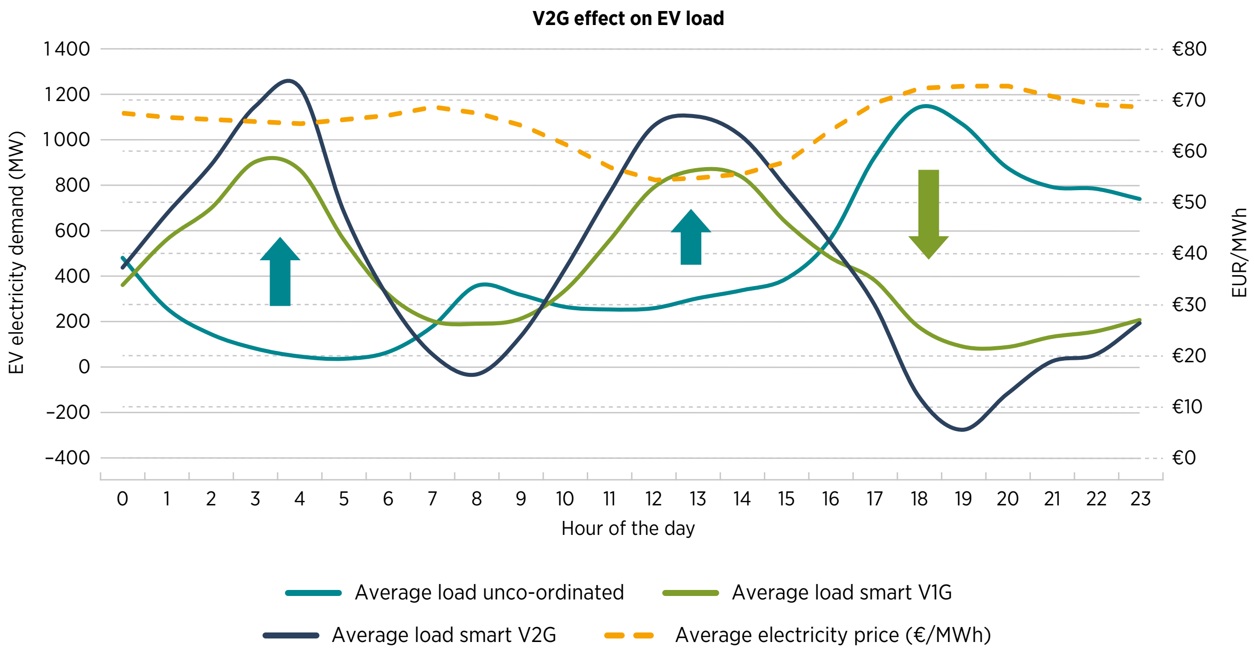
Smart charging and vehicle-to-grid (V2G) could lower the total cost of ownership of EVs by 7% to 29% across Europe (EY, 2025). Recent studies indicate that shifting charging to periods of lower electricity prices in Belgium and Germany can lower the annual electricity costs of EV users by 15% (EUR 30-35) when electricity flows only from the grid to the vehicles, and by 25% (EUR 50-55) when the vehicles feed electricity back into the grid (IRENA, 2023b).

Table 2.2 Enabling steps for the deployment of smart charging

Category	Key steps and requirements
HARDWARE AND SOFTWARE	• Widespread adoption of electric vehicles (EVs). • Smart charging infrastructure. • Smart meters and energy management systems. • Grid connection upgrades for fast charging.
TECHNICAL AND OPERATIONAL ASPECTS	• Interoperability among EVs, chargers and management platforms. • Common standards and communication protocols. • Data privacy and cyber security regulations for smart charging. • Development of standards, including on metering, and conformity programmes (*i.e.* a quality infrastructure system), resulting in more reliable products.
POLICY AND REGULATION	• Policy support for widespread time-of-use tariffs and dynamic pricing. • Regulatory frameworks that enable EVs to participate in ancillary services and incentivising smart charging by allowing revenue streams. • Equitable access to smart charging infrastructure across urban and rural areas and designing incentives to support low-income EV users in adopting flexible charging behaviours. • Streamlined permitting procedures for charging infrastructure. • Defining vehicle-to-grid codes to allow bidirectional charging.
CONSUMER ENGAGEMENT	• Consumer education and awareness campaigns. • Transparency in charging process, price and privacy. • Incentives and compensation schemes for flexibility and easy participation in energy markets.

Based on: IRENA (2023).

Figure 2.3 Smart charging of EVs for electricity cost reduction



Source: (ENTSO-E, 2021).

Notes: EUR = euro; EV = electric vehicle; MWh = megawatt hour; V2G = vehicle to grid.

Outlook 2026-2030

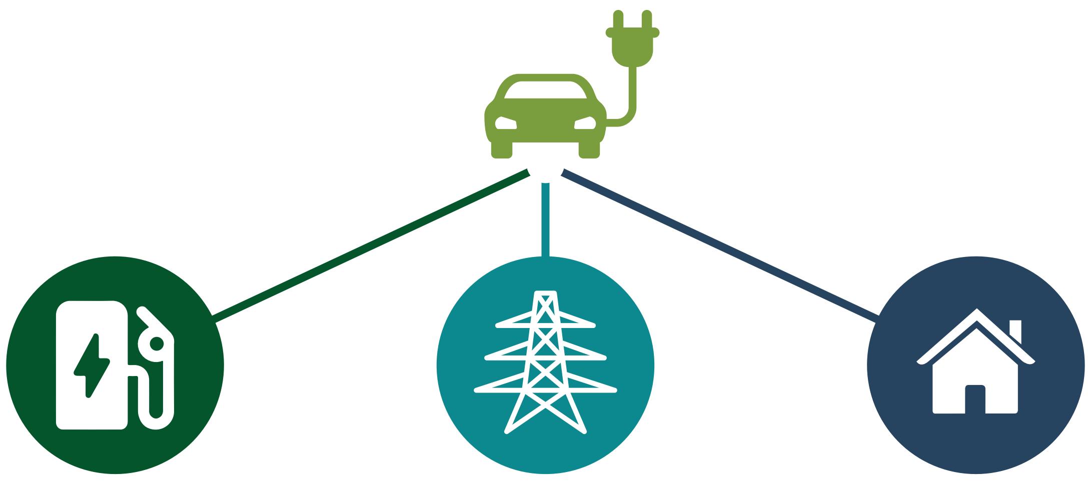
Future advances in digital technologies will enable greater optimisation at a local level (optimising EV charging, solar output and local grid conditions). Greater penetration of V2G-enabled EVs will enable higher dynamic response in low-voltage networks, help ensure reliability in constrained grids and improve voltage management. Other advances, related to monitoring and forecasting, will drive more optimised and accurate adaptive behaviour in EVs.

Advanced forms of smart charging that could support wider EV adoption include unidirectional controlled charging (V1G) and bidirectional charging (vehicle-to-grid or vehicle-to-building) using the vehicle as a source to provide flexibility to the grid and/or to buildings.

V1G, which utilises standard smart chargers with basic metering and relatively simple grid integration, is already a mature, extensively used technology governed by regulation in many regions. However, bidirectional charging is still in early development, facing challenges due to its requirement of advanced two-way chargers; more robust communication infrastructure; and advanced metering systems that can manage reverse power flows. Widespread adoption of bidirectional charging requires upgrading grid safety and protection protocols and developing regulatory and market frameworks (*e.g.* new standards, revenue methods for grid services, and clear guidelines to promote standardisation and interoperability of V2G technologies).

Although V2G can provide more benefits than V1G (*e.g.* grid flexibility services), it is also more costly and requires further technological and regulatory development. Unidirectional controlled charging, which uses off-peak hours to charge, allows the end user to pay less while providing peak shaving services. Hence, an iterative approach is generally appropriate; economies without specific regulation for V2G can leverage the benefits provided by V1G early as regulatory frameworks for V2G evolve (IRENA, 2023a, 2025c).

Figure 2.4 Advanced forms of smart charging



Source: (IRENA, 2019b).

Box 2.3 Smart charging

Market players already use smart device management: by connecting to a car, heat pump or charging equipment via the manufacturer, the system is able to manage the consumption of devices. AI cluster devices based on their flexibility and charging behaviour, and the aggregated portfolio can participate in balancing, capacity and local flexibility markets, as well as in minimising the electricity cost (delivering significant cost savings to EV users – up to 70% lower electricity costs for charging).

For example, Octopus Energy – with its flagship product, Intelligent Octopus Go – optimises EV charging by shifting it away from peak hours. Octopus Energy claims that Intelligent Octopus Go reduces costs by up to 70% while supporting grid stability. With over 270 000 customers in 2025 and over 2 GW under management, Intelligent Octopus Go has become Europe's largest virtual power plant; it participates in both the wholesale arbitrage market and distribution system operators market and in the balancing mechanism, provides demand flexibility services and participates in the capacity market. Intelligent Octopus Go was launched in Spain at the end of 2024. There, it currently manages over 1 500 EVs. It has also been launched in New Zealand (2023), the United States (2023), Germany (2023), France (2025) and Italy (2025).

This kind of digital solution unlock demand flexibility, reduce reliance on fossil fuels and accelerate the global integration of renewables. However, cyber security concerns must be addressed and managed carefully to safeguard user privacy and ensure the devices cannot be maliciously operated to disrupt the power system.

In the European Union, smart charging can save the regional energy system an estimated EUR 22 billion (USD 23 billion) per year by 2040. EV owners can also save up to EUR 780 (USD 813) annually in electricity bills (or more than half of the average annual electricity bills). In addition, smart charging helps reduce stress on distribution grids, supporting the optimisation of investments in strengthening networks.

Source: (Octopus Energy, n.d.; IRENA, 2024e, 2025a).

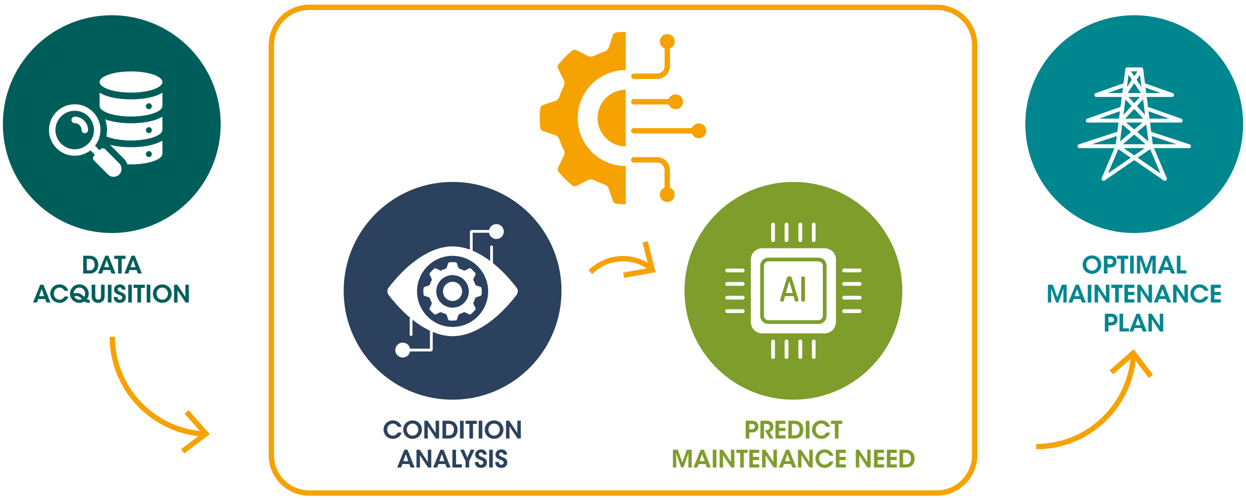
2.3.2 Bolstering security of supply: Predictive maintenance

Predictive maintenance leverages real-time condition- and status-related data for specific power system assets and components, collected by digital monitoring equipment (*e.g.* sensors and IoT-enabled devices). AI- and machine-learning-based processing of these data yields projections of equipment failure risk and triggers just-in-time maintenance; this in turn minimises downtime, optimises system reliability (ensuring continuity of power supply) and extends asset life (Platform Executive, 2025).

