Scaling up Electricity System Flexibility in Bulgaria through Digital Solution

Sofia University „St. Kliment Ohridski“, 2026
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Cover illustration: Antoaneta Lambert

Published by Sofia University „St. Kliment Ohridski“

Faculty of Economics and Business Administration

Net-Zero Lab

ISBN

Sofia, 2026

EXECUTIVE SUMMARY

Bulgaria's electricity system is at a structural inflection point. Renewables now account for 54.5% of installed generation capacity, solar PV alone reached 6,505 MW in 2026, and the system is already producing sustained periods of negative wholesale prices – clear evidence that the flexibility challenge is no longer a future concern but a present operational reality. On a typical spring day, solar dominates midday generation while evening prices spike to 250 EUR/MWh as output collapses. Managing this daily cycle is the defining challenge of Bulgaria's energy transition, and digital technologies are the primary lever for doing so.

This report examines how digitalisation can unlock the flexibility required to manage a high-renewables grid, assesses Bulgaria's current position relative to EU peers, and identifies priority actions for practitioners across the value chain.

The scenario analysis delivers one unambiguous finding: adding more renewable capacity without accompanying flexibility investment yields rapidly diminishing returns. Increasing installed solar capacity by 50% reduces the evening flexibility deficit by only 5% compared to baseline – the improvement curve saturates. The system requires approximately 1.5 GWh of battery storage and active demand-side management just to compensate the flexibility gap in a moderate growth scenario. Every euro invested in new generation beyond a certain threshold must now be matched by investment in flexibility infrastructure.

Bulgaria's digital readiness is uneven. The transmission system is technically modern: over 9,000 km of optical fibre, fully digitalised 110kV substations, and a live SCADA/EMS modernisation programme under the Recovery and Resilience Mechanism. The distribution layer tells a different story. Smart meter penetration ranges from 15% to 75% across the three DSOs, there is no mandated national communication standard, and DSOs rely on commercial mobile networks rather than dedicated infrastructure – a combination that structurally constrains real-time flexibility services. Bulgaria sits closer to Greece, which inherited the same fragmentation, than to Romania, which resolved it with a single regulatory decision mandating DLMS/COSEM as the national metering standard.

The regulatory framework is largely in place but incompletely implemented. NIS2 obligations apply to Bulgarian energy operators regardless of the incomplete national transposition. The Network Code on Cybersecurity (C/2024/1366) requires designated national authorities and recurrent risk assessments. The EU AI Act classifies grid control AI as high-risk with mandatory compliance obligations. Energy community and aggregator frameworks are legally enabled but operationally underdeveloped.

Four priority actions stand out. First, mandate a single interoperable metering communication standard before the next DSO investment cycle locks in further fragmentation – this is the most consequential single policy decision available. Second, implement NIS2-aligned cybersecurity procedures now, without waiting for full national transposition. Third, develop a national investment roadmap that sequences RRF, Horizon Europe and CEF funding coherently around the distribution digitalisation gap. Fourth, simplify aggregator and energy community procedures to allow small participants to engage with flexibility markets at scale.

The window is 2026–2029. The regulatory conditions, the funding instruments and the technology are all available. What is needed is the sequencing and the political commitment to act on the investment signals the system itself is already sending every day.

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List of abbreviations

Abbreviation	Full Form
ACER	Agency for the Cooperation of Energy Regulators
aFRR	Automatic Frequency Restoration Reserve
AI	Artificial Intelligence
AI Act	Regulation (EU) 2024/1689 on Artificial Intelligence
AMI	Advanced Metering Infrastructure
API	Application Programming Interface
AUER	Agency for Sustainable Energy Development
BEMS	Building Energy Management System
BESS	Battery Energy Storage System
BGN	Bulgarian Lev
BMS	Building Management System
BSI	Bundesamt für Sicherheit in der Informationstechnik (German Federal Office for Information Security)
CBA	Cost-Benefit Analysis
CEF	Connecting Europe Facility
CHP	Combined Heat and Power
CIE	Competitiveness and Innovation in Enterprises Programme
DER	Distributed Energy Resource
DESI	Digital Economy and Society Index
DLMS/COSEM	Device Language Message Specification / Companion Specification for Energy Metering
DSO	Distribution System Operator
DSR	Demand-Side Response
EMS	Energy Management System
ENERGO-PRO	ENERGO-PRO Bulgaria – Distribution System Operator (North and South-West Bulgaria)
ENTSO-E	European Network of Transmission System Operators for Electricity
ERN West	Electrodistribution Network West – Distribution System Operator (Western Bulgaria)
ESCRI	Electricity Storage and Control for Renewable Integration (Dalrymple, Australia)
ESO	Electricity System Operator
EU	European Union
EUR	Euro
EV	Electric Vehicle

EVN	EVN Bulgaria – Distribution System Operator (South-East Bulgaria)
FCR	Frequency Containment Reserve
GDPR	General Data Protection Regulation
GRAVITECA	Gravitational Storage, Quantum Computing and AI for Clean Energy Transition
GW	Gigawatt
GWh	Gigawatt-hour
HEMS	Home Energy Management System
HPP	Hydroelectric Power Plant
IACS	Industrial Automation and Control System
IBEX	Independent Bulgarian Energy Exchange
ICT	Information and Communication Technology
IEC	International Electrotechnical Commission
IED	Intelligent Electronic Device
IoT	Internet of Things
ISMS	Information Security Management System
ISO	International Organization for Standardization
IT	Information Technology
kbps	Kilobits per second
KEVR	Energy and Water Regulatory Commission
kWp	Kilowatt-peak (peak power of solar installations)
MAS	Multi-Agent System
Mbps	Megabits per second
mFRR	Manual Frequency Restoration Reserve
ML	Machine Learning
MPLS-TP	Multiprotocol Label Switching – Transport Profile
MQTT	Message Queuing Telemetry Transport
MTR	Multiannual Financial Framework Midterm Review
MW	Megawatt
MWh	Megawatt-hour
NDC	National Dispatch Centre
NECP	National Energy and Climate Plan
NIS2	Network and Information Security Directive 2 (Directive EU 2022/2555)
NPP	Nuclear Power Plant
NSI	National Statistical Institute
OJ	Official Journal of the European Union
OT	Operational Technology
P2P	Peer-to-Peer

PLC	Power Line Communication
PSPP	Pumped-Storage Power Plant (also PSHPP)
PV	Photovoltaic
RDC	Regional Dispatch Centre
RES	Renewable Energy Sources
RRF	Recovery and Resilience Facility
RRP	Recovery and Resilience Plan
RTU	Remote Terminal Unit
SaaS	Software as a Service
SCADA	Supervisory Control and Data Acquisition
SCADA/EMS	Supervisory Control and Data Acquisition / Energy Management System
SMGW	Smart Meter Gateway
SWD	Staff Working Document (European Commission)
TCP/IP	Transmission Control Protocol / Internet Protocol
TPP	Thermal Power Plant
TSO	Transmission System Operator
TWh	Terawatt-hour
TwinEU	Digital Twin for Europe – pan-European electricity grid digital twin (Horizon Europe)
USD	United States Dollar
V2G	Vehicle-to-Grid
VPP	Virtual Power Plant

1. INTRODUCTION

Digitalising the energy system is a prerequisite for scaling electricity system flexibility and maintaining security of supply in power systems as the share of renewable energy sources grows rapidly. At EU level, this transition is anchored in the European Green Deal, which sets a legally binding target to reduce greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels. Achieving this target requires a fundamental transformation of the electricity sector, with accelerated deployment of solar photovoltaic and wind power as the primary engines of decarbonisation.

Unlike conventional generation, solar and wind are non-dispatchable and inherently weather-dependent. Their variable output creates an ongoing imbalance risk between production and consumption that, if unmanaged, threatens system stability. Flexibility - on both the supply and demand side - is therefore not a desirable feature of the future energy system; it is a structural necessity.

Digital technologies are transforming the energy sector by enhancing real-time visibility across the grid, enabling automated control, and connecting previously passive consumers to energy markets. These advancements are driving a shift towards a more sustainable and resilient energy system. The EU Action Plan on Digitalising the Energy System1 frames this ambition at policy level, with the goal of building a sustainable, cybersecure and transparent market for digital energy services while protecting data privacy and sovereignty.

Digital transformation is a phenomenon introduced by the transformative power of digital technologies, and it has become a key driver for the energy sector2, with advancements in technology leading to significant changes in the way energy is produced, transmitted, and consumed. The impact of digital transformation on the energy sector is profound, with benefits such as improved efficiency, cost reduction, and enhanced customer experience3.

ENTSO-E defines system flexibility as "the ability of the power system to cope with variability and uncertainty in demand, generation and grid availability."[4] As the number of active participants in the system - prosumers, aggregators, energy communities, electric vehicles - continues to grow, and as generation becomes increasingly weather- and behaviour-dependent, more sophisticated and responsive control solutions are required to manage stochastic events in real time.

The modern energy system is, in essence, a data system: a network of participants integrated through shared data flows, common data spaces and interoperable digital platforms. This report examines how Bulgaria can scale up that integration to unlock the flexibility its electricity system will need through 2030 and beyond.

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[1] Dig European Commission. (2022). *Digitalising the Energy System – EU Action Plan (SWD(2022) 341 final)*.

[2] Nazari, Z., & Musilek, P.. (2023). *Impact of Digital Transformation on the Energy Sector: A Review. Algorithms, 16(4):211*.

[3] Nazari, Z., & Musilek, P.. (2023). *Impact of Digital Transformation on the Energy Sector: A Review. Algorithms, 16(4):211*.

[4] ENTSO-E. (2021). *Vision on Flexibility and the Electricity Markets of the Future*.

2. DIGITALISATION OF THE ENERGY SYSTEM: POLICY CONTEXT AND PRACTICAL IMPLICATIONS

Across the European Union, a growing set of coordinated policy initiatives, funding instruments, and governance mechanisms is shaping how digital technologies are deployed in electricity networks, markets, and end-use sectors. For practitioners - such as system operators, energy communities, aggregators, technology providers, and public authorities - understanding this policy landscape is essential for aligning investments, ensuring regulatory compliance, and unlocking new operational and market opportunities.

At the center of this transformation is the EU Action Plan on Digitalising the Energy System, which sets a strategic framework for secure connectivity, real-time data exchange, and smart grid deployment through a portfolio of 24 key actions. This Action Plan is closely linked to the development of the Common European Energy Data Space[5], which aims to enable secure, standardized, and interoperable sharing of energy data across stakeholders. Together, these initiatives establish the foundations for data-driven system operation, customer empowerment, and new digital energy services.

The regulatory backbone that gives these initiatives binding force consists of three interlocking instruments. The Electricity Market Regulation (EU) 2019/943 establishes the framework for competitive, consumer-centred electricity markets and is the primary legal basis for demand response, aggregation and the participation of energy communities in balancing markets. Building on this foundation, the NIS2 Directive (EU) 2022/2555 significantly raises the bar for cybersecurity across critical sectors: energy operators classified as "essential entities" - which includes transmission and distribution system operators - are now subject to mandatory risk management, supply-chain security requirements, and incident reporting within 24 hours of detection, with non-compliance carrying fines of up to €10 million.

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[5] European Commission. (2022). *Common European Energy Data Space*.

Cutting across both market and security dimensions, the EU AI Act (Regulation EU) 2024/1689 introduces binding requirements for AI systems deployed in critical infrastructure, classifying them as high-risk and requiring technical documentation, human oversight and robustness testing before deployment. For practitioners planning AI-based forecasting or grid control applications, these obligations must be factored into project design and procurement from the outset.

Sitting alongside these broader instruments is the Network Code on Cybersecurity for the Electricity Sector (C/2024/1366) - the first binding, sector-specific cybersecurity framework for electricity. Published in 2024 and developed with contributions from ENTSO-E, the EU DSO Entity and ACER, the Code establishes a recurrent process of risk assessments targeting entities with a critical or high impact on cross-border electricity flows. It sets common minimum requirements for risk management, monitoring, reporting and crisis management, and required all EU Member States to designate a competent national authority for its implementation by 13 December 2024. For system operators, the Network Code is not an abstract compliance exercise - it defines concrete operational obligations that must be embedded in investment planning, vendor contracts and incident response procedures.