Predictive maintenance architecture includes layers, for data collection (sensors, IoT), communication (5G, edge), analytics (cloud) and operational visualisation dashboards for actionable insights (IEA, 2025; IRENA, 2019c; Righetto *et al.*, 2021). But although predictive maintenance relies on foundational monitoring technologies, at its core it uses data analytics to anticipate asset failure and schedule maintenance just-in-time.

Within the power sector, applications of predictive maintenance are diverse and critical for ensuring reliability and efficiency. These include vibration analysis for rotating machinery, such as turbines, generators and pumps; continuous temperature monitoring to detect overheating; analysis of moisture content and dissolved gases in transformers to assess insulation health; detection of partial discharge in high-voltage components; and real-time monitoring of the condition of circuit breakers, switchgears and other critical assets (Mazi Hosseini, 2024; WorkTrek, 2025).

Figure 2.5 Basic building blocks of predictive maintenance

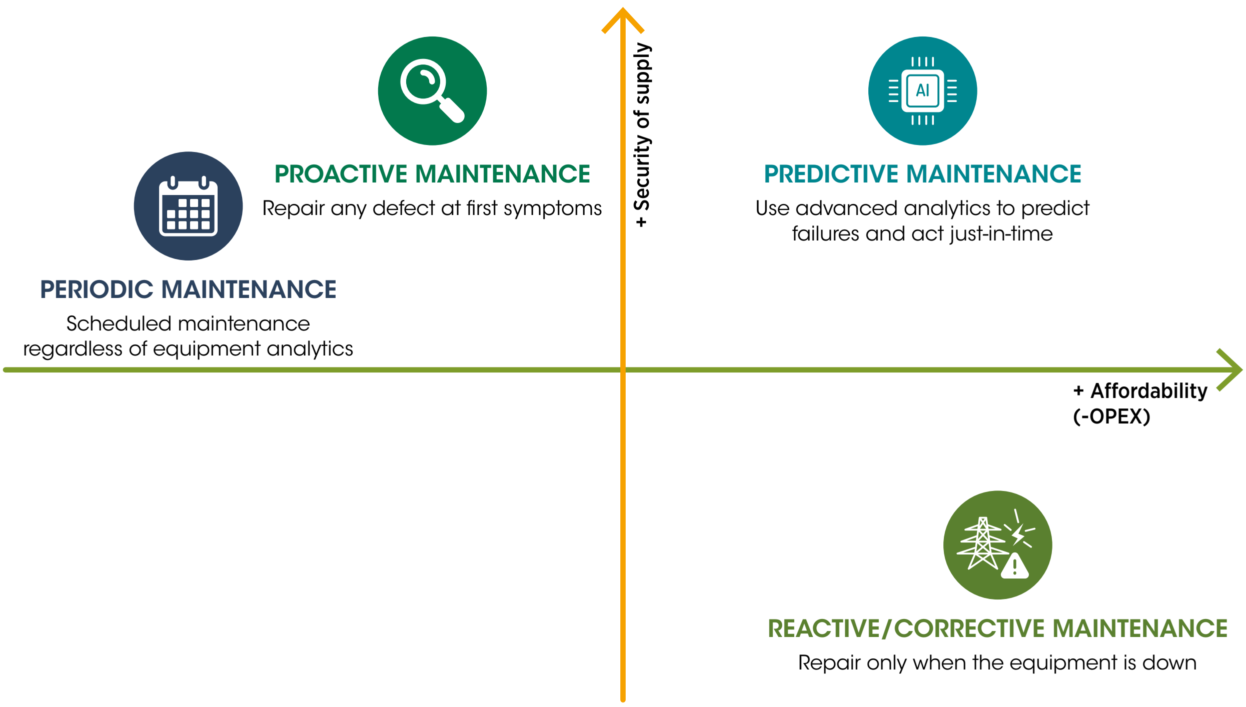


Based on: (Righetto *et al.*, 2021).

How predictive maintenance boosts security of supply

Through early detections of faults or anomalies detection, predictive maintenance can contribute significantly to reduced downtime through proactive maintenance planning. The continuous data collection, analysis, monitoring and reporting for power system equipment through numerous IoT-enabled interconnected sensors, can enable maintenance scheduling and timely maintenance of power generation, transmission and distribution assets. This prevents cascading failures and boosts security of supply across the power system (Cademix Institute of Technology, 2024; IRENA, 2019c; Platform Executive, 2025). In addition, this gain in security of supply is achieved while reducing maintenance operational expenditures, due to avoidance of inefficiencies (*e.g.* early replacement of healthy components) that alternative approaches often entail because of lacking advanced analyses.

Figure 2.6 Comparison of alternative approaches to power-asset maintenance



In 2019, Enel Italy launched a project to improve the reliability of its power lines using predictive maintenance. Sensors were installed to collect data, analysed using machine learning algorithms to detect potential issues before they occurred. As a result, Enel successfully reduced power outages by 15% (Clou, 2023).

Table 2.3 Enabling steps for the deployment of predictive maintenance

Category	Key steps and requirements
HARDWARE AND SOFTWARE	• Research and development supporting the wider adoption of digital technologies such as IoT sensors, AMI and digital twins.
POLICY AND REGULATION	• Regulations that promote data formats that are interoperable and favour communication protocols that are standardised across multiple systems and manufacturers. • National and regional grid codes that include provisions for and guidance on predictive maintenance.
TECHNICAL AND OPERATIONAL ASPECTS	• Policies and procedures that incentivise data sharing among utilities, original equipment manufacturers, and key services providers (*e.g.* of cloud-based platforms), while strictly enforcing cyber security protocols and standards to protect sensitive power system operational data (Won Shin *et al.*, 2021).

Outlook 2026-2030

The implementation of digital twins for predictive maintenance could lead to significant improvements in fault and anomaly detection and other analysis, as digital twins are constantly updated with real-time data on the physical condition of power systems.

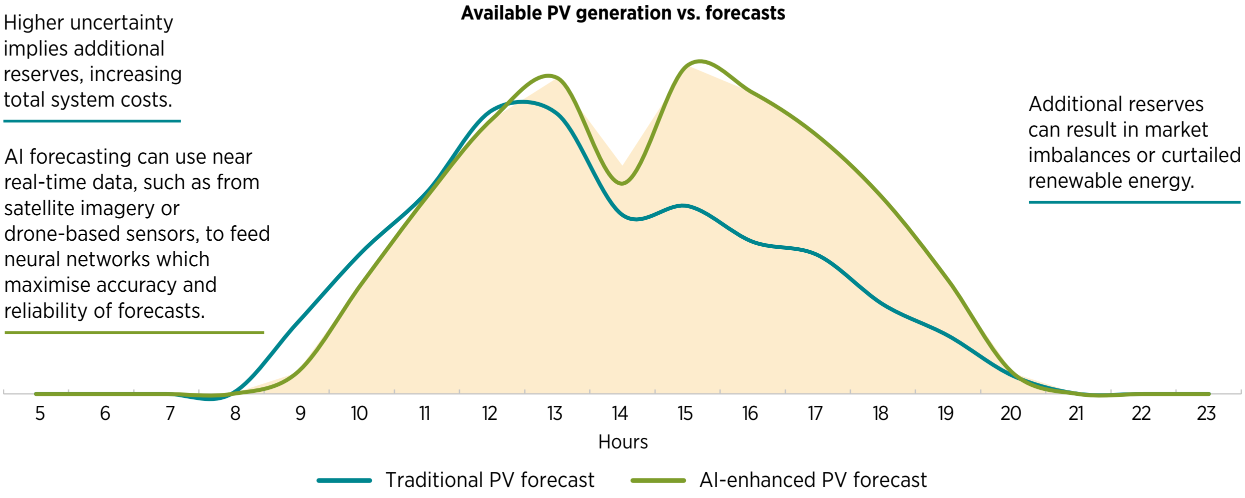
Using edge computing for predictive maintenance could be a future step as it reduces latency, improves security and reliability, lowers cloud storage costs and enables business scalability by eliminating overloaded centralised data systems.

Prescriptive maintenance adds value by providing digital advisory on the optimal course of action based on predictive maintenance outputs, moving beyond simply predicting failures to recommending solutions.

2.3.3 Greater renewables penetration: AI-enhanced VRE forecasting

AI-enhanced VRE forecasting leverages the use of relevant AI algorithms (*e.g.* neural networks, ensemble or other hybrid methods) for analysing historical and real-time weather data and data on power plant characteristics to predict (from forecasting to nowcasting) VRE power output levels with increased accuracy and time granularity. Weather data are collected using advanced weather and climate sensors, including drone-based sensors, which can collect high-resolution measurements of different parameters, such as temperature, air pressure and even wind speed at high altitudes (NIPR, 2025). AI models and machine learning techniques can process satellite imagery to produce better forecasts for parameters such as solar radiation and cloud cover compared with classic numerical models alone.

Figure 2.7 AI-enhanced forecasting of variable renewable generation



Note: AI = artificial intelligence; PV = photovoltaic.

VRE forecasting helps power plant operators effectively plan operations, minimises curtailments and optimises the use of the resources for participation in ancillary markets, supporting frequency regulation and reserve functions (Arosio and Falabretti, 2023).

How AI-enhanced VRE forecasting contributes to higher renewables penetration

AI-enhanced VRE forecasting improves forecast accuracy at a smaller time granularity (short- to long-term predictions). The reduced need for operating reserves and, consequently, the higher efficiency of generation dispatch, make power system management more effective. More precise forecasts also allow more renewable energy generators to participate in electricity markets, thereby reducing potential curtailments and/or imbalancing penalties (IRENA, 2020).

Recent studies show advances in nowcasting algorithms by combining geostationary satellite imagery with recurrent neural networks to predict cloud cover at PV plants with a lead time of up to four hours. A pilot system was tested across five PV plants in China and showed a strong correlation (≈0.8) between predicted clear-sky ratios and actual power generation. This enabled more accurate short-term forecasts, allowing grid operators to optimise reserve dispatch and reduce the need for conservative curtailment buffers. The study highlights how satellite-based nowcasting can significantly improve solar PV integration by enabling just-in-time balancing and minimising curtailments resulting from forecast uncertainty (Xia *et al.*, 2024).

Table 2.4 Enabling steps for the deployment of AI-enhanced VRE forecasting

Category	Key steps and requirements
HARDWARE AND SOFTWARE	• Wide deployment of innovative solutions for collecting weather data, such as drone-based sensors and satellite imagery leveraging AI and machine learning.
TECHNICAL AND OPERATIONAL ASPECTS	• Development of protocols between developers, asset owners and system operators for interoperability. • Open weather data databases (*e.g.* Copernicus) can enable asset owners to implement AI-enhanced variable renewable energy forecasting more quickly.
POLICY AND REGULATION	• Market incentives to improve forecasting accuracy (*e.g.* rewards for reliable predictions and penalties for deviations [costs of imbalances]), access to flexibility markets and support for aggregated bidding.

Outlook 2026-2030

Future advancements in upstream digital technologies, which form the building blocks of forecasting efforts, are expected to make forecasting even more accurate. Such advances include the development of advanced AI algorithms and agents for AI-driven energy and grid management under high VRE penetration (Enlitia, 2025), the proliferation of cloud and edge computing, and the creation of scalable and transferable/adaptable AI models that are critical for wider adoption and impact (Ukoba *et al.*, 2024).

The latest advancements in quantum computing are opening new possibilities for improving wind energy forecasting. Quantum computers are being used to simulate fluid dynamics equations such as the Navier-Stokes equations, which govern atmospheric processes but require enormous classic computing resources to manage. This new capability enables more accurate short-term weather forecasts, allowing wind turbine operators to optimise power generation, reduce energy costs and add to grid stability. Hybrid models that combine classical deep learning with quantum neural networks have demonstrated higher accuracy in short-term wind speed predictions. These models leverage quantum computing's ability to recognise complex patterns; in turn they produce more robust forecasts, despite seasonal variations in wind data, improving energy yield and integration (Hong *et al.*, 2023).

Box 2.4 How digitalisation helps integrate more renewables: Case studies

Companies like Solcast and RisingStack Engineering are utilising satellite imagery and AI to nowcast solar irradiance and solar PV output with high spatial and temporal resolution. Solcast's three-dimensional cloud modelling and live satellite feeds update every 5-15 minutes. Grid operators can use the cloud modelling and live satellite feed data to anticipate solar fluctuations and dispatch reserves just in time. RisingStack's deep learning model, trained on MSG-SEVIRI satellite data, achieved a 7.72% normalised mean absolute error at 150-minute horizons. These systems make more accurate reserve planning possible, reducing the need for conservative curtailment buffers, and improve the integration of solar PV (Boros, 2025; Solcast, 2025).

Another practical case can be found at the Hornsdale Wind Farm in South Australia, where AI forecasting systems analyse wind patterns, atmospheric conditions and turbine performance data to optimise energy production and grid integration. These systems have achieved up to 45% greater accuracy compared with traditional forecasting methods, enabling operators to anticipate wind variability better and reduce curtailments. By combining real-time weather data with historical performance metrics, the AI models support dynamic reserve scheduling and more efficient dispatch decisions (Sustainable Future Australia, 2025).

2.3.4 Added value for customers: Granular renewable energy certificates

Energy attribute certificates, for example, guarantees of origin in Europe and renewable energy certificates (RECs or international renewable energy certificates [I-RECs]) in other regions, certify that electricity comes from renewable sources. They allow companies and households to demonstrate green energy use. Most energy attribute certificates today are issued monthly or annually. Consequently, it is difficult to verify whether renewable generation coincides with consumption, an important aspect for 24/7 clean energy goals.

Granular certificates, issued hourly, enable closer alignment between generation and use. This strengthens credibility, supports demand flexibility and storage, and enables services like automated hourly reporting (AFRY *et al.*, 2024; EnergyTag, 2025).

Digitalisation can make energy attribute certificate systems faster and more transparent. Blockchain can add value by creating tamper-proof, time-stamped records; automating processes; and enabling participation by smaller producers. It is particularly relevant where institutional capacity is limited, or cross-border co-ordination is needed. Blockchain also supports features such as real-time monitoring and community energy sharing, while promoting decentralisation and equal access. (IRENA, 2019d, 2019e) These capabilities can also be achieved with other technologies, but blockchain embeds them in a distributed and transparent framework.

However, broader adoption of blockchain-based energy attribute certificates depends on regulatory updates and interoperability with existing registries. In mature markets, trust in central registries is high, and so, blockchain often complements rather than replaces these registries. In emerging markets, cryptographic verification can help offset weaker institutional frameworks, provided integration with recognised systems like I-RECs is maintained.

How energy attribute certificates add value for customers

Smart system design based on granular certificates adds value for the customer by blending precision and transparency, building trust. Granular, timestamped GOs/RECs – matching hourly consumption – empower buyers with transparent, immutable proof of their clean energy use, enabling them to substantiate their environmental, social and governance claims and protect their reputation. Blockchain further streamlines GO issuance and trading by reducing administrative burdens, as well as by lowering market friction – enabling prosumers, energy communities and industrial users to access certificates directly and efficiently. These features boost consumers' trust, increase market participation, and elevate GOs from mere compliance tools to strategic assets that differentiate brands and industrial consumers, support decarbonisation, and enable domestic customers to be engaged and empowered (Powerledger, 2023). To ensure compatibility with existing GO/REC systems, platforms must support integration with legacy registries and enable seamless data exchange across national and regional systems.

Table 2.5 Enabling steps for the deployment of energy attribute certificates

Category	Key steps and requirements
HARDWARE AND SOFTWARE	• Deployment of software platforms including but not limited to blockchain. • Interoperability of national registries and new digital solutions.
TECHNICAL AND OPERATIONAL ASPECTS	• Open standards for data storage and smart contracts.
POLICY AND REGULATION	• Regulations that incentivise hourly guarantees of origin/renewable energy certificate (GO/REC) systems. • Regulations across different sectors that incentivise or mandate the use of energy certificates. • Pilots in emerging markets where digital tools can fill gaps in market infrastructure.
CONSUMER ENGAGEMENT	• Consumer education and awareness campaigns. • Engaging with consumers through pilot projects.

Outlook 2026-2030

By 2026, granular certificates are expected to move beyond pilot projects into targeted deployment, especially in markets with advanced renewables penetration and liberalised electricity trading. Early adoption is likely to focus on industrial corporate power purchase agreements, where precise, auditable sourcing is already in high demand. Regulatory recognition of blockchain-based systems will be a decisive factor in scaling the adoption of granular certificates.

Between 2026 and 2030, three major trends are likely to unfold. The first is the integration of granular certificates with flexibility services like demand response and energy storage programmes, allowing both industrial and residential consumers to maximise financial and environmental value by aligning consumption with the availability of renewables. The second is the expansion of energy communities, wherein the adoption of granular certificate systems by local co-operatives and municipalities to certify, trade in and consume locally generated renewable power will strengthen engagement within communities and keep value within local economies. The third is the mainstreaming of granular certificates, supported by blockchain and other digital enabling tools, in corporate procurement standards, with leading multinational companies potentially making them a contractual requirement in renewable energy sourcing, setting new market norms (AFRY et al., 2024; WRI, 2023).

Box 2.5 Real-life examples of how granular certificates add value for the customer

Électricité de France has tested automated tokenised renewable energy certificates (RECs) at an electric vehicle charging station in Singapore. Electric vehicle owners in Singapore, who often prefer charging their vehicles with renewable energy sources, could purchase RECs.

The charging station was connected to a micro-grid, and the proof of concept also gathered data on the green energy produced by the micro-grid, besides issuing the RECs. This arrangement was to ensure green energy production by the micro-grid matched the consumption for charging the electric vehicles (Ledger Insights, 2023).

In Chile, Google partnered with the I-REC Standard to test the matching of hourly renewable generation and its consumption by a data centre based in the country. The pilot showed that granular certificates add transparency and credibility, as they significantly increase the share of consumption matched with renewable generation (The International Tracking Standard Foundation, 2022). The US registry of CleanCounts (formerly M-RETS) enables hourly RECs in a database framework; it offers producers a choice between hourly or monthly RECs (CleanCounts, n.d.).

In South Africa, Fuel Switch launched Africa's first blockchain-based REC exchange. It integrates with the system of international RECs and allows businesses and tenants to track and trade certificates in real time; this in turn reduces costs and builds trust in markets where central registries are less developed (African News Agency, 2025).

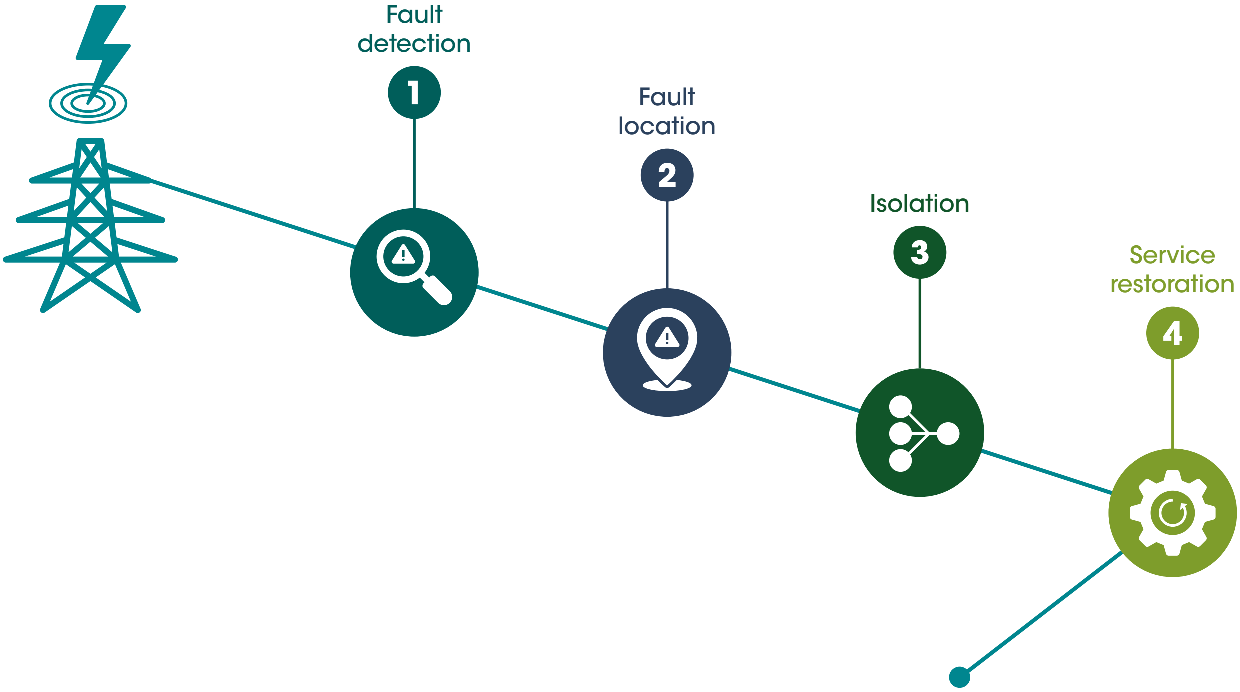
2.3.5 Improved business performance: Control centre of the future and automated fault location, isolation, service, restoration (FLISR)

Within the operational optimisation value cluster, the so-called control centre of the future – the nodes from where power systems are managed, when integrating advanced analytics, automation and AI – is redefining how system operators and utilities manage increasingly complex power systems. With new monitoring technologies generating vast data streams from sensors, phasor measurement units and smart meters, opportunities emerge for extracting meaningful insights and automatically executing optimal and just-in-time operational actions.

In this environment, automated FLISR is a cornerstone technology. Its operation involves four automated steps:

1. **Fault detection:** Intelligent algorithms continuously analyse incoming data from SCADA systems, relays and field sensors to identify anomalies that indicate faults (G-PST, 2023).
2. **Fault location:** These algorithms correlate multiple sensor inputs with the network's topology model to pinpoint fault location without waiting for field confirmation.
3. **Isolation:** Switching commands are issued automatically to remotely controlled circuit breakers or switches, containing the affected section and preventing equipment damage.
4. **Service restoration:** The system reconfigures the network dynamically. Power gets rerouted through alternative feeders and supply is restored to unaffected areas, often within seconds.

Figure 2.8 The steps automated in FLISR technology



This real-time closed-loop process, an integral part of "control centre of the future" initiatives, represents a fundamental operational shift: decision making and execution occur in seconds, with human operators supervising and intervening only when needed, rather than driving every step (G-PST, 2024).