Several initiatives focus on system-level optimisation and coordination. The Digital Twin of the European Electricity Grid,[3] supported under Horizon Europe with a budget of €25.2 million, seeks to simulate and optimise grid performance under high shares of variable renewable energy. In parallel, the Smart Energy Expert Group provides policy guidance to ensure that digitalisation efforts remain aligned with climate objectives and market realities. Interoperability is addressed through emerging EU-wide requirements for energy data, which are critical for scalable digital solutions and efficient grid operation.

On the demand side, the Code of Conduct for Energy-Smart Appliances promotes standardized interaction between appliances and the grid, enabling demand response and flexibility services. At the system level, Pan-European operational digital platforms are being developed to support real-time data exchange and renewable integration, while substantial EU research and innovation funding continues to accelerate the deployment of digital energy technologies.

Complementing these efforts, initiatives such as the Green Digital Coalition and the GEDI-EU Platform foster collaboration between the energy and digital sectors, ensuring that digital solutions contribute not only to system efficiency but also to emissions reduction and sustainability. Collectively, these initiatives define the enabling environment within which digital energy solutions are designed, tested, and deployed - setting the context for the technologies and applications discussed in the remainder of this chapter.

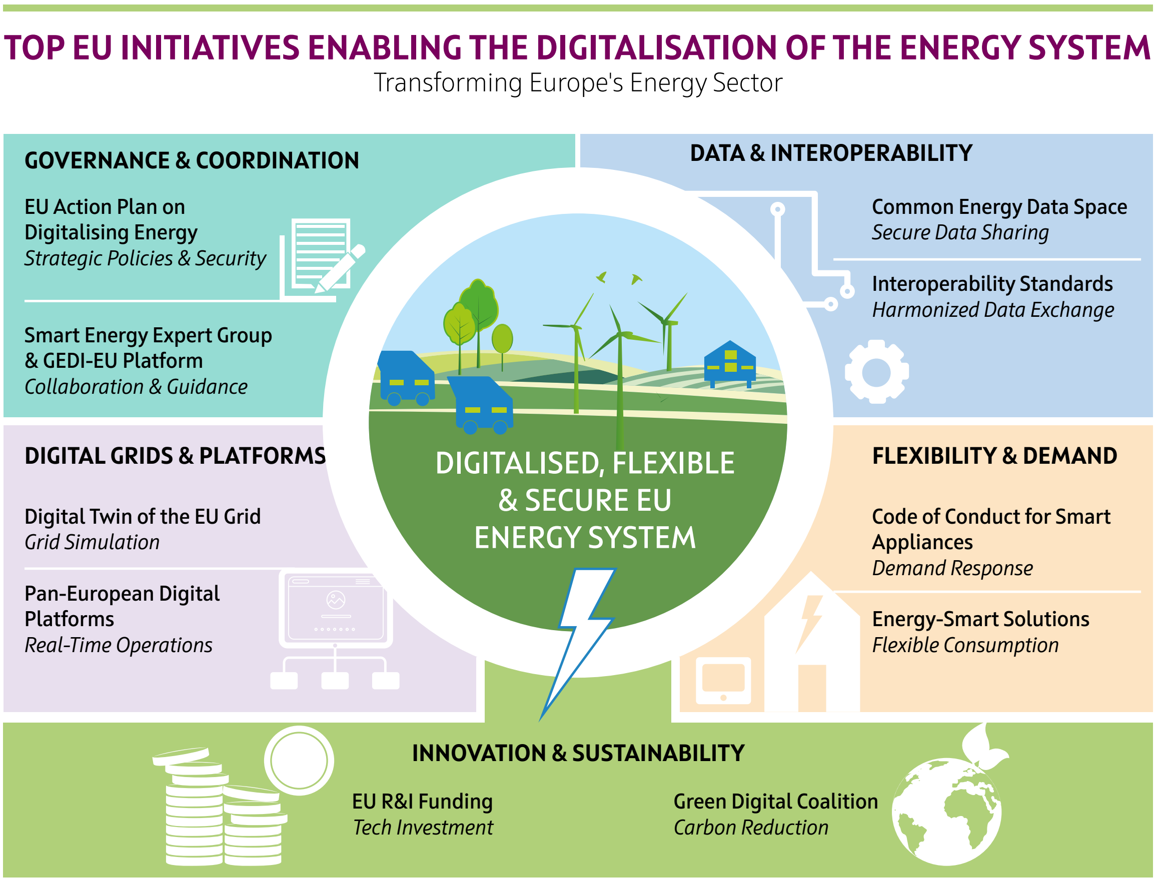

Figure 1. Top EU Initiatives Enabling the Digitalisation of the Energy System

Bulgaria's national framework sits within and responds to this EU architecture. The National Strategy for Digital Transformation 2020–2030, updated in 2024, aligns with the EU Digital Decade targets and identifies smart grid deployment, advanced metering infrastructure and data platform development as priority investment areas - providing the policy basis for accessing EU structural funds in these domains. The framework is given quantitative shape by the National Energy and Climate Plan (NECP), also updated in 2024, which translates EU climate targets into national trajectories for renewable deployment and emissions reduction through 2030. Together, the Strategy and the NECP define both the ambition and the pace of change that grid infrastructure must accommodate.

The operational response to these commitments is set out in the ESO Transmission Network Development Plan 2025–2034, which maps the investment programme for substation digitalisation, SCADA/EMS modernisation and communication infrastructure expansion needed to manage a grid with a rapidly growing share of variable renewables. Practitioners across the value chain - from technology suppliers to municipal energy communities - should treat this Plan as the primary reference for understanding where the transmission system is heading and where investment signals are strongest.

Table 1 TOP 10 EU INITIATIVES FOR DIGITALIZING THE ENERGY SYSTEM: TRANSFORMING EUROPE'S ENERGY[6]

INITIATIVES TO REALIZE AN EFFICIENT AND SUSTAINABLE DIGITALIZED ENERGY SYSTEM.	
1 EU Action Plan on Digitalizing the Energy System	The Action Plan aims to enhance connectivity and security, emphasizing a real-time data exchange framework and energy efficiency through smart grids and 24 key actions.
2 Common European Energy Data Space	Under development to securely share energy data, supported by the Digital Europe Program to facilitate smart grid utilization and energy efficiency.
3 Digital Twin of the European Electricity Grid	Seeks to simulate and optimize grid performance, especially incorporating fluctuating renewable energy sources, supported by Horizon Europe funding.
4 Smart Energy Expert Group,	Established to guide digitalization of the energy sector while aligning with climate targets, promote policy advice and innovation.
5 Interoperability Requirements for Energy Data.	Set to enable data sharing, critical for customer empowerment and grid efficiency
6 Code of Conduct for Energy-Smart Appliances	Standardize interaction of appliances with the grid, enhancing demand response and flexibility of the energy system.
7 Pan-European Operational Digital Platforms.	Being developed to support real-time data exchange and renewable integration, funded by the Connecting Europe Facility
8 R&I Funding supports digital energy technology	Substantial investments from various EU programs.
9 Green Digital Coalition endeavors	Creating tools to measure digital technologies' environmental impact, aiming to decrease carbon emissions and improve energy conservation.
10 GEDI-EU Platform facilitates	Collaboration among energy and digital innovators, working to integrate digital solutions in support of the energy transition.

On cybersecurity, Bulgaria is among the EU Member States that had not fully transposed the NIS2 Directive by the October 2024 deadline. The practical implications are significant: while the Directive's obligations apply regardless of transposition status, the absence of a fully operational national supervisory framework creates uncertainty for operators seeking regulatory clarity on compliance timelines, audit procedures and incident reporting channels. Practitioners are advised to implement NIS2-aligned risk management and incident reporting procedures now, in anticipation of the supervisory framework being completed, rather than waiting for full national transposition.

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[6] Jürgen Ritzek (2023). *Top 10 EU Initiatives for Digitalizing the Energy System*. EEIP.

3. DIGITAL TECHNOLOGIES with Application in Energy Sector

The modern energy system encompasses a wide range of participants – generators, transmission and distribution operators, market traders, industrial and domestic consumers, and data service providers – all interacting across three levels of digital control: production, transmission and distribution, and consumption. This hierarchical structure, illustrated in Figure 2, increasingly extends to electricity markets, aggregators and cloud-based service providers whose data and analytical capabilities are becoming integral to system operation.

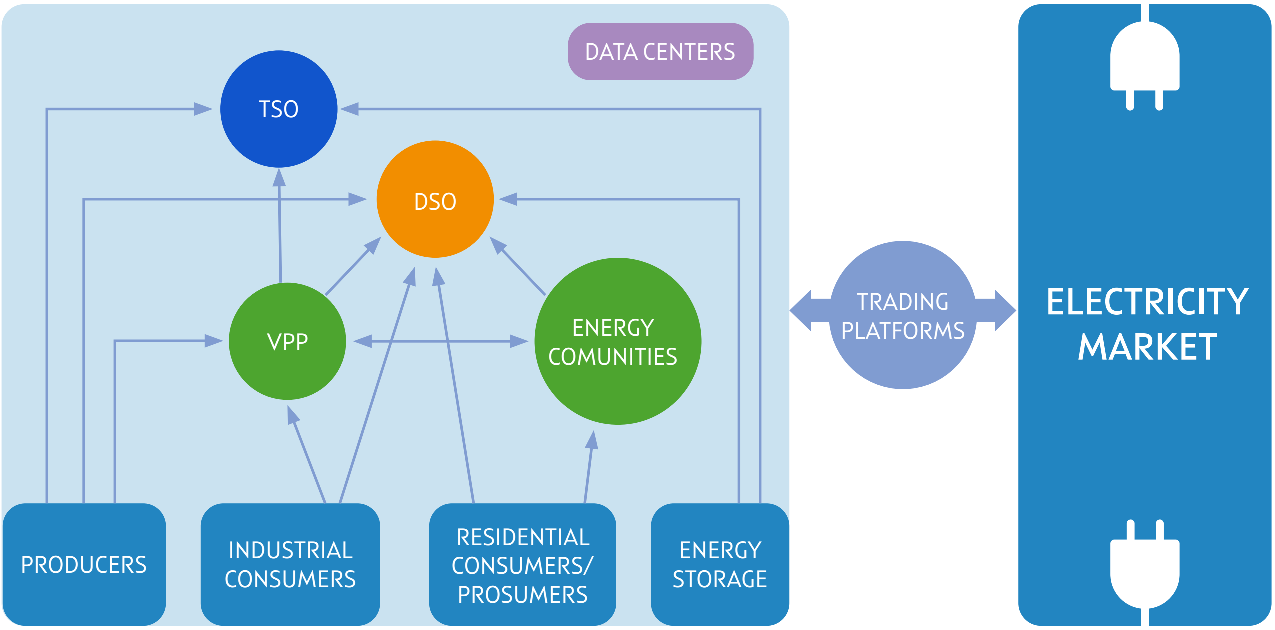
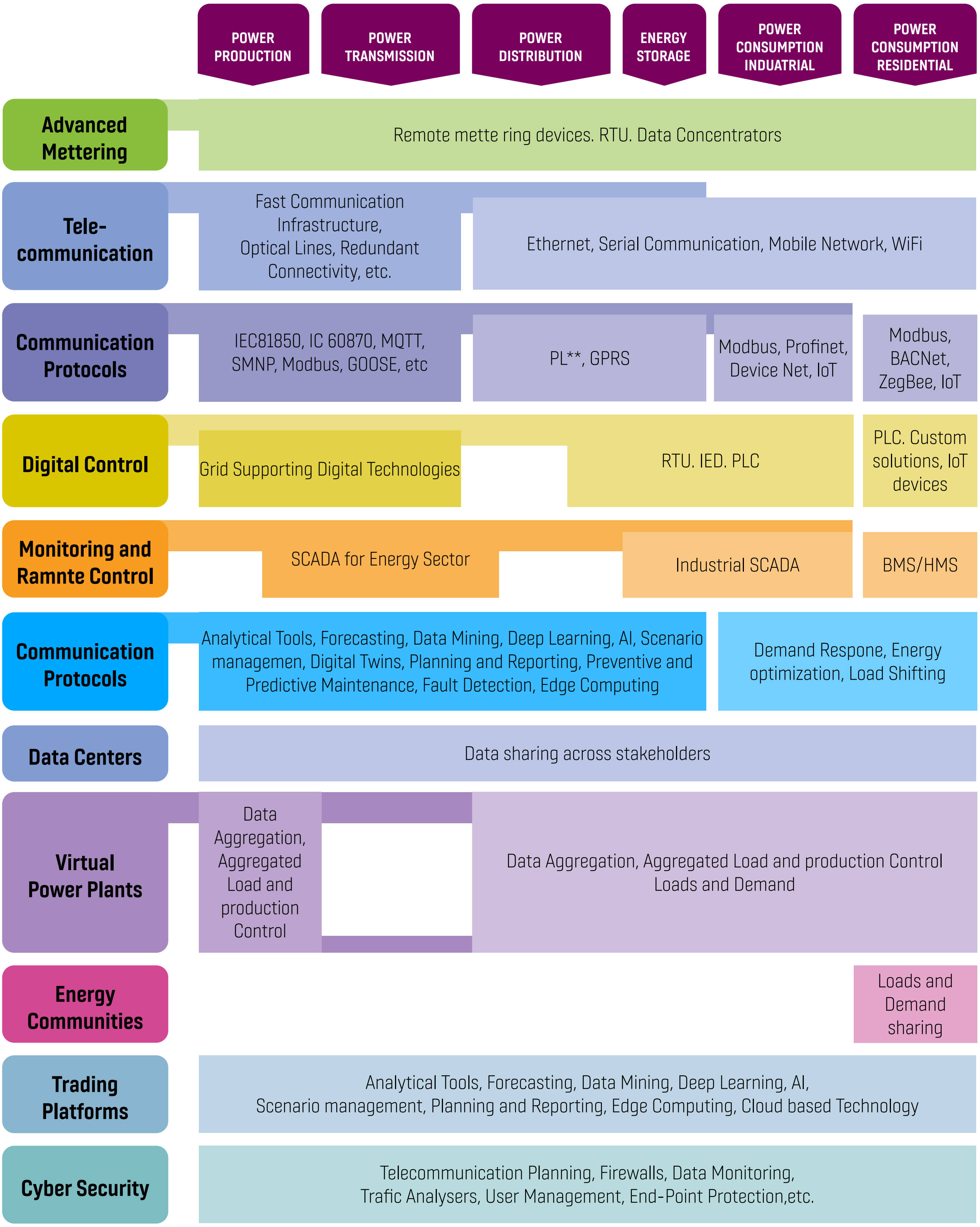