How automated FLISR improves business performance

Automated FLISR eliminates many manual steps in fault-finding and switching, reducing the need for crew mobilisation, travel and overtime. Dynamic network reconfiguration avoids unnecessary equipment stress, balances the load across the network and enables more targeted maintenance scheduling. This helps defer capital investment in new infrastructure. Shorter outages minimise unserved energy, preserving revenue streams. Meeting or exceeding reliability targets also helps avoid regulatory penalties in performance-based frameworks, further strengthening financial performance (T&D World, 2019).

This approach goes beyond traditional monitoring. Insights are turned into immediate, automated action. This means operating more reliably at a lower cost, as utilities can scale operations in complexity without proportionally increasing staff or costs and are able to benefit from operational savings, thanks to these automations. By restoring services within seconds rather than hours, FLISR not only improves reliability metrics (*e.g.* the System Average Interruption Duration Index and System Average Interruption Frequency Index), but it also builds resilience against extreme weather and scenarios of high penetration of DERs.

Table 2.6 Enabling steps for the deployment of FLISR

Category	Key steps and requirements
HARDWARE AND SOFTWARE	• Widespread deployment of high-performance analytics and AI-driven automation, which are capable of interpreting millions of data points per second and issuing safe, reliable control actions (G-PST, 2023).
TECHNICAL AND OPERATIONAL ASPECTS	• Interoperability standards and communication advances that seamlessly integrate field devices, control software and operator interfaces. • Redundancies in communications. • Efforts to tackle cyber security concerns, as done by demonstrators that prove the need for and benefits of making power grid digitally resilient (TU Delft, 2022). • Training programmes for operators.
POLICY AND REGULATION	• Regulatory frameworks that incentivise utilities to improve reliability indices without proportionally increasing operational expenditure.
CONSUMER ENGAGEMENT	• Consumer education and awareness campaigns, namely, through field-proven impact: utility trials show that FLISR (fault location, isolation and service restoration) can reduce interruptions experienced by customers by up to 45% and reduce outage duration by over 50%, which directly translate into avoided costs and higher service quality (T&D World, 2019).

Outlook 2026-2030

By 2026, leading utilities will demonstrate clear reductions in operational expenditure and outage metrics through widespread deployment of FLISR in next-generation control centres.

Between 2026 and 2030, the integration of FLISR with DER management systems will enable co-ordinated fault restoration and dispatch of DERs in a unified operational workflow. By the end of the decade, cloud-based, AI-enhanced control room platforms will bring these capabilities to smaller operators, embedding cost efficiency and reliability improvements as standard practice across the sector.

Beyond 2030, quantum computing offers a significant performance advantage over classical methods in solving large-scale, nonlinear optimisation problems such as load flow and contingency analysis, making it an ideal candidate for inclusion in the control centres of the future. Traditional algorithms often struggle with scalability and convergence when dealing with high-dimensional, real-time grid data. Quantum annealers, by contrast, can explore vast solution spaces simultaneously and identify optimal or near-optimal configurations faster. In the context of automated FLISR and control centre operations, this means faster fault isolation, more efficient power re-routing and better co-ordination of distributed resources. Studies show that quantum-enhanced optimisation can reduce computation time by orders of magnitude, enabling near-instantaneous decision making even under future highly complex grid scenarios (Quantum Quants, TNO, 2024).

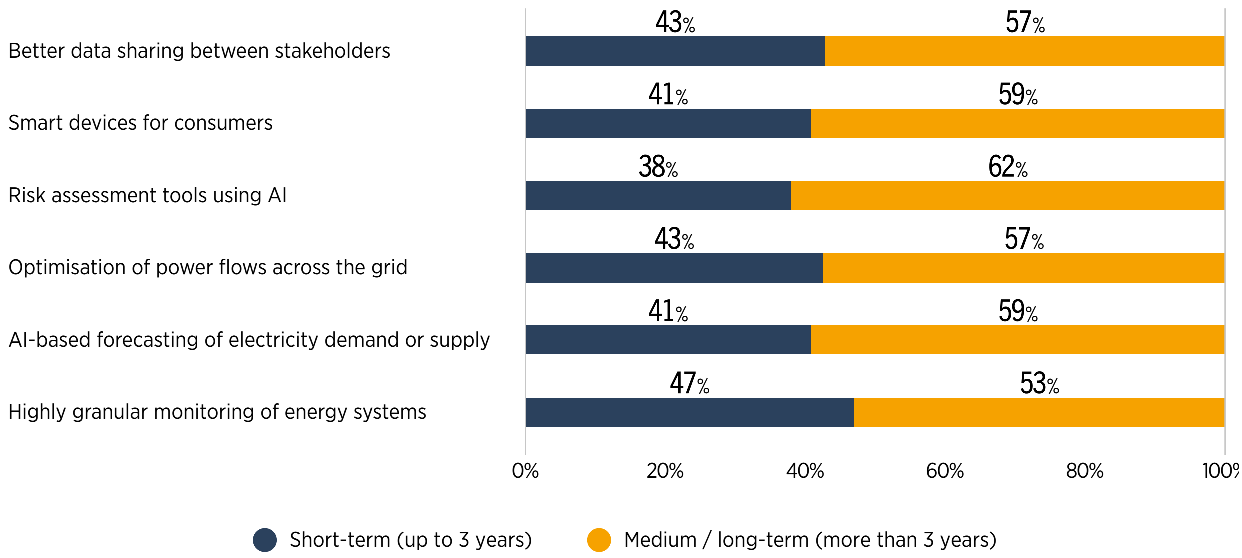
Box 2.6 Real-world application of FLISR

Australia's United Energy implemented a comprehensive distribution automation strategy centred on FLISR and integrated the strategy with its advanced metering infrastructure and outage management system. This created a highly responsive, automated grid control system. United Energy reported a **10x return on investment** from its FLISR implementation over five years. The Australia-based electricity distributor reported that the FLISR implementation enabled it to **reduce** the average time to fix a fault by 30 minutes (Oracle, 2022).

3. IMPLEMENTING DIGITAL SOLUTIONS: CHALLENGES AND STRATEGIC RESPONSES

As explained in the previous chapter, digital solutions significantly reduce electricity costs, and boost system reliability and renewable energy penetration, among other benefits. Digital solutions for power systems are thus key levers to accelerate the energy transition at the required scale to mitigate climate change, while at the same time creating economic opportunities for people, companies and public budgets through savings or improved energy access worldwide. Despite the growing awareness of digital solutions through proven use cases, barriers to implementation persist. In IRENA's 2025 survey among country members (see annex for survey methodology), most respondents were not convinced that any of the described use case examples (shown in figure 3.1) would be available in their country within the next three years.

Figure 3.1 Anticipated timeline for impact of digitalisation use cases



Note: AI = artificial intelligence.

The several implementation barriers that exist are often interconnected. Key barriers identified in IRENA's 2025 stakeholder consultation[2] process, survey and literature review include:

- **Fundamentals first – data, interoperability and cyber security:**
  - **High-quality, accessible and standardised data** for power system operation and related activities are lacking. Additionally, structural changes related to new roles and responsibilities for data collection are given increasing importance (*e.g.* clear roles for data ownership and access control must be established). Restricted access to data and models for stakeholders such as system operators, due to sensitivity and security concerns, can delay the development and trial of digital solutions such as digital twins.
  - **Cyber security concerns.** Increased digitalisation is closely connected with cyber security concerns, as connecting more systems and devices together introduces more entry points for malicious actors. The greater the reliance on digital systems and AI, the more significant the potential impact on social and economic life in the event of a cyber disruption.
- **Capacity building and trust**:
  - **Skills.** The shortage of skilled workers to address digitalisation needs is increasing. Innovation outstrips the pace of education and workforce development, a trend that is particularly concerning in fields like digitalisation and the energy sector.
  - **Low stakeholder awareness or trust.** Scepticism is common due to fears surrounding data privacy, device reliability and the "black box" nature of AI.
- **Enabling environment:**
  - **Regulation** of (digital) energy systems is typically fragmented, slow to adapt or, in some cases, non-existent. Regulatory incentives for grid operators and utilities often promote conventional hardware, such as power lines or transformers, over digital solutions, making it advisable to consider more holistic regulatory schemes and technologically agnostic approaches.
  - **Limited financial incentives.** Many regions either do not have financing mechanisms dedicated to digitalisation projects, or, even if financing mechanisms exist, they are limited to pilot projects. Further, in some cases, there are incentives for the deployment of a technology or piece of infrastructure – thought to be the problem solver – rather than for the desired service or result; this constrains digital innovation.
  - **Insufficient infrastructure readiness.** Physical information technology systems and data networks, needed to support digital solutions, are inadequate, especially in rural and remote areas. Legacy infrastructure needs to be updated and transformed.

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[2] *This section presents insights derived from the global survey (see methodology in Annex), expert interviews and desk-based research. Together, these sources provide a comprehensive overview of the key priorities identified worldwide for improving co-ordination in the context of the energy transition.*

3.1 IMPLEMENTATION BARRIERS: UNDERSTANDING CHALLENGES TO DEFINE ACTIONS

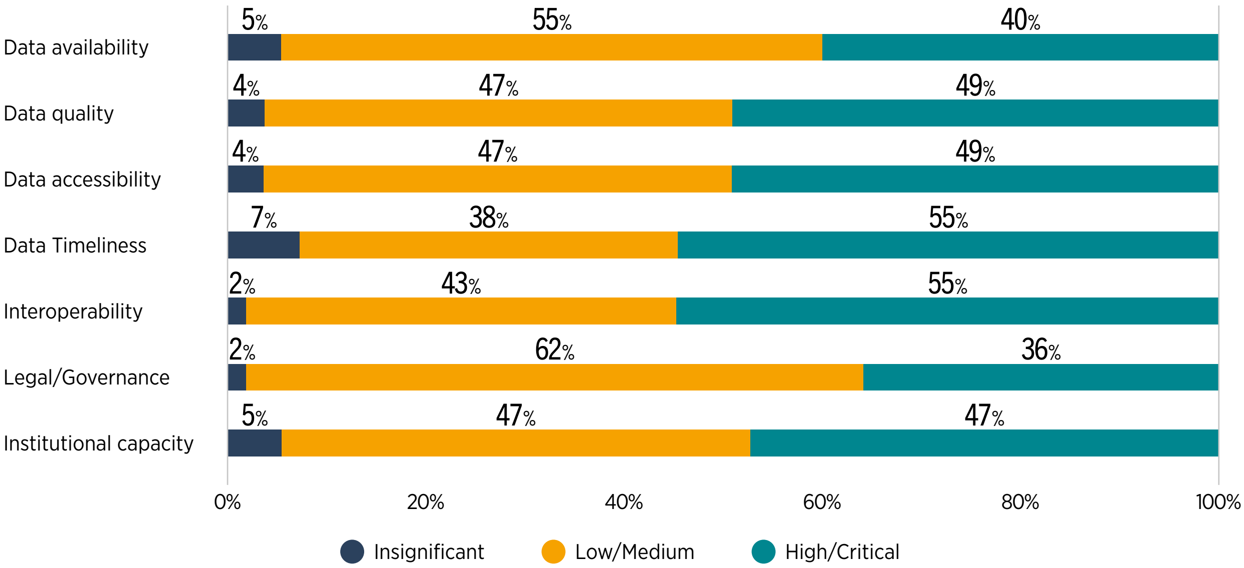
3.1.1 Data and interoperability

Digital solutions in power systems require data for accurate monitoring, analysis and integration of new technologies. At times, however, the challenge is not the lack of data per se but rather the effort required to find, clean and organise data. These steps can take up to 80% of the practitioners' time, leaving them only 20% to analyse the data (Pragmatic Institute, 2022).

Moreover, poor data governance exacerbates other challenges (*e.g.* skill and financing gaps), underscoring their systemic nature. In line with recent studies (El Zein and Gebresenbet, 2024; G7, 2024), lack of timely data and interoperability are among the important barriers to implementing digital solutions in the energy sector – 55% of respondents agree (figure 3.2).

Interoperability refers to the ability of different devices, platforms and organisations to exchange, interpret and use data seamlessly through standardised protocols and formats (ENTSO-E, 2019). Interoperability is yet another implementation barrier.

Figure 3.2 Perceived barriers to the implementation of data in the energy sector



Another challenge is bias. Training AI models on energy data sets with systemic bias, which disproportionately represent certain regions, populations or technologies, leads to inaccurate or unfair decisions. For example, if data sets are trained mainly on urban data, then they may undervalue the needs of rural populations (Shen, 2025).

Key action: Develop regional frameworks for data interoperability; define principles, standards and layers (legal, organisational, technical, semantic) for any type of cross-agency or cross-organisation data sharing. Establishing clear rules for data ownership and access control is also critical. Likewise, clearly delineate roles for external parties; this will maintain compliance by defining transparent boundaries for data sharing.

Example: Several countries have developed a special framework, addressing multiple layers of interoperability: examples includes European Interoperability Framework (EIF) which seeks to establish a framework for information exchange between the public sectors of its member states and the Common European Energy Data Space, that aims at facilitating seamless data exchanges among key actors in the energy value chain. The work to establish the Data Space is ongoing, as it was provided for in the EU action plan on digitalising the energy system (European Union, 2022) mainly because the currently developed framework unlocks the participation of flexible energy resources in the power markets. Similar frameworks have been established in Canada (Digital Standards), the United States (Network Centric Operations Industry Consortium) and other countries (Berkhout *et al.*, 2023).

While these general frameworks laid the foundation for power systems digitalisation, sector-specific initiatives demonstrate their impact in practice. The following are some examples of how interoperability projects yield benefits beyond efficiency gains for the energy sector:

- **Creating more dynamic energy markets:** Danish Energinet's DataHub interoperable platform, which enables data exchange among customers, suppliers and other third parties, has created a competitive energy market for consumers.
- **Unlocking grid flexibility from distributed energy resources (DERs):** One example is Energy Web's "Digital Spine" enabling the real-time communication needed to unlock flexibility from DERs, as proven in Australia's Project EDGE. Another example is the CharIN project, which ensures reliable integration of EVs into the grid based on interoperability testing between vehicles and power infrastructure providers; the objective is to validate communication and charging services.
- **Improving grid planning and operations:** The Intelligent Grid Platform (E.ON One), a smart grid technology platform, brings diverse grid data onto a single platform to digitalise and automate processes ranging from grid impact studies and short- and long-term grid planning to grid monitoring. Combined with an AI-powered grid planning software solution, the platform evaluates the effects of grid expansion measures and helps speed up network planning processes.

Together these examples show that interoperability is a crucial enabler for implementing advanced digital solutions for power grids, to advance energy markets and optimise grid management, among several objectives.

Cyber security – privacy

Power system digitalisation introduces significant challenges for securing data and privacy against cyber threats. As systems become increasingly interconnected and reliant on real-time data flows, the volume and sensitivity of data ranging from operational metrics to consumer usage patterns increase substantially. This raises concerns about unauthorised access to data, data breach and misuse of personal information, especially in jurisdictions with weak data protection frameworks.

While advanced economies often have stronger regulatory and technical safeguards, emerging markets and developing economies (EMDEs) may face greater risks due to limited institutional capacity and fragmented cyber security governance. In a survey conducted by the **Association of Power Utilities of Africa (APUA)**, roughly 85% of the association's member companies reported having already suffered a cyberattack. Nearly 40% reported being attacked multiple times a year. A total of 69.3% of the surveyed companies spend under EUR 300 000 annually on information security for an average turnover of EUR 713 million, or 0.04% (APUA, 2022). Addressing these challenges requires co-ordinated policy action, robust encryption standards and clear accountability mechanisms across the data life cycle.

"*With widespread digitalisation, cyberattacks on utility systems are a growing concern across Africa, leading to service disruptions and significant financial losses,*" an interviewee said.

Key action: In IRENA's stakeholder survey conducted for this report, around 71% of respondents indicated a need for close **co-ordination among different actors in defining cyber security measures** that ensure grid security, while also preventing cyber security standards from becoming a roadblock for digitalisation.

Examples of responses include:

- **Regional response centres:** APUA is actively promoting the establishment of **regional virtual response centres** (*e.g.* in Cabo Verde, Kenya or Mauritius) to secure data and provide rapid response in the event of cyber incidents.
- **Industry-led response:** This could be illustrated by the industry-led initiative Trusted Energy Interoperability Alliance, which has E.ON, Intertrust, JERA and Origin Energy, among others, as founding members. Zero-trust describes a cyber security approach wherein every interaction (user, device, application) is continuously verified, regardless of where it originated.

Cyber security – physical infrastructure

Digitalisation also makes physical power infrastructure more vulnerable to cyber threats. As operational technologies become more integrated with digital control systems, the risk of remote manipulation, sabotage or disruption grows. This is especially concerning for critical assets like substations, transmission lines and DERs, which are increasingly managed via automated systems. Cyberattacks targeting industrial control systems demonstrate how digital vulnerabilities can translate into physical impacts, including operational failure and widespread service outages.

Key actions: While mitigation strategies like network segmentation and intrusion detection systems have proven effective in some contexts, their deployment is uneven across regions. Advanced economies tend to have more mature cyber security protocols and incident response capabilities, whereas EMDEs may struggle with outdated infrastructure and limited technical expertise. Regional differences in threat exposure and institutional readiness mean that cyber security strategies must be context specific, balancing digital innovation with robust risk management.

Regulatory examples: In Europe, responsibilities for cyber security are largely on market actors, while regulators set key standards. Each company or system operator is responsible for developing cyber security solutions that follow general regulatory guidelines outlined by the European Union through frameworks such as the Network and Information Security Directive (NIS2), Cyber Resilience Act, and sector-specific network codes:

- The **NIS2 directive** requires member states to address cyber security for critical sectors, including the power system. It mandates establishing stringent requirements for risk management, incident reporting and business continuity.
- The EU's **Cyber Resilience Act** complements the NIS2 directive and sets region-wide cyber security requirements for all digital products. It ensures digital products are secure by design, regularly updated and compliant with the CE mark before they are sold on the market.
- **Network code on cyber security for the EU electricity sector**, published in 2024, establishes a recurrent process of cyber security risk assessments in the electricity sector (European Commission, 2024).

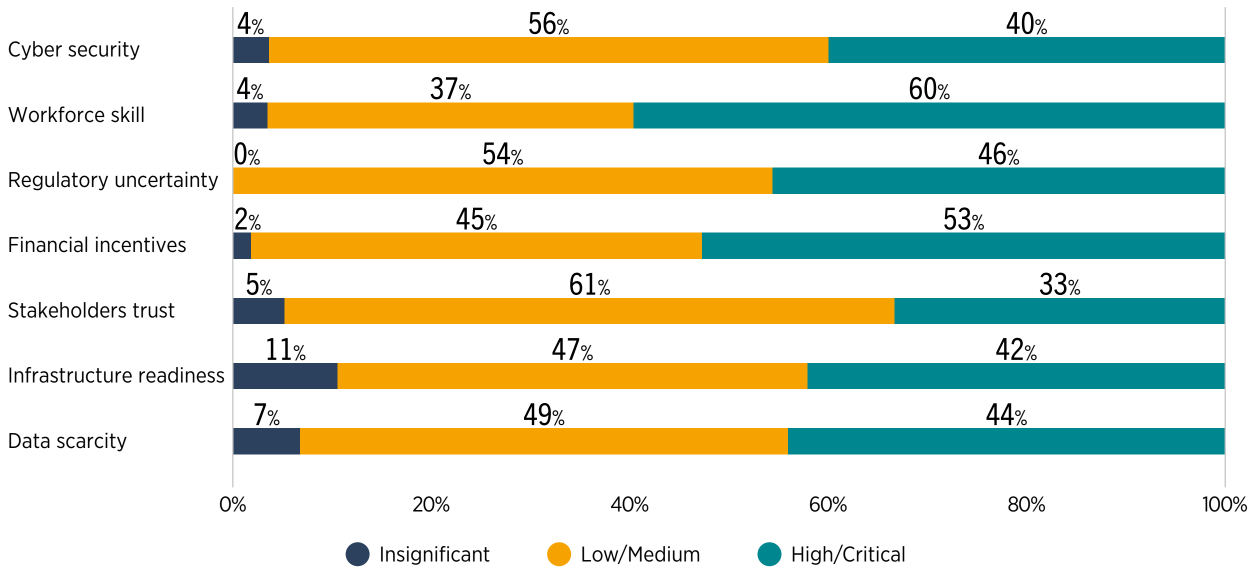
Public procurement example: A more specific action could be an enhancement of public procurement rules on the cyber security issue. An example of this approach is the toolkit on Cybersecurity Considerations for State Procurement of Solar Assets developed by the United States (NASEO, 2024).

3.1.2 Digital skills

In IRENA's stakeholder survey conducted for this report, 60% of respondents believe that a shortage of skilled professionals is a critical or high barrier to power system digitalisation (figure 3.3). Consistent with IRENA's findings, recent surveys by the UK's Energy Systems Catapult and the European Commission also highlight significant skill and technology gaps (especially in AI, big data and cyber security) that hinder digitalisation in the energy sector (Catapult UK, 2023; European Commission, 2025).

In their "AI for Prosperity" statement, the G7 countries recognised the importance of a human-centric approach to AI and committed to fostering cross-border talent exchange to better connect AI expertise with businesses (G7, 2025). This recognition, however, should extend beyond these seven countries and promote broader international co-operation on the subject. Building on this recognition, evidence from surveys, interviews and desk research highlights several practical challenges that need to be addressed.

Figure 3.3 Perceived barriers to digital solutions in the energy sector



Upskilling and re-skilling considering local conditions will ensure that an adequate workforce at all levels of the power system is available to pursue a transformation. Investment in upskilling and training was identified as the most important policy action governments can take towards a more equitable digitalisation of the energy sector (70% of survey respondents agreed to this). Public as well as private sector funding of education brings concrete benefits: a research study finds that a one-point increase in human capital investment scores leads to a significant improvement in a company's innovation capabilities and digital adaptation (Kuzmin *et al.*, 2024). While some energy systems jobs in the future may require basic information technology training and only secondary training on energy, there will be many employees – possessing very high skills to lower skills – who require digital literacy and knowledge of application in some form.

In EMDEs, lack of specialised technicians in the technology sphere is a key issue (Pereira *et al.*, 2025). There is no one-size-fits-all solution to a skills gap. EMDEs must implement holistic policy frameworks for training that consider the local context (IRENA Coalition for Action, 2023). As digitalisation accelerates, it is vital to ensure digital technologies do not widen the divide between developed and emerging economies but serve as enablers to bridge this gap. So-called "just transition funds" in many countries could be among the financial mechanisms for ensuring a fair and inclusive digital shift for the energy sector, especially for regions and workers dependent on fossil fuels.

Key action: Grants or co-funded training programmes are important to support upskilling. Linking existing financial incentives in the energy sector to digitalisation-focused upskilling could also boost additional private sector investment. Beyond developing vocational training and special programmes for re-skilling, donors or governments could consider combining investments in digital infrastructure with mandatory or incentivised training. This could strengthen both technology adoption and workforce readiness. The design of such programmes thus needs to include local actors.