Figure 2 Hierarchical structure of Energy system

At any level of the structure common and specific digital tools and devices could be applied as it is shown on Figure 3.



POWER PRODUCTION
POWER TRANSMISSION
POWER DISTRIBUTION
ENERGY STORAGE
POWER CONSUMPTION INDUATRIAL
POWER CONSUMPTION RESIDENTIAL

Advanced Mettering
Remote mette ring devices. RTU. Data Concentrators

Tele-communication
Fast Communication Infrastructure, Optical Lines, Redundant Connectivity, etc.
Ethernet, Serial Communication, Mobile Network, WiFi

Communication Protocols
IEC81850, IC 60870, MQTT, SMNP, Modbus, GOOSE, etc
PL**, GPRS
Modbus, Profinet, Device Net, IoT
Modbus, BACNet, ZegBee, IoT

Digital Control
Grid Supporting Digital Technologies
RTU. IED. PLC
PLC. Custom solutions, IoT devices

Monitoring and Ramnte Control
SCADA for Energy Sector
Industrial SCADA
BMS/HMS

Communication Protocols
Analytical Tools, Forecasting, Data Mining, Deep Learning, AI, Scenario managemen, Digital Twins, Planning and Reporting, Preventive and Predictive Maintenance, Fault Detection, Edge Computing
Demand Respone, Energy optimization, Load Shifting

Data Centers
Data sharing across stakeholders

Virtual Power Plants
Data Aggregation, Aggregated Load and production Control
Data Aggregation, Aggregated Load and production Control Loads and Demand

Energy Communities
Loads and Demand sharing

Trading Platforms
Analytical Tools, Forecasting, Data Mining, Deep Learning, AI, Scenario management, Planning and Reporting, Edge Computing, Cloud based Technology

Cyber Security
Telecommunication Planning, Firewalls, Data Monitoring, Trafic Analysers, User Management, End-Point Protection,etc.

Figure 3 Relationship in a modern electricity system

All these participants implement different digital and engineering and economical tools to improve the performance and efficiency of the energy system in technical and financial aspects.

3.1. Monitoring and Control

SMART METERS AND ADVANCED METERING INFRASTRUCTURE (AMI)

Smart metering is a foundational milestone of the energy transition. The defining characteristic of a truly ‘smart’ meter is not the device itself but its ability to communicate using digital protocols and respond to signals from higher-level management systems – making ‘Advanced Metering Infrastructure’ a more precise term than ‘smart metering’ alone. AMI is the key enabler of customer participation in electricity system management, providing the real-time consumption and production data on which demand response, community energy and prosumer services depend.

The principal benefits of AMI deployment are well established in the literature:[7]

- **Energy efficiency:** granular consumption data enables customers and energy managers to identify waste and optimise usage patterns;
- **Grid flexibility:** real-time visibility of distributed generation and consumption enables DSOs to manage network loading dynamically;
- **Renewable integration:** AMI provides the data foundation for matching variable supply from solar and wind with adjustable demand;
- **Market participation:** customers can respond to price signals and participate in demand response programmes only if they can receive and act on near-real-time data;
- **HEMS/BEMS integration:** AMI enables connection with Home and Building Energy Management Systems, unlocking automated load control at the building level.

Despite these advantages, AMI penetration across EU Member States remains highly uneven.[8] As discussed in Chapter 4, Bulgaria’s three DSOs report penetration rates ranging from approximately 15% to 75% – a gap that directly determines which flexibility services are operationally feasible in each network territory today.

SCADA/EMS SYSTEMS

Above the metering layer, Supervisory Control and Data Acquisition (SCADA) and Energy Management Systems (EMS) form the operational core of grid control at every level. SCADA provides real-time online monitoring, control interfaces, alarm management and data archiving across the network. EMS extends this with analytical tools for forecasting, optimisation and loss minimisation – functions that are increasingly dependent on the quality and granularity of data flowing up from AMI and field sensors. The modernisation of SCADA/EMS is a primary objective of ESO’s Digital Transformation of the Electricity Grid project, currently financed under Bulgaria’s Recovery and Resilience Mechanism.

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[7] MENAFN; Mordor Intelligence. (2022). *Smart Metering Market Report*.

[8] European Commission, Joint Research Centre. (2023). *Smart Grids in the European Union: Status Report on Technology Development, Trends, Value Chains & Markets*.

IoT AND SENSOR NETWORKS

The Internet of Things extends digital monitoring to assets and environments that were previously invisible to grid operators – distributed solar installations, battery systems, EV chargers, industrial processes and building systems. IoT sensors provide the granular, continuous data streams that AI forecasting and optimisation algorithms require. Bulgaria's IoT market is growing at 9.57% annually and is projected to reach USD 1.08 billion by 2029, with deployments already active in smart city applications across Sofia, Varna, Burgas, Plovdiv and Vratsa. The challenge for the energy sector is integrating these IoT data streams into operational grid management systems in a way that meets the reliability and cybersecurity requirements of critical infrastructure.

3.2. Communication Infrastructure

PROTOCOLS: IEC 61850, IEC 60870 AND EEBUS

Communication networks are the connective tissue of the digital energy system. At the transmission and distribution level, two IEC standards dominate. **IEC 61850** defines communication protocols for intelligent electronic devices at electrical substations, enabling interoperability between protection, control and monitoring equipment from different manufacturers.[9] **IEC 60870-5** governs telecontrol communications between control centres and remote field equipment, and remains the primary protocol for SCADA data exchange between TSOs, DSOs and generation facilities.[10] Together, these standards provide a robust, internationally recognised framework for the upper layers of grid communication – but they do not extend naturally to the building and household level.

This is where **EEBus** addresses a critical gap. EEBus is a communication interface standard that allows energy-relevant devices in buildings – heat pumps, EV chargers, battery systems, appliances – to connect and interact with each other and with grid and market operators.[11] By providing a common language for 'behind-the-meter' communication, EEBus is a prerequisite for activating the demand flexibility potential of the building stock – a resource that remains largely untapped in Bulgaria and across most of the EU.

SPEED AND RELIABILITY REQUIREMENTS

Different grid functions impose very different communication performance requirements, and understanding these distinctions is essential for infrastructure planning. Primary frequency control requires response within seconds, meaning the full data loop – sensor to control system to actuator – must complete in under one second. Fast demand response services require activation within one to five minutes. Market settlement and billing require data delivery within 15 minutes to

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[9] International Electrotechnical Commission. (2020). *IEC 61850: Communication Networks and Systems for Power Utility Automation*.

[10] International Electrotechnical Commission. (2006). *IEC 60870-5: Telecontrol Equipment and Systems – Part 5: Transmission Protocols*.

[11] EEBus Initiative e.V.. (2023). *EEBus – The Language of Energy*.

one hour. The infrastructure that is adequate for billing is therefore structurally inadequate for real-time control, and investments in communication infrastructure must be designed with the most demanding target application in mind, not the least demanding.[12]

The Gaia-X Energy Data-X project, which began testing in the German power market in 2022, offers a relevant architecture for secure, scalable data space communication that could support near-real-time market processes.[13] Multi-agent systems (MAS) offer a complementary approach: by distributing decision-making locally rather than centralising it, MAS architectures reduce data communication requirements while improving privacy and resilience – an approach that is gaining traction in VPP and microgrid contexts.

CHALLENGES FOR DSOS: THE ABSENCE OF PRIVATE NETWORKS

DSOs across Bulgaria face a structural communication constraint that is common to many EU Member States but particularly acute in countries where metering modernisation is incomplete: they do not operate private communication networks. Instead, they rely on existing commercial broadband and mobile networks – infrastructure that was designed for consumer applications and was not built to the reliability, latency and security standards required for grid control.[14,15]

The practical consequences are significant. Commercial mobile networks are subject to congestion during peak hours, degraded coverage in rural and mountainous areas, and outages during the emergencies when grid communication is most critical. Real-time control services that depend on sub-minute data exchange cannot be reliably designed around commercial network availability. The wide range of protocols deployed by Bulgarian DSOs – PLC, MQTT, Modbus TCP and others – compounds this problem by creating an interoperability gap that no single aggregator or flexibility platform can bridge without bespoke integration work.

The strategic implication is that investment in private or dedicated communication infrastructure – whether licensed spectrum, fibre to substations or a hybrid architecture – must be evaluated alongside metering and platform investments when planning distribution-level flexibility services. The cost is significant, but so is the opportunity cost of building flexibility programmes on a communication foundation that cannot support them at scale.

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[12] ENTSO-E. (2019). *Towards Smarter Grids: Developing TSO and DSO Roles and Interactions for Efficient Flexibility Deployment*.

[13] Gaia-X Association. (2022). *Energy Data-X Project Overview*.

[14] European Commission, Joint Research Centre. (2023). *Smart Grids in the European Union: Status Report on Technology Development, Trends, Value Chains & Markets*.