Example: The Centre for Renewable Energy and Energy Efficiency of the Economic Community of West African States (ECOWAS) and the African Network of Centres of Excellence in Electricity already provide training on digitalisation in the energy sector, alongside other related subjects, but they target different stakeholders. These organisations are clear examples of how regional actors, in collaboration with international institutions, can not only provide support for digital equipment in the energy sector but also link this support directly to training and capacity building.

"We did many regional programmes on capacity building and data harmonisation and now countries need to adopt regional policies and update them accordingly." - Sediko Douka, Commissioner for Infrastructure Energy Digitalisation, ECOWAS.

Mapping of digital skill requirements to strengthen analysis and implement industry-aligned programmes, along with clear policy and energy planning, will support successful energy sector digitalisation. A shared understanding of regional and global skill requirements can facilitate the mobility of professionals across borders. Such an approach would help increase efficiency, foster knowledge exchange and ensure the better matching of skills to demand.

Key actions: Before moving forward, all countries should assess whether the skills being developed are aligned with emerging needs and future objectives. IRENA's "Call to Action on Skilling for the Energy Transition" (IRENA, 2025d) aims to drive international co-operation and leverage collective expertise on skill development for a sustainable energy future by showcasing skilling and workforce development efforts from around the world. The platform is working to build an enhanced awareness of the global skill landscape, encouraging efforts to replicate promising initiatives, inspire more ambitious actions and invite collaboration across borders.

Example: Electricity Human Resources Canada (EHRC), in partnership with the Future Skills Centre, launched an initiative to assess and address the transformative impact of AI on Canada's electricity workforce (EHRC, 2025).

Meeting the growing demands of the energy sector necessitates improved digital skills and a wider workforce pool. **Societal workforce participation needs to widen** to expand the workforce pool available to the industry (OECD, 2025); greater female workforce participation is needed (currently 32% in renewables and 26% in the digital sector [Carroll, 2025; IRENA, 2019]). Encouraging young women to participate in digital-skilling programmes allows them broader access to opportunities in science, technical, engineering and medical (STEM) fields, including information technology. This contributes towards building a larger and more innovative workforce.

Key action: While many programmes focus separately on digitalisation or women in renewable energy, few integrate both areas into a single training initiative. Further collection of gender-disaggregated data should be promoted (United Nations, 2025).

Example: Local initiatives, for example, Remote energy and Solar Sisters, combine digital training with renewable energy and are designed specifically for women (Remote Energy, 2025; Solar Sister, 2025).

Power system transformation, including an increase in DERs and greater remote access, will require **improving digital literacy of the workforce as well as the entire population**. Digitalisation in energy and transport can strengthen the influence of established actors, limiting communities and excluded groups from experiencing the benefits (Sareen *et al.*, 2023). Without attention to these aspects, digitalisation efforts can lead to resistance, low uptake and issues such as non-payment or energy theft. It is known from energy planning that ignoring user behaviour and preferences leads to ineffective solutions (IRENA, 2025).

"Change is not easy for most people, so adaptation to new technologies, like smart metering, has been slow but is now showing finally some benefits, which change people's perception," an interviewee noted.

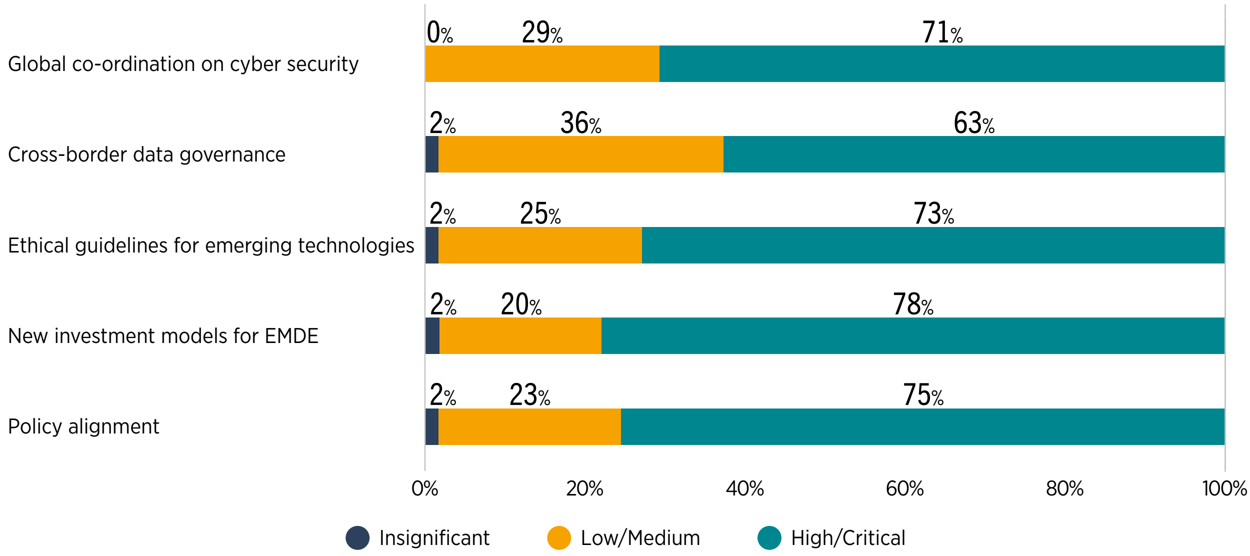
Key action: There is a clear need for better communication with end users and stronger civic education to build their trust and understanding and promote their inclusion in the digitalisation process. Key areas to address include increasing public awareness, transparency (AI as a "black box"), minimisation of potential adverse impacts on people and equitable development. Early education could also support societal transformation and public acceptance in the long term (*i.e.* exposing children and youth through formal and non-formal education).

Examples: One example is AI for Good, a global movement led by the International Telecommunication Union with UN partners, which promotes the use of AI to tackle global challenges, including public trust and user inclusion.

3.1.3 Enabling factors

Digitalisation and AI-driven efficiency improvements of power systems require both innovative approaches in technology and business models and investments. Roughly 53% of survey respondents and many interviewees in IRENA's survey reported that the implementation of digital solutions is hindered by a lack of sufficient financial incentives and market readiness to adopt digital technologies at scale (figure 3.3). In the interviews, stakeholders pointed to unclear investment recovery mechanisms as a challenge, which creates uncertainty and delays. Moreover, as shown in figure 3.4, when asked about the global priorities for supporting digital energy solutions, 78% of the respondents agreed that new investment models are needed for EMDEs.

Figure 3.4 Global priorities for supporting digital energy solutions



Note: EMDE = Emerging market and developing economies.

Uncertainty around returns on investment in digital solutions can result in a preference for aging legacy grid assets being replaced or reinforced, for example. While reinforcement generally benefits from clear and regulated repayment, digital innovation enabling optimisation (*e.g.* a direct line rating system) often faces uncertain returns because it is not included in grid retribution schemes. The gradual phase-out of legacy systems, many of which are incompatible with new digital technologies, further prolongs the transition and raises costs.

"We struggle with serious funding limitations, as grids that rely mainly on domestic consumption cannot generate enough revenue from tariffs," an EMDE interviewee explained.

Innovative approaches that offer new opportunities for revenue generation from digital, innovative services such as demand response, virtual power plants and enhanced customer experiences, create business cases for investments. Several examples below illustrate these innovative approaches.

Performance-based incentives for the implementation of digital solutions compensate utilities based on their performance against targeted outcomes (*e.g.* improving efficiency or providing added value to grid operation) (de Olivera *et al.*, 2025). Performance-based incentives can also be viewed as measures complementing conventional cost-of-service environments (Joskow, 2024). Incentives would be tied to quantifiable key performance indicators for smart grids, which can be developed individually based on pre-defined goals.

Example: A review of Australia's performance-based incentives scheme reveals that it successfully delivered on efficiency improvement and cost reduction (AER, 2023).

Regulatory sandboxes allow for the testing of digital solutions and business models within a limited (time) frame in a real-world environment. The tests are for finding gaps in the solutions and models, and the results inform the preparation of appropriate regulatory measures that enable market access.

Example: By 2025, Germany started the pilot operation of its Regulatory Sandboxes Innovation Portal for multiple sectors (Federal Ministry of Economic Affairs and Energy, 2025). Moldova (an EU accession candidate) launched a specialised Energy Sandbox Mechanism in February 2025 (Ministry of Energy of the

Republic of Moldova, 2025). The United Nations Economic and Social Commission for Asia and the Pacific and United Nations Department of Economic and Social Affairs developed, with the Government of Kazakhstan, a dedicated sandbox toolkit for energy sector digitalisation (UN ESCAP and UN DESA, 2024).

Example: Malaysia's National Technology and Innovation Sandbox spans over 10 sectors, including energy. Since 2020, 133 of over 900 applications received funding. The sandbox accompanies companies at and through different stages of innovation and facilitates exchanges between industry and governments (Ministry of Science, Technology and Innovation, 2024).

Regulatory frameworks enabling neighbouring/community aggregation models – Allowing communities or clusters of neighbouring consumers and producers to share and optimise energy resources unlock significant efficiency gains and cost reductions. When regulation permits collective self-consumption or local energy sharing, as in a neighbourhood or by connecting nearby mini-grids, digitalisation becomes indispensable: smart metering, settlement and price responsiveness platforms, among others, emerge to provide the diverse benefits explored earlier in this report. Frameworks for collective self-consumption enable consumers without rooftop access (*e.g.* apartment dwellers), who otherwise could not become prosumers, to participate; this is shown in studies in Portugal where community schemes enable passive consumers to save up to 48% on costs, also reducing stress in distribution grids (Belmar *et al.*, 2023).

"Mini-grids are a great door opener for technology. By nature, they are rural and dispersed, and you have to form a cluster. Then, they need a company to manage this cluster," an interviewee noted.

Example: Bekele *et al.* (2024) explored the impact of micro-grid clustering in Ethiopia by interconnecting three individual systems and then conducting a techno-economic analysis. Comparing stand-alone operation and clustered micro-grids revealed that, despite the added cost of interconnection, the benefits in terms of technological, economical and reliable operation of the clustered system were comparable to that of stand-alone micro-grids (Bekele *et al.*, 2024).

Example: Spain's recent regulation enabling collective self-consumption within a 5-kilometre radius sets a global benchmark for community energy aggregation. Households and businesses across neighbourhoods, with smart meters installed, are allowed to share resources such as solar generation, storage and demand responsiveness. This resource sharing unlocks digital business models that accelerate local renewables integration (MITECO, 2025).

Long-term energy planning is an effective tool to address the energy transition's critical investment gap. Clear energy planning informed by data, which potentially mitigates investment risks, fortifies energy security and mobilises capital towards sustainable energy and infrastructure, has received renewed attention as being vital to bridge this gap. In 2024, the Global Coalition for Energy Planning emerged from Brazil's G20 presidency to support countries on their transition journey.

Energy planning can also help governments to clearly define future technological needs and ensure they are met in a timely manner – through improved co-ordination, as exemplified in the previous section. Better exchange with the digital sector, including through quality assurance and transparency mechanisms, can improve procurement processes and strengthen the planning process in general. According to the World Bank, institutions in EMDEs often lack capacities not only in managing smart grid services but also in procuring them for the private sector (ESMAP *et al.*, 2018). An International Telecommunication Union report highlights how orchestration of investments can help close the investment gap for digital infrastructure with a ready-to-use framework for countries (ITU, 2025).

Key action: Inclusion of digitalisation in energy planning to promote investments and better co-ordination among sectors.

Example: In India, the Power Grid Corporation deployed optical ground wire cables alongside its power transmission lines, enabling remote monitoring of grid and also providing broadband connectivity for the use of commercial telecom (ITU, 2021).

Inclusion of digitalisation objectives for power grids into **Nationally Determined Contributions (NDCs)** is a possible step to signal that the application of AI for emission mitigation is a national priority. Countries increasingly include grid upgrade/modernisation in their climate change mitigation measures, as seen in the third edition of the NDCs (NDC 3.0). IRENA, furthermore, advocates for alignment with other national energy and climate plans, where digital solutions might already be considered.

Key action: Consider addressing the inclusion of digital solutions in NDC revisions.

Example: The United Arab Emirates' NDC 3.0 mentions digital solutions like AI and big data as advanced technologies for transitioning to a net-zero economy. Maldives' NDC 3.0 also touches upon AI and IoT as technologies for enabling efficient climate action.

3.1.4 Co-ordination

The energy sector is a multi-stakeholder environment. Digitalisation and integration of AI solutions into this sector bring another set of actors to the table with very swift progress timelines. While each actor plays a critical role, their differing objectives, risk appetites and timelines may lead to slow adoption and missed opportunities. To effectively drive digitalisation benefits in the energy sector, different actors (utilities, governments, digital and energy companies, consumers and others) need to be better aligned. While digitalisation aims to manage the increased complexity of power systems, improved stakeholder co-ordination and best practice sharing are vital. **IRENA proposes to base this co-ordination on three pillars**, outlined below.

1. Aligning policy priorities and actions

In many countries, responsibilities for the energy sector, innovation, digital development and also education are spread across ministries and agencies, as was highlighted in the stakeholder interviews. Accordingly, private sector actors operating at the intersection of energy and digital technologies have to work with different focal points. Such increasing complexity requires greater co-ordination. In larger power systems specifically, some challenges require cross-border co-ordination. Countries and regions are addressing these challenges in multiple ways:

National example: After recognising the essential role of digitalisation and the current lack of a co-ordinated approach, the UK energy regulator, Ofgem, proposed the creation of a "Digitalisation Orchestrator" in 2024. The Digitalisation Orchestrator is an independent organisation responsible for co-ordinating the energy sector's shared digital energy system infrastructure (ARUP *et al.*, 2024). Locally, platforms like "Net Zero Places" support innovative companies based in the United Kingdom to test their new products and equip local authorities with access to innovative ecosystems to accelerate their energy planning (Catapult Energy Systems, 2023).

Regional example: The ECOWAS promotes public-private partnerships (PPP) as a procurement model for a regional approach for infrastructure development. The ECOWAS PPP Online Platform functions as a knowledge management platform for governments to exchange with the private sector. Its holistic regional approach to public-private partnerships contributed to the harmonisation of supervisory control and data acquisition (SCADA) systems, which further allowed cross-border energy trading among 14 continental ECOWAS countries (ECOWAS, 2022).

2. Ensuring the technical interoperability of systems at the national, regional and global level

The creation of expert groups: The European Commission established the "Smart Energy Expert Group" under the "Digitalising the Energy System – EU Action Plan" (European Commission, 2022) for co-ordination of stakeholders across different countries, including grid operators, digital technology providers, regulators and consumers, to accelerate the secure and inclusive digital transformation of the energy sector. As part of the action plan, the European Network of Transmission System Operators for Electricity (ENTSO-E) and the EU distribution system operator (DSO) are jointly developing a framework for the development and deployment of interoperable digital twins of the EU electricity grids. The proposal includes the development of smart grid KPIs (key performance indicators) to focus investments on smart grids and help track the progress made in the EU member states.

Nationally, Germany started tracking digitalisation at different levels of the power system. The tracking effort revealed higher rates of digitalisation for transmission operations (E-Bridge and FGH, 2025). Specifically in developing regions, additional sectors like telecommunications must see higher rates of digitalisation: many regions, and especially remote communities, lack (reliable) access to the internet, but connection (either internet or satellite) is essential to process data for improving access to energy and energy security. Improving co-ordination between energy and telecommunication sectors (*i.e.* procuring smart appliances with antenna) can address this gap.

On international co-operation, the MENALINKS programme provided regulatory and technical support to the adoption of the first dedicated regulatory framework for smart mini-grids in Egypt (MENALINKS, 2025).

3. Supporting initiatives and business models that incentivise collaboration

Example: Specialised platforms such as the Electron Vibe help match utilities with solution providers for addressing their concrete issues. The process is collaborative: Climate Collective Foundation (CCF) works with electricity utilities to define problem statements, and then start-ups that can solve those problems are selected through a worldwide open call. The selected start-ups then create business cases, wherein they evaluate operational, techno-commercial and regulatory feasibility. Based on this feasibility, utilities decide to progress to pilot projects demonstrating tangible economic and operational benefits (Electron Vibe, 2025).

"We need some sort of a platform, where TSOs, DSOs, and regulators sit together, and work on innovation together," one interviewee noted.

Global platforms such as the Utilities for Net Zero Alliance (**UNEZA**) Digital Academy on Net Zero contribute to not only better co-ordination but also workforce upskilling. They foster learning among utilities and help them improve their digital skills. Further, the **Regulatory Energy Transition Accelerator (RETA)** seeks to facilitate knowledge sharing and peer-to-peer learning among regulators globally (RETA, n.d.). Additionally, **Digital Demand-Driven Electricity Networks (3DEN)** – a collaboration of the Italian Ministry of Environment and Energy Security, the International Energy Agency, and the United Nations Environment Programme – supports the acceleration of power system modernisation through digitalisation, smart grid solutions and demand-side resource integration (Ministry of the Environment and Energy Security (MASE), 2024). These examples illustrate how co-ordination already happens at different levels, from local to global, underlying the emerging need for these platforms across the world.

4. RECOMMENDATIONS FOR THE G7 AND INTERNATIONAL COMMUNITY

4.1 UNLOCK SYSTEM VALUE THROUGH TAILORED DIGITALISATION STRATEGIES

Assess the status of national power systems through the prism of digitalisation value clusters (monitoring, forecasting, operational optimisation, end-use automation and transparency) to identify gaps and opportunities that can be addressed with concrete policy action.

Promote flexible power systems investment frameworks that enable digital solutions to deliver services such as grid congestion management and asset management, without prescribing specific technologies. A technology-agnostic approach in regulated businesses such as transmission and distribution encourages innovation and the adoption of efficient digital solutions while maintaining system reliability.

Support the development of digital platforms and tools that improve visibility, co-ordination and automation across the power system, including interoperable data hubs, real-time analytics engines and user-facing interfaces that empower consumers and operators alike.

Encourage the inclusion of digitalisation in national energy planning and procurement processes. Integrating digital priorities in energy planning, procurement and regulatory frameworks helps to ensure coherence and long-term value creation.

4.2 ACCELERATE DIGITAL ORCHESTRATION THROUGH SYSTEM-WIDE CO-ORDINATION

Promote national and subnational strategies that align digitalisation efforts across system layers, from transmission to distribution and end-use. This entails that digital solutions are considered alongside physical infrastructure upgrades and contribute to the long-term needs of the power system.

Support the development of interoperable digital ecosystems that facilitate co-ordination among generators, grid operators, aggregators, digital sector and consumers. Shared data platforms, common standards and open digital frameworks can reduce transaction costs and foster innovation.

Promote inclusive digital market design, which allows for the development of modular building blocks for energy services, including, among others, the participation of distributed energy resources and flexible load operations. This includes enabling aggregation, simplifying access to flexibility markets and ensuring fair compensation for digital services.

Facilitate international collaboration on digitalisation by sharing reference architecture, toolkits and capacity-building programmes. While avoiding the duplication of capital investments, this helps emerging markets and developing economies substantially advance legacy systems and adopt proven digital solutions tailored to their contexts.

4.3 FUNDAMENTALS FIRST: DATA COLLECTION AND MANAGEMENT, INTEROPERABILITY AND CYBER SECURITY

Improve data collection and quality. Basing digitalisation on the collection of relevant, high-quality data is inevitable. Such systems can be established step by step. Rollout of smart meters and other smart appliances is vital, and ambitious targets for their early deployment opens diverse opportunities for digitalisation and for realising the associated benefits of digital solutions. Further, digital solutions should be considered in technical assistance and in investment in upgrading outdated infrastructure (*e.g.* analogue control systems, fragmented grids), especially in areas with growing demand and reliability issues.

Promote interoperability frameworks through international partners. Interoperability can unlock innovation and improve data exchange across a range of platforms and jurisdictions. International co-ordination can reduce fragmentation, facilitating open-source initiatives or applications that strive for affordability. Encourage working groups on interoperability and standard setting.

Raise awareness and support early adoption of smart devices among end users, helping them tackle the long replacement cycles for items such as home appliances, vehicles and industrial machinery. Timely deployment of representative numbers of demand-responsive elements prevents or mitigates stress in power systems and allows end users to benefit from – otherwise potentially overlooked – smart capabilities.

Foster cross-sector co-ordination among different actors in defining cyber security measures that keep those risks under check in power systems, while preventing cyber security standards from becoming a digitalisation barrier. Adopting and strengthening cyber security “by design” for all electricity value chain elements builds trust among stakeholders, potentially unlocking initiatives and investments. Regional differences in threat exposure and institutional readiness mean that cyber security strategies must be context specific, balancing digital innovation with robust risk management.

4.4 RETHINK SKILLS AND TRAINING: THE INTEGRATION OF EDUCATION TOPICS AND DIGITAL LITERACY

Blending investments in re-skilling and upskilling in the energy sector with digital skills improves alignment with power sector transformation. The transformation of power sectors requires new skills across all industries. A total of 60% of the respondents of IRENA's survey identified a shortage of skilled professionals as a critical barrier to power systems' digitalisation. Such re-skilling and upskilling must keep up with the transition and ensure that the corresponding technologies do not widen the divide between developed and emerging economies but serve as enablers to bridge this gap.

Mapping skill gaps and understanding industry needs will help train the right workforce for a fast-paced environment. This entails analysis along the value chain and changes in skill requirements. For training to have maximum impact, it should be co-designed with industry, tailored to local contexts and have low entry barriers.

Acknowledge the importance of diversity and non-professional digital literacy to meet sector demands. The future power system will need all segments of society to participate, both professionally and in everyday life. There is a need to design programmes that help underrepresented groups participate more in the workforce and enhance digital literacy.

4.5 ENABLING FACTORS: LONG-TERM PLANNING, INCENTIVISING INVESTMENTS AND SUPPORTING INNOVATION

The introduction of performance-based incentives can attract investments in innovative digital solutions for underfunded power grids. Encouraging the achievement of quantifiable key performance indicators (*i.e.* % of performance improvement) will attract investments in digital solutions.

To further enable such innovation, regulatory sandboxes at the digital energy intersection can help transform ideas into market-ready solutions in a very fast-paced environment. Innovative applications, specifically in sensitive environments such as power grids, need environments that allow testing and adaptation. Innovation that drives power system transformation can only work in suitable ecosystems.

Long-term energy planning helps channel investments in grid infrastructure by boosting investors' confidence. Considering digital solutions in these plans can make investments more attractive. Including proven digital solutions, backed by use cases and international experience, early planning can not only boost the general benefits of those solutions for the power system but also mobilise funding for the solutions themselves. Supporting platforms such as the Global Coalition for Energy Planning, spearheaded by Brazil's COP30[3] presidency, and long-term energy planning initiatives (such as IRENA's) present an opportunity to align the agenda of major global fora, promote capacity building and encourage the sharing of best practices and peer-to-peer learning.

Inclusion of digital solutions in Nationally Determined Contributions, along with alignment with other national energy and climate plans, helps global investors gain confidence in strategic planning for power sector transformation across various countries. It is important to address digitalisation targets in international co-operation formats, and their intersection with other targets (*e.g.* skill development or

[3] *UN climate conference in Belém, Brazil, in November 2025.*

financing ambition), to create more coherent plans. Support tracking efforts (*i.e.* IRENA's) so that policy makers have more visibility on plans, ambitions and implementation.