[15] Electricity System Operator JSC. (2025). *Transmission Network Development Plan for Bulgaria for the Period 2025–2034*.

3.3 Data Analytics and Artificial Intelligence

GENERATION AND CONSUMPTION FORECASTING

Forecasting is currently the most mature and widespread application of AI and machine learning in the energy sector. Accurate short-term forecasts of solar and wind generation – typically at 15-minute to hourly granularity over a 24–48 hour horizon – are essential for scheduling, balancing market participation and dispatch optimisation. On the consumption side, load forecasting enables DSOs to anticipate congestion, plan preventive switching and optimise asset utilisation. In Bulgaria, as noted in Chapter 4, AI adoption in the energy sector is concentrated in exactly these forecasting and data analytics functions, with ESO's participation in the GRAVITECA project representing the frontier of what is being demonstrated at national level.

AI FOR GRID MANAGEMENT

Beyond forecasting, AI applications in grid management are expanding rapidly across the EU, though most remain at pilot or early deployment stage. Key applications include: congestion management through predictive load flow analysis; fault detection and predictive maintenance using pattern recognition on sensor data streams; optimisation of renewable dispatch and storage charge/discharge cycles; demand response automation in industrial facilities; and sector coupling – integrating electricity, heating, cooling and transport through AI-driven coordination.[16] AI can also support cybersecurity by analysing data traffic patterns to detect anomalies and prevent intrusions in operational technology networks.

The most challenging requirement for all these applications is data: AI algorithms require large volumes of high-quality, real-time data to train and operate effectively. This creates a direct dependency on the communication infrastructure and metering coverage discussed in Sections 3.1 and 3.2 – reinforcing the point that investment in data infrastructure is a prerequisite for AI value, not an alternative to it.

EU AI ACT REQUIREMENTS FOR CRITICAL INFRASTRUCTURE

The EU AI Act (Regulation EU 2024/1689), applicable from 2024, introduces binding requirements that directly affect energy sector practitioners planning AI deployments.[17] AI systems used in the management or operation of critical energy infrastructure are classified as **high-risk** under Annex III of the Act. This classification triggers a set of mandatory obligations that must be satisfied before any such system can be deployed:

- **Technical documentation:** detailed documentation of the system's design, training data, performance metrics and known limitations
- **Human oversight:** the system must be designed to allow human intervention and override at all times
- **Robustness and accuracy testing:** the system must be tested against adversarial inputs and out-of-distribution conditions before deployment

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[16] European Commission. (2024). [Regulation (EU) 2024/1689 – Artificial Intelligence Act (AI Act), OJ L, 2024]().

[17] European Parliament and of the Council. (2024). [Regulation (EU) 2024/1689 of the European Parliament and of the Council of 13 June 2024 laying down harmonised rules on artificial intelligence (Artificial Intelligence Act), OJ L, 12.7.2024]().

- **Registration:** high-risk AI systems must be registered in the EU database prior to market placement
- **Conformity assessment:** operators must conduct or commission a conformity assessment demonstrating compliance with the Act's requirements

For practitioners, the AI Act means that AI-based forecasting tools used for internal optimisation are relatively lightly regulated, while AI systems that generate or influence real-time control decisions – dispatch signals, protection settings, demand response activation – require full high-risk compliance. This distinction should be factored into project design, procurement specifications and vendor contracts from the outset. The compliance burden is significant but manageable if addressed early; retrofitting documentation and oversight mechanisms onto deployed systems is considerably more expensive.

3.4 Digital Twins

A digital twin is a real-time virtual replica of a physical system, continuously updated with operational data and used for simulation, optimisation and scenario testing. In the energy sector, digital twins at the asset level – individual substations, wind farms or battery systems – are already in industrial use. The strategic ambition at EU level is to federate these local twins into a pan-European Digital Twin of the electricity grid: a system-wide simulation capability that would allow operators, planners and policymakers to test the impact of technology deployments, extreme weather events, market designs and regulatory changes before committing to real-world implementation.[18]

The **TwinEU project**, launched in January 2024 under Horizon Europe, is the primary vehicle for realising this ambition.[19] With a total budget of €25.2 million (including €20 million in EU funding), TwinEU aims to develop the concept of the pan-European digital twin based on the federation of local twins, with ENTSO-E and the EU DSO Entity as the central coordinating bodies. For Bulgarian practitioners, TwinEU's relevance is twofold: as a source of modelling tools and methodologies that can be applied to national and regional grid planning, and as a demonstration that the data quality and communication infrastructure required to feed a digital twin is not a future aspiration but an active investment target at EU level today.

At the national level, ESO's SCADA/EMS modernisation programme creates the data foundation on which a Bulgarian grid digital twin could eventually be built. The practical value – improved network planning under high renewable penetration, better emergency response simulation, more accurate flexibility procurement – is directly relevant to the challenges identified in Chapter 5.

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[18] European Commission. (2024). *Digital Twin of the European Electricity Grid – Horizon Europe Project Documentation*.

[19] TwinEU Consortium. (2024). *TwinEU – Digital Twin for Europe, Horizon Europe Grant Agreement*.

3.5 Cybersecurity

THE THREAT LANDSCAPE

Cybersecurity has become a frontline operational challenge for the energy sector. A January 2025 report by TrustWave recorded an **80% increase in ransomware attacks targeting the energy and utilities sector in 2024**, driven by the intersection of geopolitical tensions and the rapid expansion of connected devices, cloud platforms and IoT infrastructure in operational environments.[20] The attack surface will continue to grow as digitalisation deepens: every new smart meter, IoT sensor, cloud connection and remote control capability is a potential entry point. The energy sector's criticality – and the potential for cascading failures across interconnected infrastructure – makes it a persistent high-value target for state-sponsored actors and criminal organisations alike.

The world's largest grid-forming battery storage system, the ESCRI Dalrymple project in South Australia, demonstrates both the potential and the risk of large-scale digital energy infrastructure: the same digital control systems that enable fast frequency response also represent a critical attack surface that must be defended with the same engineering rigour applied to the physical infrastructure.[21]

THE REGULATORY FRAMEWORK: NIS2, NETWORK CODE AND TECHNICAL STANDARDS

Three interlocking instruments now define the binding cybersecurity obligations for Bulgarian energy operators.

The NIS2 Directive (EU) 2022/2555, which came into force in October 2024, classifies energy sector operators – including TSOs, DSOs and key market participants – as 'essential entities', subject to mandatory risk management measures, supply-chain security requirements and incident reporting within 24 hours of detection.[22] Non-compliance carries administrative fines of up to €10 million or 2% of global annual turnover. Bulgaria's transposition of NIS2 was incomplete at the October 2024 deadline; practitioners should implement NIS2-aligned procedures now, in anticipation of the supervisory framework being completed.

The Network Code on Cybersecurity (C/2024/1366) is the first binding, electricity-sector-specific cybersecurity instrument in the EU.[23] Developed with contributions from ENTSO-E, the EU DSO Entity and ACER, it establishes a recurrent risk assessment cycle targeting entities with a critical or high impact on cross-border electricity flows. Article 4 required all Member States to designate a competent national authority for implementation by 13 December 2024. For TSOs and DSOs operating cross-border infrastructure, this Code creates direct, legally binding obligations for risk assessment, mitigation and governance.

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[20] TrustWave. (2025). *Energy & Utilities Sector Threat Intelligence Briefing*.

[21] Hitachi Energy. (2023). *ESCRI Dalrymple BESS Project – Grid-Forming Energy Storage, Project Case Study*.

[22] European Parliament and of the Council. (2022). *Directive (EU) 2022/2555 on Measures for a High Common Level of Cybersecurity across the Union (NIS2 Directive), OJ L 333, 27.12.2022*.

[23] European Commission. (2024). *Commission Regulation (EU) C/2024/1366 – Network Code on Cybersecurity for Cross-Border Electricity Flows, OJ 2024*.

At the technical level, two standards define the operational baseline. **ISO/IEC 27001:2022** provides the framework for information security management systems (ISMS), covering the full lifecycle of information assets.[24] **IEC 62443** addresses the specific requirements of industrial automation and control systems (IACS), covering the security architecture of OT environments from the field device level to the enterprise network.[25] Together, they provide a comprehensive technical framework – but one that requires significant investment to implement in legacy OT environments where security was not part of the original design.

For practitioners, the cybersecurity challenge is not primarily regulatory comprehension but operational implementation: embedding security requirements into procurement specifications, vendor contracts, change management processes and incident response procedures across the full lifecycle of digital energy infrastructure. The regulatory framework is now clear and comprehensive; the gap between regulation and practice is where the real work lies.

The main task of TSO is the control of the grid stability and to ensure control of the electricity production in a way supporting stable voltage and frequency regulation. The reaction of the electricity systems should be in function of the variable loads to keep the frequency and the voltage stable which is done by activating or deactivating electricity production facilities at steps known as primary, secondary and tertiary control (Figure 3). Conventional power plants are traditionally the main contributor to the stability of the grid, in terms of voltage and frequency. Therefore, a higher share of renewables in the power supply can potentially bring major challenges to power systems.

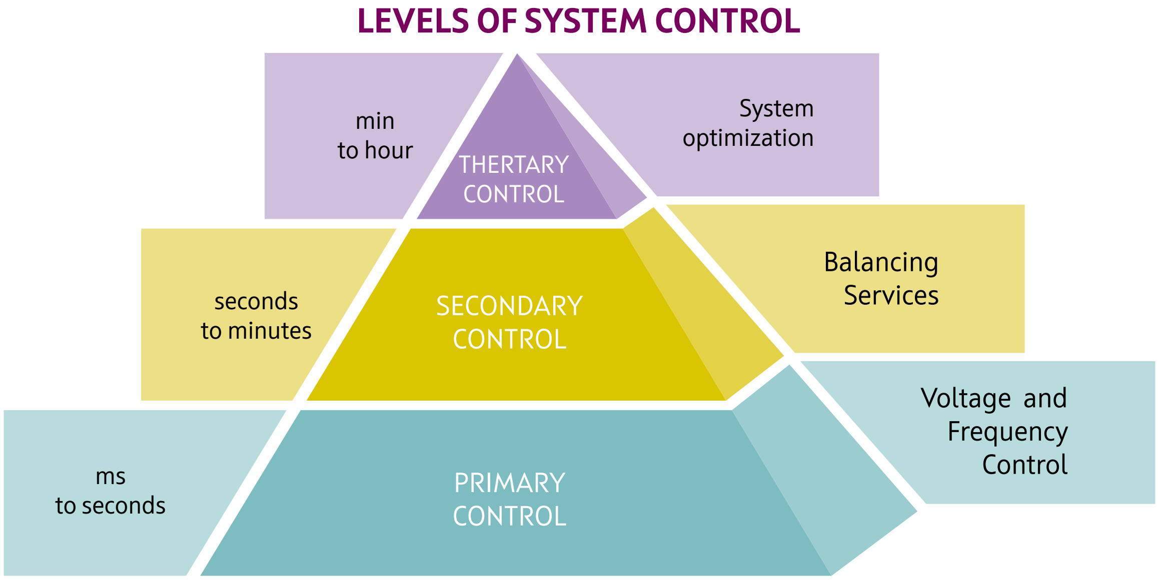

Figure 4 Levels of system control

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[24] International Organization for Standardization. (2022). *ISO/IEC 27001:2022 – Information Security Management Systems Requirements*.

[25] International Electrotechnical Commission. (2023). *IEC 62443 Series – Security for Industrial Automation and Control Systems*.

The RES domination in the energy system has strong impact on the system's reaction potential and provision of indispensable quality of electric power. The stochastic behavior of the energy produced by solar and wind power plants causes difficulties controlling the balance between production and consumption and as a result it leads to potential fluctuations in frequency and voltage. One of the major properties of the energy system is the existing inertia, Usually, it is a result of the rotating synchronous machines in the system used for electricity production from fossil fuels. Stopping these machines will be followed by lack of inertia and unacceptable fluctuations of the frequency and voltage. In case of increasing share of renewable energy (mainly solar and wind) it is necessary to provide additional services to support the energy system stability and reliability. Different solutions could be used to support grid inertia like utilization of synchronous condensers System Flexibility Technologies

Fexibility technologies can be grouped into three categories: supply-side, storage and demand-side. All three are required simultaneously – the scenario analysis in Chapter 6 confirms that any single pathway in isolation reaches saturation rapidly. All three also depend on digital infrastructure to function: the communication, metering and data platforms are the enabling layer for every flexibility technology discussed here.

3.4. Supply-Side Flexibility

Virtual Power Plants (VPPs) aggregate distributed energy resources – solar installations, batteries, flexible industrial loads – into a single software-controlled portfolio that can participate in balancing markets and provide ancillary services. VPP communication requirements are demanding: reliable, low-latency connectivity to all aggregated assets, and standardised data exchange with DSOs, TSOs and market platforms. Europe's largest VPP, operated by Statkraft in Germany, aggregates over 1,600 wind and solar parks totalling approximately 12,000 MW – illustrating the scale achievable with mature market and regulatory conditions.

Pumped-storage hydropower plants (PSHPPs) are Bulgaria's most valuable existing flexibility asset: they operate in generation mode during periods of low renewable output and as consumers during high-generation periods, directly buffering the solar duck curve. Grid-forming inverters and synchronous condensers provide synthetic inertia and fast reactive power support – services that become increasingly critical as conventional synchronous generators are displaced by inverter-connected renewables.

3.5. Battery Energy Storage Systems (BESS)

Battery energy storage is the fastest-growing flexibility technology in the EU. BESS charges during midday solar surplus and discharges during the evening peak – directly addressing the flexibility gap identified in the scenario analysis. The ESCRI Dalrymple project in South Australia, the world's first large-scale grid-forming BESS, demonstrates the operational feasibility of battery storage providing both energy shifting and grid stability services simultaneously. In Bulgaria, the scenario analysis estimates that approximately 1.5 GWh of BESS capacity is needed to compensate the evening flexibility deficit in the +30% PV scenario. Battery costs continue to decline, improving the investment case; the key enablers are grid connection rules, market access for storage and the digital control systems required for optimal dispatch.

3.6. Demand-Side Response (DSR)

Demand-Side Response shifts the consumption of industrial processes, buildings and households to periods of high renewable generation and low prices. Industrial DSR – shifting energy-intensive processes such as electrochemical production, refrigeration and compressed air – is the most immediately accessible flexibility resource because the loads are large, controllable and already metered at adequate granularity. Building and household DSR through HEMS and BEMS systems requires higher AMI penetration and customer engagement. Electric vehicle smart charging (V2G) represents a significant future resource: a fleet of EVs with bidirectional charging capability effectively constitutes a distributed battery system. All DSR services require advanced metering, aggregator platforms and real-time price signals – the digital infrastructure discussed in the next chapter.

3.7. Energy Communities

Energy communities enable collective, citizen-driven energy actions: pooling rooftop solar, sharing surpluses, procuring jointly, and participating in local flexibility markets. ICT systems provide communities with two core capabilities: monitoring power flows among members, and controlling flexible DERs to optimise collective energy consumption. An advanced metering infrastructure simplifies community operation by providing standardised, near-real-time data for monitoring, settlement and DSO coordination. The regulatory framework for energy communities in Bulgaria became operational following transposition of the Clean Energy Package, though implementation gaps – discriminatory provisions, lack of secondary legislation – remain to be addressed.

4. STATE OF DIGITALIZATION IN BULGARIA

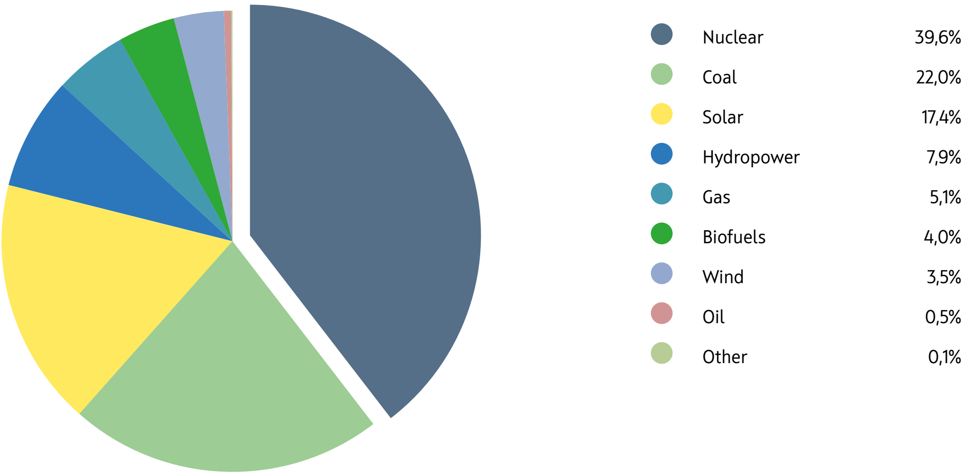
Bulgaria's energy system is undergoing a structural transition that mirrors broader EU trends but proceeds at its own pace and from its own starting point. Understanding where Bulgaria stands today - across generation, grid infrastructure, metering, artificial intelligence and market organisation

4.1 Generation Mix and the Growing Role of Renewables

By mid of 2026, renewables accounted for 54.5%[26] of Bulgaria's total installed electricity generation capacity - a figure that places the country broadly in line with the EU average for installed renewable share. However, installed capacity and actual generation are two very different things. Due to the inherent variability of solar and wind output, the utilisation factor of renewable sources meant they produced a bit more than 30 % of total electricity in 2025[27]. This gap between installed capacity and effective generation as depicted in Figure 5 is not unique to Bulgaria - it is a structural feature of all power systems with high renewable penetration - but it illustrates precisely why flexibility, rather than capacity alone, is the defining challenge of the energy transition.

ANNUAL ELECTRICITY GENERATION BY TECHNOLOGY (2025)

Source: Electricity Maps, 2025 | Low-carbon share: 72%



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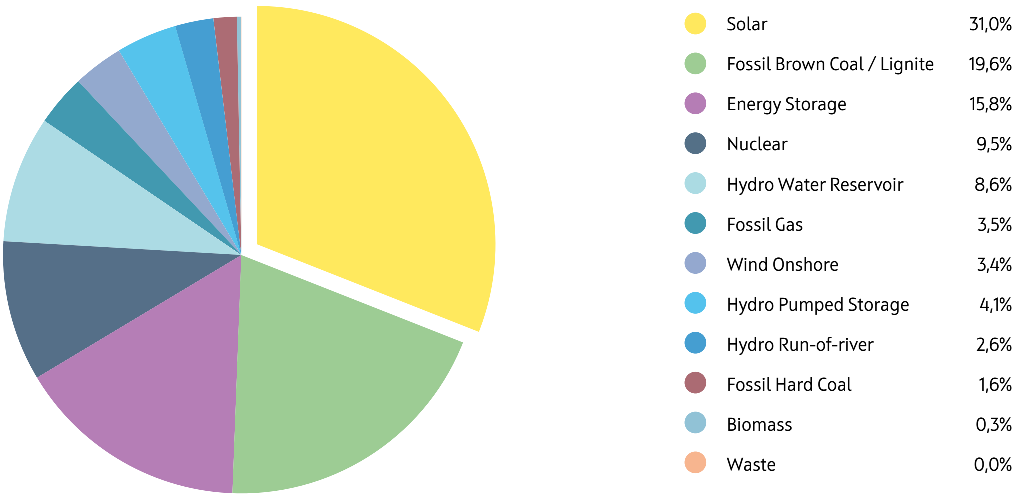
[26] ENTSO-E (2026): *Transparency Register*

[27] LowCarbonPower (2026): *Electricity in Bulgaria in 2025*



INSTALLED POWER CAPACITY BY ENERGY SOURCE (2026)

Source: ENTSO-E Transparency Platform, 01/01/2026 - 01/01/2027

Figure 5 The utilisation gap: Bulgaria's installed renewable capacity versus actual generation share (2025–2026)

The pace of change is accelerating. Solar PV capacity grew by 47.7% in 2024 compared to 2023, marking one of the highest growth rates in the region. In 2025, capacity expanded by a further 33.6% year-on-year, reaching 6,505 MW in 2026.

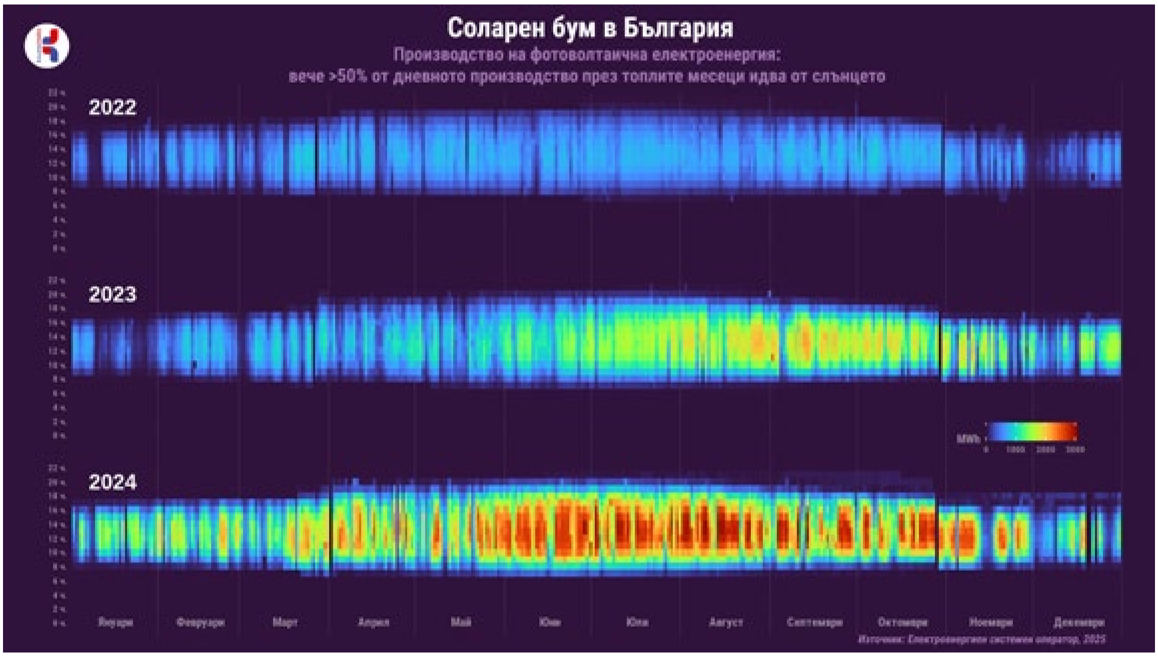


Figure 6 Participation of solar-based electricity in the Bulgarian power generation (2022-2024) [28]

On favourable weather days, renewables already supply more than 60 % of Bulgaria's total electricity production. Figure 6 illustrates a concrete example from 18 May 2026: real-time generation data shows solar PV dominating the midday profile, peaking at approximately 3,000 MW between 10:00 and 15:00 and effectively crowding out thermal generation during those hours. Equally striking is the evening transition:

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[28] Klimateka based on ESO data. Read more here.

as solar output collapses after 18:00, pumped storage discharge (PSPP) steps in as one of the largest single contributors to the generation mix, while IBEX prices spike to approximately 250 EUR/MWh - a near-daily illustration of the flexibility gap that storage and demand response must fill. Condensing thermal plants, once the backbone of the system, are now reduced to a thin baseload band at the bottom of the stack, with lignite capacity visibly retreating as its economics deteriorate. The missing piece in this picture is onshore wind, which would provide generation precisely in the evening and overnight hours when solar is absent and prices are highest - the gap that the current development pipeline must close. This pattern is no longer an exceptional event; it is becoming the operational norm that grid planning, market design and investment decisions must be built around every day.