As partners of international funding institutions, encourage wider and targeted funding for digital solutions in energy sector applications. This can entail guarantees, blended finance and concessional funding to reduce the upfront costs of digital energy projects especially in contexts with uncertain returns, while promoting financial frameworks that recognise social and environmental value (*e.g.* access, emissions reduction, social inclusion), to enable more equitable investment decisions.

4.6 STRENGTHEN (INTERNATIONAL) CO-OPERATION TO SUPPORT POWER SYSTEM TRANSFORMATION, INCLUDING IN EMDEs

Accelerating the transformation of power systems requires better co-operation among the energy, digital and public sectors in light of increasing system complexities. The policy priorities and actions of ministries and agencies overseeing energy, innovation, digitalisation and education must be aligned, so that private sector actors at the intersection of energy and digital technologies can navigate more coherent frameworks. Co-ordinated approaches (*e.g.* the United Kingdom's proposed Digitalisation Orchestrator) can support shared infrastructure and foster experimentation. Regionally, initiatives such as the European Union's Smart Energy Expert Group can promote cross-border collaboration and progress tracking. Global platforms such as UNEZA and RETA further improve co-ordination and capacity building, while partnerships like 3DEN demonstrate how international co-operation can drive digital integration and modernisation of power systems. Further, IRENA's collaborative frameworks have a track record of successful knowledge exchange and international co-ordination among IRENA members (on a variety of topics, from offshore wind to critical materials), which can be replicated for digitalisation and AI.

IRENA, with its membership of 170 countries and the European Union, alongside the utilities alliance UNEZA, the industry alliance AFID, its collaborative frameworks, the Global Coalition for Energy Planning and its technology and socio-economic workstreams, is well placed to **host a global dialogue with the G7 and all other member states on digital solutions for power system transformation**.

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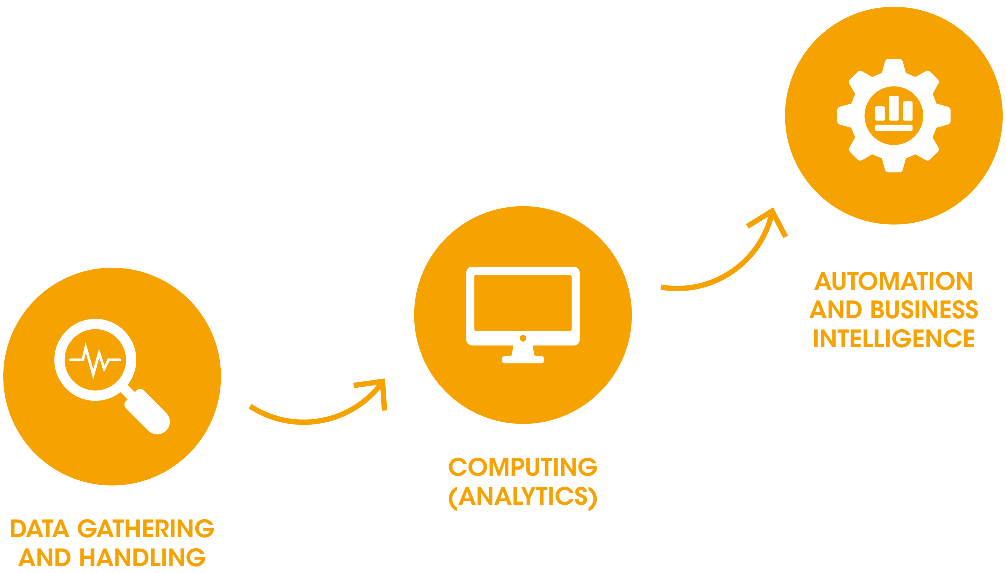
ANNEX

GLOSSARY

This glossary contains explanations of some of the basic technologies that have multiple applications in power system digitalisation. Digitalisation relies on measuring large volumes of data collected using technologies like sensors, smart meters, supervisory control and acquisition (SCADA) systems, and advanced monitoring systems. Technologies like artificial intelligence (AI) and the Internet of Things (IoT), among others, leverage these data (which can be related to assets, weather, renewable energy resources, market and system operation and consumer behaviour, among others), enabling digitalisation across various use cases. This annex describes data collection technologies and digital technologies that are vital for digitalisation.

Figure A.1 A framework for power system digitalisation



Sensors

Sensors are fundamental components of digitalisation. They serve as the bridge between physical systems and digital platforms. Sensors measure physical and environmental parameters, such as temperature, light, motion and sound, transmitting as digital signals, which can be processed and analysed (zeroinstrument, 2025).

As core enablers of IoT, sensors facilitate data-driven applications across various sectors, including energy, manufacturing, healthcare and mobility. The growing demand for automation and intelligent systems has accelerated innovation in sensor technologies, including flexible, nanoscale and AI-driven sensors. These advancements make more accurate, context-aware and adaptive data collection possible, enabling real-time monitoring, increased safety and enhanced operational efficiency.

Internet of Things

IoT refers to physical devices embedded with sensors, electronics and software that connect to the internet and exchange data. These smart devices enable remote monitoring and control through cloud-based control systems. IoT devices can automatically adjust the energy consumption of appliances like heat pumps and water heaters in response to price signals or grid conditions, thereby optimising operations and providing flexibility to the grid (IRENA, 2023a).

Smart meters

Smart meters are advanced electronic devices that record and communicate near-real-time measurements of energy consumption (*e.g.* kilowatt hours, voltage, current, power factor) back to utilities and consumers via two-way communication (wireless radiofrequency, power line communication, cellular or mesh networks). They form the backbone of advanced metering infrastructure (AMI). Importantly, they enable meter reading at frequent intervals (*e.g.* every 15 minutes) instead of manual reading once a month and support functions like remote connect/disconnect, time-of-use pricing and outage detection.

Advanced monitoring systems

Advanced monitoring systems integrate diverse types or sources of data (*e.g.* advanced meters, phasor measurement units [PMUs] and real-time weather data) to improve grid operations. They support the development of wide-area monitoring systems, which provide holistic and geographically detailed views of critical systems elements; in turn they improve grid situational awareness.

SCADA systems

SCADA systems are digital platforms for monitoring and controlling key power system components, from generators and specific electrical equipment to substations and transmission networks. They collect real-time data from field devices such as sensors, actuators and meters and transmit them to centralised dashboards for human interaction. From field technicians to control centre operators, they use SCADA interfaces to visualise system status, issue control commands, and respond to faults or anomalies. These systems provide the ability to observe power systems. They facilitate remote supervision, automated switching and integration with other digital tools in more sophisticated computational environments that can deliver diverse insights and automation.

Digital twins

Digital twins are dynamic, virtual replicas of physical power system assets or network segments. They enable early anomaly detection, degradation forecasting and proactive maintenance scheduling by leveraging AI and machine learning algorithms to analyse incoming high-frequency, real-time data, which they constantly receive from embedded sensors or PMUs capturing electrical parameters such as temperature, vibration, partial discharge and load. In turn, they help prevent unexpected failures and optimise asset lifecycle management.

Although digital twins are less frequently mentioned in the literature than technologies like blockchain (El Zein and Gebresenbet, 2024), they represent a powerful tool within the broader digital transformation, enabling improved situational awareness, operational efficiency and decision making within smart grids. The continuous data integration and advanced analytics embody the essence of digitalisation as an ongoing, value-adding innovation process driving the evolution of modern power systems.

Blockchain

Blockchain is a distributed, digital ledger for verifying transactions. It provides a shared, secure and transparent environment where all transactions are registered, documented and processed (IRENA, 2019a).

The technology enables, among other applications of digitalisation in the energy sector, peer-to-peer trading, management of electric vehicle charging, smart contracts for automated grid services and renewable energy certificate verification. In turn it offers a solution for managing increasing complexity in the energy sector. The transparency and immutability of blockchains boost trust, reduce transaction costs, and support new business models, such as decentralised energy marketplaces and tokenised financing. Utilities and market actors have piloted the so-called distributed ledger technology–based issuance of settlement/bills and certificates, improving auditability and reducing administrative burden (IRENA, 2018; World Bank, 2020).

Cloud computing and edge computing

Cloud computing centralises huge volumes of data from diverse energy assets, offering scalable storage, advanced analytics and real-time monitoring. These centralised data help optimise operations, improve efficiency, integrate renewable sources and improve grid management through predictive maintenance and automation.

Edge computing, on the other hand, processes data locally, at the network's periphery. The local processing of data enables instant responses to grid-wide fluctuations and demands. This reduces latency; ensures critical operations remain uninterrupted; and supports rapid decision making for grid reliability, outage management and integration of distributed energy resources such as solar and wind.

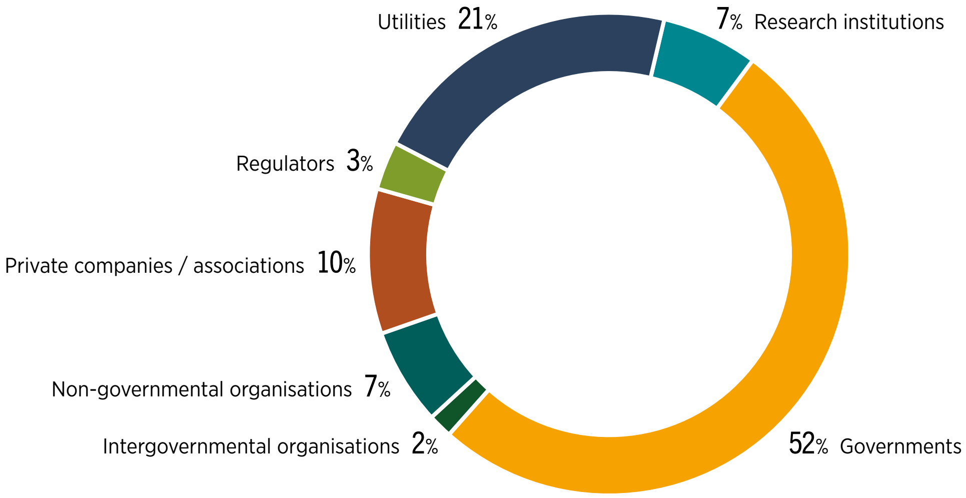
AI applications in the power sector

AI is a transformative digital technology that enables the integration of variable renewable energy into power systems through intelligent analysis and decision making based on big data. AI systems process huge volumes of data (related to assets, weather, renewable energy resources, market operations and consumer behaviour) collected via sensors and IoT devices, in turn improving forecasting (of renewable energy generation and demand); helping manage grid stability; and enabling efficient demand-side management, optimised energy storage operation, and improved market design and operation (IRENA, 2019a). AI can also leverage datasets originating from sensors, meters and other digital appliances to improve anomaly detection and asset management and enable autonomous control of distributed energy resources (IRENA, 2019c). AI techniques such as machine learning and big data analytics support automation and optimisation in energy systems.

SURVEY METHODOLOGY

To gain deeper insights into the current level of digitalisation in the energy sector, along with specific challenges and potential policy solutions, IRENA conducted a survey covering all 170 IRENA member countries down to IRENA's focal points in each country. Due to the limited time frame, 61 responses were received, most of them from government agencies and utilities. Respondents came from a wide range of countries, including developed economies as well as emerging markets and developing economies. IRENA also conducted detailed interviews with 14 experts to further the analysis behind this report.

Figure A.2 Survey respondents by sector



The survey also assessed the respondents' familiarity with digitalisation. Among them, 28% were slightly familiar, 33% somewhat familiar and 39% quite familiar with the topic.

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