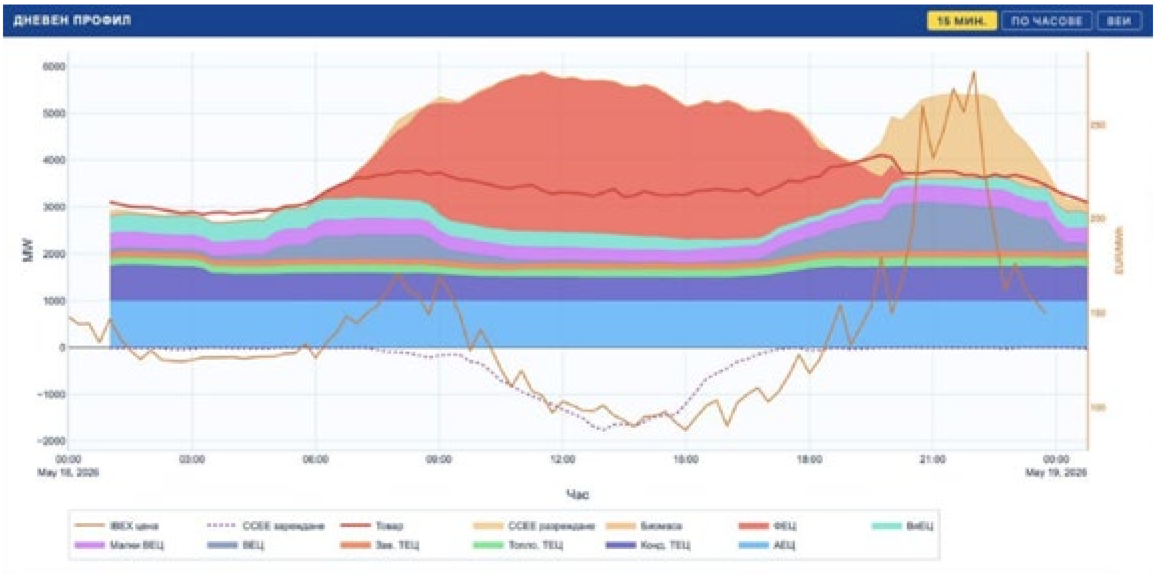

Figure 7 Daily generation profile in Bulgaria, 18 May 2026, 15-minute intervals[29]

More than half of the installed renewable capacity is connected to the transmission network, with the remainder distributed across distribution grids. According to the Agency for Sustainable Energy Development, 13,292 renewable installations are currently in operation in Bulgaria, of which 12,783 are solar. The vast majority of these are small, self-sufficient installations that do not participate in system balancing. Yet their aggregate effect on load profiles and grid quality parameters is substantial and growing. Managing this distributed generation base - ideally in real time - requires data collection, reliable communication channels and digital aggregation platforms capable of handling thousands of individual sources while meeting privacy and cybersecurity requirements. This is an area where Bulgaria has significant ground to cover.

The data shows a significant increase in renewable energy production installations, with the large number of installations being self-sufficient. Although these installations do not participate in balancing the energy system, they can influence the change in the load on the system and hence its quality parameters. It is obvious that data from these systems about their production and behavior should be collected (if possible, in real time) and analyzed in digital platforms (data spaces), which entails the need to provide reliable communication channels and technologies that ensure data authenticity, reliability and protection. It should be

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[29] Electricity System Operator (ESO). (2026). *Daily Generation Profile – Real-Time Dashboard*.

noted that the collection of this information must be carried out in accordance with privacy and cybersecurity requirements. In this case, the management of such many participants in the energy system would involve information aggregation services (like VPP) and the use of business and management models such as energy communities providing general management for a part of the participants in the energy system (producers and/or consumers).

4.2. Digital Infrastructure: A Strong Foundation, Uneven Deployment

Bulgaria's broader digital infrastructure provides a more encouraging starting point than is sometimes assumed. According to the National Statistical Institute, 92.1% of Bulgarian households had internet access in 2024, growing at 3.6% annually.[30] Among companies with more than ten employees, 96.4% are connected, and 89.2% of these have speeds exceeding 100 Mbps[31] - a connectivity level comparable to EU peers. In the energy sector specifically, 95.4% of companies in the electricity, heating and fuel sub-sector report internet connectivity. These figures suggest that the communication backbone needed for large-scale digitalisation is largely in place; **the challenge is not connectivity per se, but the integration and standardisation of what is built on top of it.**

At the transmission level, Bulgaria's digitalisation journey began in the 1980s and has progressed steadily. Today, the TSO (ESO) operates more than 440 monitoring points, of which 298 are within the ESO system itself, with the remainder covering electricity producers and DSOs.[32] All 110kV/medium-voltage substations have been digitalised, and the optical communication layer now extends to more than 9 000 km - a backbone that is both extensive and technically modern. Command latency from relay protection has been reduced to 6–9 milliseconds through linear optical infrastructure, approximately five to six times faster than classical technologies. The system uses MPLS-TP protocol with fixed addressing, balancing high data speeds with low data volumes - an appropriate choice for real-time grid control.

Since 2010, automated dispatch control systems have been progressively deployed, with connections established between the National Dispatch Centre (NDC) and Regional Dispatch Centres (RDCs), and remote switching rooms added across the network. Security standards have been progressively tightened in parallel. ESO is currently implementing the 'Digital Transformation of the Electricity Grid' project[33], financed under the Recovery and Resilience Mechanism, which will further modernise the SCADA/EMS platform, upgrade communication systems and strengthen the ability to respond to emergency situations. The planned improvement of the telecommunication network will also enhance real-time data exchange with ENT-

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[30] National Statistical Institute of Bulgaria (NSI). (2024). *Usage of Information and Communication Technologies in Households and Individuals*.

[31] National Statistical Institute of Bulgaria (NSI). (2024). *Usage of ICT in Enterprises*.

[32] Electricity System Operator (ESO). (2023). *Digital Transformation of the Electricity Grid – Project Documentation, Recovery and Resilience Mechanism*

[33] Electricity System Operator JSC. (2025). *Transmission Network Development Plan for Bulgaria for the Period 2025–2034*.

SO-E member TSOs across borders – a requirement that will become increasingly important as cross-border electricity flows grow.

Compared to EU peers, Bulgaria's TSO infrastructure compares favourably in terms of optical network coverage and substation digitalisation. Where gaps remain is in the speed and granularity of data exchange at the distribution level, and in the integration of the growing number of distributed renewable installations into a coherent, real-time monitoring framework.

4.3. Smart Metering: A Country Divided by Operator

The state of smart metering in Bulgaria is best understood through two lenses simultaneously: the EU benchmark and the differentiated reality on the ground.

At EU level, the 2023 Smart Grids Status Report[34] found that 21 Member States had decided to proceed with full smart meter rollout on the basis of positive cost-benefit analyses, four (Belgium, Czech Republic, Germany and Slovakia) reported negative CBAs, and two – Bulgaria and Hungary – had not communicated their CBA results at all. The EU report records Bulgaria's smart meter utilisation rate as below 10%, placing it among the least advanced Member States on this indicator. For comparison, leading countries such as Finland, Sweden and Italy have achieved penetration rates above 90%, while even regional neighbours such as Romania are progressing with structured national rollout programmes.

However, the picture within Bulgaria is more nuanced than the EU aggregate suggests, and practitioners should not interpret the sub-10% figure as uniformly descriptive of all distribution networks. Bulgaria has three DSOs operating in distinct geographic territories, and their metering progress diverges sharply[35]:

Table 2 SMART METER PENETRATION BY DSOS IN BULGARIA COMPARED TO THE EU AVERAGE (2023)

DSO	Smart meter penetration (approx.)	Territory
EVN Bulgaria	~75%	South-East Bulgaria
ERN West	>40%	Western Bulgaria
ENERGO-PRO Bulgaria	~15%	North and South-West Bulgaria
EU average (2023)	~56%	Source: EU Smart Grids Status Report 2023

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[34] European Commission, Joint Research Centre. (2023). Smart Grids in the European Union: Status Report on Technology Development, Trends, Value Chains & Markets.

[35] EVN Bulgaria; ERN West; ENERGO-PRO Bulgaria. (2024). *Annual Reports and Data Communicated to the Authors* Note: the EU 2023 Smart Grids Report records Bulgaria's national utilisation rate as below 10%; the operator-level figures reflect each DSO's own reported deployment within its licensed territory

This threefold variation within a single country reflects differences in investment strategy, network topology and the pace at which each operator has pursued modernisation. It also means that the operational opportunities available to practitioners, aggregators and prosumers vary significantly depending on location: a demand response programme that is technically feasible in EVN territory may be practically unworkable in ENERGO-PRO territory today, even under identical regulatory conditions.

4.4. Communication Protocols and Data Infrastructure at the Distribution Level

The communication layer of a distribution network is, in practical terms, the nervous system of any flexibility service. Without fast, reliable and standardised data exchange between field devices, control systems and market platforms, demand response programmes cannot function, aggregators cannot bid accurately into balancing markets, and real-time grid management remains out of reach.

Bulgarian DSOs currently deploy three main communication technologies at the field level, each reflecting a different engineering trade-off between cost, speed, reliability and coverage:

- *PLC – Power Line Communication* uses the existing electricity cable itself as the communication medium, transmitting data signals over the same infrastructure that carries power. This makes it highly cost-effective for meter reading, since no separate communication network needs to be built alongside the grid. PLC is the dominant technology for smart metering rollout across Europe, including in EVN's territory in Bulgaria. Its limitations are significant, however: data speeds are low (typically 2–100 kbps in narrow-band PLC, which is the most widely deployed variant), latency is high and variable, and the signal quality degrades with cable length, network topology and electrical interference from connected devices. PLC is well-suited for collecting consumption data every 15 minutes or hourly – the granularity needed for billing and market settlement – but it is structurally unsuitable for real-time control applications that require sub-second or even sub-minute response times.
- *Modbus TCP* is one of the oldest industrial communication protocols still in widespread use, originally developed in 1979 and subsequently adapted for TCP/IP networks. It is a simple, robust master-slave protocol widely used for communication between RTUs, data loggers and SCADA systems at substations and larger production facilities. Its simplicity is both its strength and its limitation: Modbus TCP has no built-in security features, no native support for complex data structures, and was not designed for the large-scale, multi-party data exchange required by modern smart grid applications. In the Bulgarian DSO context, it is primarily used for substation automation and industrial connection points rather than for customer-facing metering.

- *MQTT – Message Queuing Telemetry Transport* is a lightweight publish-subscribe protocol originally designed for low-bandwidth, high-latency environments such as satellite links and remote industrial sensors. It has gained significant traction in IoT applications and is increasingly used in smart metering and demand response platforms because of its efficiency in transmitting small data packets over commercial mobile networks. MQTT is more modern than Modbus and better suited to cloud-based aggregation platforms, but it was not designed as a grid control protocol and lacks the deterministic timing guarantees required for protection and real-time stability applications.

> A patchwork without a standard:
> Bulgaria's DSOs each chose their protocols independently, at different times, for different purposes – and the result is a fragmented communication layer that no aggregator, no demand response platform and no real-time control system can work across without bespoke, costly integration.

The use of PLC, MQTT and Modbus TCP side by side – alongside other proprietary protocols not listed here – reflects the absence of a single, mandated communication standard for distribution-level grid operations in Bulgaria and, to varying degrees, across the EU as a whole. Each protocol was selected at a different time, by a different operator, for a different application, and the result is a fragmented communication landscape that creates three specific problems for practitioners building flexibility services.

- ***First, interoperability is limited***. An aggregator seeking to control loads across all three Bulgarian DSO territories must interface with different communication systems, different data formats and different latency profiles. This raises development costs, slows deployment and effectively restricts the addressable market for flexibility service providers.
- ***Second, real-time control is structurally constrained.*** The combination of narrow-band PLC's inherent latency and the absence of private, dedicated communication networks means that the data pipeline between a customer's meter and a DSO's control system is not fast enough, or reliable enough, to support the response times required for primary frequency control (seconds) or fast demand response (minutes). This is not a configuration problem that can be solved with software; it reflects the physical and architectural limitations of the underlying infrastructure.
- ***Third, cybersecurity is inconsistent.*** PLC and Modbus TCP were designed in an era when grid communication networks were closed and physically isolated. Neither

protocol was built with encryption, authentication or access control in mind. As DSOs increasingly route data over commercial mobile networks and cloud platforms, the security assumptions embedded in legacy protocols become active vulnerabilities – a concern that is directly addressed by the NIS2 Directive and the Network Code on Cybersecurity discussed in Chapter 2.

The protocol fragmentation described above is not unique to Bulgaria, but the degree of exposure varies significantly across Member States, and the gap between Bulgaria and leading EU countries is widening as those countries implement structured modernisation programmes.

The Netherlands and Denmark represent the most advanced end of the spectrum. Both countries have deployed DLMS/COSEM (Device Language Message Specification / Companion Specification for Energy Metering) as a mandatory standard for smart meter communication, ensuring full interoperability across all DSOs and enabling third-party service providers to access standardised data streams. DLMS/COSEM supports two-way communication, time-stamped data, remote configuration and – critically – the data granularity and speed required for near-real-time demand response. The Netherlands completed its national smart meter rollout under this standard, achieving over 90% penetration, with a single P1 data port on every meter that any certified third party can read in real time. This infrastructure directly enables the aggregator and energy community ecosystem that has made the Dutch market one of Europe's most advanced for flexibility services.

Germany and France present a more complex picture. Both countries have been slower to standardise than the Netherlands, and both have faced criticism for the fragmented state of their DSO communication infrastructure. Germany's smart meter rollout, which uses a dedicated Smart Meter Gateway (SMGW) architecture with strict cybersecurity requirements under BSI (Federal Office for Information Security) standards, has been significantly delayed – but when complete will deliver one of the most secure and standardised metering infrastructures in Europe. France's Linky meter rollout, completed at near-universal penetration by 2021, uses PLC-G3 with a proprietary data model, which has enabled mass deployment but limits interoperability with third-party platforms.

Italy, which completed one of Europe's earliest large-scale smart meter rollouts in the early 2000s and is now deploying second-generation meters, has moved to a more open architecture that supports both PLC and cellular communication, with standardised interfaces for aggregators. The Italian experience is particularly relevant for Bulgaria because Italy similarly has a highly distributed renewable generation base and a complex distribution network, and has used metering modernisation as a direct enabler of its demand response and virtual power plant market.

Among regional peers, Romania is implementing a structured national smart metering programme under its Recovery and Resilience Plan, with DLMS/COSEM as the mandated communication standard – a deliberate policy choice to avoid the interoperability problems that have plagued earlier EU rollouts. Greece, despite leading Europe in energy community numbers, has a DSO communication infrastructure that remains fragmented, and the lack of standardised metering data is frequently cited by Greek aggregators as the primary operational barrier to scaling flexibility services. Bulgaria sits closer to Greece than to Romania in this picture – inheriting a fragmented legacy without yet having made the policy commitment to a single standard that would set a clear direction for the next investment cycle.

4.5. Artificial Intelligence: Early-Stage Adoption

The adoption of AI in Bulgarian companies remains limited but is accelerating rapidly. In 2024, 6.9% of Bulgarian companies reported using AI technology – a figure that has roughly doubled compared to 2023, suggesting that adoption is entering a steeper growth phase.[36] The EU average for enterprise AI adoption stands at approximately 13–14%,[37] meaning Bulgaria remains below the European mainstream, but the trajectory is encouraging.

Current AI applications in Bulgaria are concentrated in supporting functions: text, image and speech recognition, machine learning for data analysis and process optimisation. No verified cases of AI deployment for real-time grid control purposes have been reported to date – a gap that reflects both the early stage of the technology and the conservative risk culture appropriate to critical infrastructure. This picture is broadly consistent with the EU average: most Member States are still deploying AI in administrative and forecasting roles rather than operational control, with the notable exception of a small number of TSOs running pilot programmes under regulatory sandbox frameworks.

Bulgaria's most significant AI engagement in the energy sector is through the GRAVITECA project, in which ESO participates as a partner. With a budget of €2.5 million, GRAVITECA combines gravitational energy storage, quantum computing and AI-driven analytics – representing the frontier of what digital and AI technologies may contribute to grid stability and flexibility management.[38] While this remains a research and demonstration project, it positions ESO to develop internal expertise that will be essential as AI transitions from supporting function to operational tool in the years ahead.

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[36] National Statistical Institute of Bulgaria (NSI). (2024). *Enterprises Using Artificial Intelligence Technologies*.

[37] Eurostat. (2024). *Enterprises that Used Artificial Intelligence Technologies – EU Average Based on Available Member State Data*

[38] GRAVITECA Consortium. (2024). *GRAVITECA – Gravitational Storage, Quantum Computing and AI for Enhanced Circularity and Reliability, Horizon Europe Grant Agreement*.

4.6. Virtual Power Plants and Energy Communities: Momentum Building from a Low Base

Bulgaria's development of virtual power plants and energy communities has accelerated in recent years, driven primarily by regulatory change rather than voluntary market initiative. The introduction of Regulation (EU) 2195/2017 on Energy Balancing Guidelines and the liberalisation of the balancing market were the primary catalysts: by making market participants financially responsible for their own imbalances, the regulation created a direct economic incentive to aggregate, forecast and actively manage generation portfolios.[39] In response, large producers began building control centres, developing forecasting capabilities and offering balancing services – in practice operating as virtual power plants, even where that term is not formally applied.

This market-driven aggregation is a meaningful development, but Bulgaria remains far behind EU leaders in the formal organisation of VPPs and energy communities.[40] Greece leads with 884 registered energy communities, followed by the Netherlands with 705 and Austria with 200.[41] Bulgaria currently has two operational energy community, one under construction and three at project stage – a total of six, all concentrated in several municipalities. The contrast is stark but should be read in context: countries such as Greece and the Netherlands have benefited from enabling regulatory frameworks for community energy for more than a decade. In Bulgaria, by contrast, the legal framework for energy communities only became operational following the transposition of the Clean Energy Package. Even then, the transposition remained incomplete and poorly implemented, with persisting discriminatory provisions, regulatory uncertainty, and a lack of secondary legislation and practical implementation procedures.

The operational community – Energy Community Gabrovo, established in 2023 – is Bulgaria's first, and its design reflects the pragmatic, asset-based approach characteristic of early-stage community energy in countries without an established tradition in the sector.[42] Built around a 100 kWp solar installation generating approximately 119 MWh per year, it serves a straightforward but important function: 50% of output is consumed on-site by the Regional Landfill for Non-Hazardous Waste, a founding participant, with the remainder sold to other community members. A second Gabrovo project is in development, targeting 150 kWp of solar capacity on the rooftop of the Municipal Passenger Transport company.

The Energy Community Burgas, currently under construction, is a municipality-initiated but citizen-managed project built around a 420 kWp installation on the roof of the Park Arena OZK swimming facility, with more than 85% of the energy

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[39] European Parliament and of the Council. (2017). *Regulation (EU) 2017/2195 Establishing a Guideline on Electricity Balancing, OJ L 312, 28.11.2017*.

[40] European Parliament and of the Council. (2018). *Clean Energy for All Europeans Package – Directive (EU) 2018/2001 and Directive (EU) 2019/944*.

[41] REScoop.eu. (2024). *European Energy Communities Tracker*.

[42] Gabrovo Municipality. (2023). *Energy Community Gabrovo – Project Documentation*. Read more at https://sharerenewables.bg/

destined for local use.[43] Both projects are small in absolute terms, but they are significant as proof-of-concept demonstrations in a country with no prior experience in community energy.

The table below provides a summary comparison of selected EU VPP operators, illustrating the scale and sophistication of what has been achieved in markets where aggregation and virtual power plant operation have had time to mature – and defining the direction of travel for Bulgarian operators.

Table 3 SELECTED EU VPP OPERATORS IN EUROPE

No	Owner / Country	Description
1	**CNR / France**	Operates wind, solar and run-of-river hydro along the Rhône; offers direct marketing services for third-party wind and solar operators.
2	**MVV / Germany**	Operates a VPP for day-ahead and intraday trading since June 2014; provides FCR, aFRR and mFRR ancillary services across four TSO control areas (50Hertz, Amprion, TransnetBW, TenneT).
3	**Kelag / Austria**	SaaS-based VPP with integrated wind and solar forecasting; digitally connected 30 wind farms within weeks of contract signature in October 2021.
4	**Protergia / Greece**	Manages conventional and renewable assets totalling 1.5 GW in a single integrated VPP framework.
5	**Statkraft / Germany**	Europe's largest VPP: over 1,600 wind and solar parks aggregated to approximately 12,000 MW of combined capacity.

Sources: CNR,[44] MVV/emsys VPP,[45] Kelag/emsys VPP,[46] Protergia,[47] Statkraft.[48]

The gap between Statkraft's 12,000 MW and Bulgaria's nascent several-community ecosystem should not be read as discouraging – it reflects the difference in the maturity of the regulatory and market frameworks within which operators are working, not an inherent national incapacity. What the comparison makes clear is that the regulatory conditions Bulgaria now has in place – the balancing market reform, the transposition of the Clean Energy Package provisions on energy communities and active customers – are the same conditions that enabled aggregation and VPP development to take off in Germany, France and Austria. The trajectory is set; the pace of progress will depend on whether practitioners, municipalities and policymakers choose to build on it.

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[43] Burgas Municipality. (2024). ***Energy Community Burgas – Project Documentation***. Read more at https://share-renewables.bg/

[44] CNR (Compagnie Nationale du Rhône). (2024). *VPP Portfolio Description*.

[45] emsys VPP. (2023). *MVV Energie Case Study*.

[46] emsys VPP. (2021). *Kelag Case Study*.

[47] Protergia. (2024). *Corporate Portfolio Data*

[48] Statkraft. (2024). *Virtual Power Plant Germany – Corporate Communications*.

5. CHALLENGES IN APPLYING DIGITAL TECHNOLOGIES

Digitalising the energy system affects every layer of the grid - from high-voltage transmission down to the individual household meter. The barriers are not purely technical; they span finance, regulation, cybersecurity and human behaviour. Understanding each dimension is essential for practitioners who need to plan investments, design projects or advise policymakers. This chapter consolidates the challenges identified across all sources and links them to the actionable instruments available in Bulgaria.

5.1. Technical Complexity and Scale

Bulgaria's IoT market is among the fastest-growing in the region, with double-digit annual growth rates projected through 2029.[49] Yet the energy system's requirements go significantly further than urban IoT: they demand real-time data exchange across thousands of generation assets, millions of consumption points and multiple control layers simultaneously, all while maintaining the sub-second stability tolerances on which system security depends.

System control and stability sit at the core of this challenge. Every digital technology introduced into the grid must be assessed not only for its individual performance but for its effect on the system as a whole – on frequency, voltage, inertia and the speed of response to disturbances. As the number of active participants grows – prosumers, aggregators, energy communities, electric vehicles – the control problem becomes exponentially more complex. The need for real-time data at scale drives the requirement for large, secure and reliable communication infrastructure at every level of the system, from transmission substations to household meters. Enhanced control algorithms and AI applications in real-time grid management further require common standards for testing and deployment before they can be safely embedded in operational systems. Common data spaces must be established to provide all market participants with easy, secure and reliable access to the data they need – without which competitive flexibility markets cannot function. Finally, technologies for grid stability support – battery storage systems and grid-forming inverters – require further development and systematic integration into network planning before they can fulfil their potential as flexibility assets.

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[49] Statista. (2024). *Internet of Things (IoT) – Bulgaria*. Statista Market Insights

5.1.1. Lack of a Single Communication Protocol

The absence of a mandated, interoperable communication standard is the single most pervasive technical barrier to scaling flexibility services in Bulgaria, and it operates at every level of the system. At the transmission and distribution interface, IEC 61850 and IEC 60870 are the dominant protocols used by TSOs and DSOs for substation automation and control. These are well-established, purpose-built grid protocols – but they cover only the upper layers of the network. The moment the system needs to reach into industrial facilities, commercial buildings and homes, the picture fragments dramatically: energy management systems in industry (EMS), building management systems (BMS) and home energy management systems (HEMS) collectively deploy more than 200 different protocols. Integrating these environments into a coherent, real-time control framework without a common communication layer is technically possible but commercially prohibitive.

At the distribution metering level, as analysed in detail in Section 5.3.1, Bulgarian DSOs independently selected PLC, MQTT and Modbus TCP for different purposes at different times, producing a fragmented landscape that no aggregator or demand response platform can navigate without bespoke, costly integration work. The contrast with the Netherlands and Denmark – where DLMS/COSEM was mandated as a national standard from the outset of smart meter deployment – illustrates precisely what standardisation from the beginning makes possible: full interoperability, third-party data access through a single interface, and a functioning market for flexibility services built on top of it. Bulgaria sits closer to Greece, which similarly inherited fragmentation without yet having made the policy commitment to a single standard, than to Romania, which has taken the deliberate decision to mandate DLMS/COSEM under its Recovery and Resilience Plan and avoid repeating the mistakes of earlier EU rollouts.

The EEBus initiative offers one partial solution for the building and home layer, providing a common communication interface for energy-relevant devices to interact with grid and market operators. At the data space level, the Gaia-X Energy Data-X project provides an architecture for secure, standardised data exchange across market participants. But neither initiative substitutes for a national decision on metering communication standards – which remains the most consequential single policy choice available to Bulgarian regulators in this space.

5.1.2. Cybersecurity

Cybersecurity has moved from a background concern to a frontline operational challenge in the energy sector. According to a January 2025 report by TrustWave[50], ransomware attacks targeting the energy and utilities sectors increased by 80% in 2024, driven by the intersection of geopolitical tensions and the rapid expansion of connected devices, cloud platforms and IoT infrastructure in operational environments. The attack surface will continue to grow as digitalisation deepens – and the energy sector's criticality makes it a persistent high-value target.

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[50] TrustWave. (2025). *Energy & Utilities Sector Threat Intelligence Briefing*.

The regulatory response is now fully in place at EU level, layered across three instruments. The NIS2 Directive, which came into force in October 2024, classifies energy operators as essential entities and imposes mandatory risk management, supply-chain security requirements and 24-hour incident reporting obligations, with fines of up to €10 million for non-compliance. The Network Code on Cybersecurity (C/2024/1366), developed with contributions from ENTSO-E, the EU DSO Entity and ACER, establishes a recurrent risk assessment cycle specifically for entities with a critical or high impact on cross-border electricity flows, and required all Member States to designate a competent national authority by 13 December 2024. Together with the technical standards ISO 27001 and IEC 62443, these instruments define a comprehensive framework – but only if implemented.

The specific challenge for Bulgaria, and for the energy sector more broadly, is that cybersecurity obligations now extend well beyond IT systems into operational technology (OT): the SCADA systems, RTUs, protection relays and communication networks that control physical grid infrastructure. Many of these systems were designed in an era of physical isolation, without encryption, authentication or access control. Retrofitting security onto legacy OT infrastructure is significantly more complex and expensive than building it in from the outset – which is precisely why the Network Code's requirement for systematic risk assessment is important, and why Bulgaria's incomplete NIS2 transposition represents a concrete operational risk for operators who need regulatory clarity on compliance timelines and audit procedures.

5.2. Financial Challenges

The transition to a fully digitalised energy system requires sustained capital investment across multiple fronts simultaneously: communication infrastructure, advanced metering, data platforms, control system modernisation and cybersecurity. The business case is not always immediate or obvious, particularly for smaller assets – the cost of digital controls for a small rooftop solar installation, for example, is difficult to recover at the asset level even where the system-level benefits are clear. Rigorous cost-benefit analysis is therefore a prerequisite for investment decisions, and the absence of standardised methodologies for assessing the value of flexibility – a gap that exists across the EU, not only in Bulgaria – makes this harder than it should be.

- **Recovery and Resilience Facility**[51] - The key instrument to help EU economies emerge stronger and more resilient.
- **Horizon Europe - Horizon Europe is the EU's key funding programme for research and innovation**. Following the Multiannual Financial Framework Midterm Review (MTR) decision, the indicative funding amount for Horizon Europe for the period 2021-2027 is EUR 93.5 billion[52].
- **The procedure "Digitalization of Enterprises" (BG16RFPR001-1**.012). It is part of the Competitiveness and Innovation in Enterprises Programme 2021-2027 (CIE) and

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[51] European Commission. (2021). *Recovery and Resilience Facility*.

[52] European Commission. (2021). *Horizon Europe – Key Funding Programme for Research and Innovation*.

has a budget of BGN 80 million has been started in June 2025. The aim of the procedure is to support micro and small enterprises to invest in the introduction of modern information and communication technologies (ICT). This should increase the level of digitalization of enterprises and support their readiness for subsequent transition to higher levels of digitalization in the field of Industry 4.0.

5.3. Customer Engagement

Customer engagement is simultaneously one of the most important and most underestimated challenges in the energy transition. The flexibility potential of demand-side resources – load shifting by industrial consumers, prosumer participation in energy communities, electric vehicle smart charging – is substantial, and several of the EU projects listed in the best practice chapter (ACCEPT, COMPILE, Dedalus, DRIMAC, eCREW, REScoopVPP and others) have demonstrated that this potential can be unlocked at scale. But realising it in Bulgaria requires overcoming three persistent barriers that are as much about trust and behaviour as about technology.

The first is awareness: most household and small commercial customers in Bulgaria are not yet aware that flexibility services exist, let alone that they could benefit financially from participating in them. The second is complexity: the procedures for small participants to engage with balancing markets or energy communities remain difficult to navigate without dedicated intermediaries, and the aggregator framework – while legally enabled under Regulation EU/2019/943 – is not yet sufficiently developed in practice to provide easy access at scale. The third is trust: customers need to be confident that their data will be protected, their interests safeguarded and the financial benefits clearly quantified before they will engage with systems that require them to cede some degree of control over their consumption patterns.

Addressing these barriers requires action on multiple fronts simultaneously: regulatory simplification of aggregator procedures, targeted consumer information campaigns that translate technical opportunities into tangible personal benefits, and the development of digital platforms that make participation genuinely easy rather than merely theoretically possible.

5.4. Data Privacy

Large-scale digital infrastructure generates large-scale personal data flows, and the energy sector is no exception. High-resolution smart meter data – consumption recorded every 15 minutes or more frequently – can reveal household routines, occupancy patterns and individual appliance usage with a precision that goes well beyond what most customers understand when they agree to a smart meter installation. All collection, processing and storage of this data is governed by the General Data Protection Regulation (GDPR) and must be architected accordingly from the earliest design stage, not retrofitted after deployment.

Three principles are non-negotiable in any compliant digital energy infrastructure. *Data minimisation* requires that only the data strictly necessary for each specific function is collected – a principle that creates direct tension with the appetite of aggregators and platform operators for granular, continuous data streams, and requires explicit legal basis for each data use case. *Privacy by design* means that data protection must be embedded into system architecture from the outset, influencing decisions about data storage locations, access controls, encryption standards and retention periods before a single device is deployed. *Data subject rights* – the right of customers to access, correct and request deletion of their data – must be operationally implementable, not merely stated in terms and conditions.

The intersection of GDPR with the real-time data requirements of flexibility services creates genuine legal and operational complexity that practitioners must address proactively. The question of who owns the data generated by a smart meter – the customer, the DSO, the aggregator or the platform operator – is not yet consistently resolved across EU Member States, and Bulgaria has not yet developed sector-specific guidance that would give practitioners the clarity they need. Until it does, this ambiguity will continue to slow the deployment of data-dependent services and create legal risk for operators who proceed without it.

Table 4: KEY NATIONAL POLICY AND REGULATORY DOCUMENTS SHAPING BULGARIA'S DIGITAL TRANSFORMATION FRAMEWORK, 2019–2024[53]

Law on personal data protection	2024
Strategy Digital Transformation2020-2030	2024
Bulgaria road map "Digital Decade" program until 2030	2024
Digital transformation of Bulgaria - Analytical report	2023
National Cybersecurity Strategy "CYBER-RESISTANT BULGARIA 2023"	2021
Cybersecurity Law	2022
Digital Economy and Society Index (DESI),	2022
Bulgaria AI Strategy	2020
Concept for the development of artificial intelligence in Bulgaria until 2030	2020
National Program "Digital Bulgaria 2025" and Road map for its implementation are adopted by CM Decision №730/05-12-2019	2019

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[53] Ministry of Electronic Governance, Bulgaria. (2024). *National Strategies and Policies for Digital Transformation*.

6. FLEXIBILITY ASSESSMENT: DIGITALISATION SCENARIOS FOR BULGARIA

The electricity supplied by renewable sources varies greatly over the course of any given day. During midday hours, thousands of solar installations simultaneously feed large quantities of electricity into the grid, output drops dramatically in the evening. This causes significant price volatility on wholesale markets and, increasingly, periods of negative prices - a signal that the system cannot absorb all available generation. Both businesses and households can profit by shifting consumption to low-price periods. Battery operators can amplify this effect by charging during surplus periods and discharging during scarcity.

The following scenario analysis quantifies the scale of the challenge for Bulgaria and demonstrates why increasing renewable capacity alone - without corresponding investment in flexibility and digital infrastructure - yields rapidly diminishing returns.

6.1. Methodology and Baseline Data

The scenario analysis draws on one full year (2025) of hourly electricity production and consumption data for Bulgaria. As illustrated in Figure 7 the system operates at low to very low flexibility throughout most of the period. Total electricity produced during the year amounts to 3 722 TWh, with the breakdown by source shown in Figure 8. The share of the thermal power plants and the nuclear power plant is about 75%. The share of electricity produced by wind and solar sources is about 18%. This distribution reflects a system still heavily dependent on inflexible baseload capacity, and points to the scale of the structural change needed to accommodate a higher share of variable renewable generation.

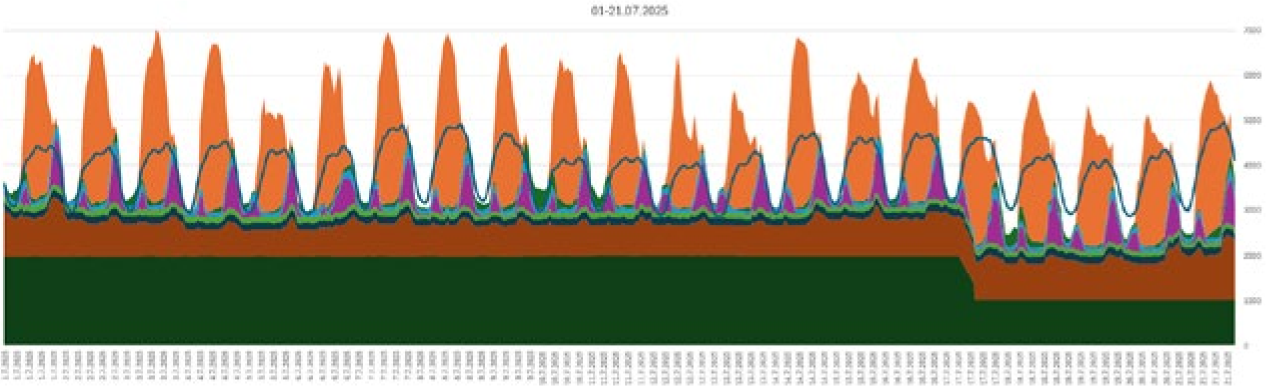


Figure 8 Energy production for one summer week

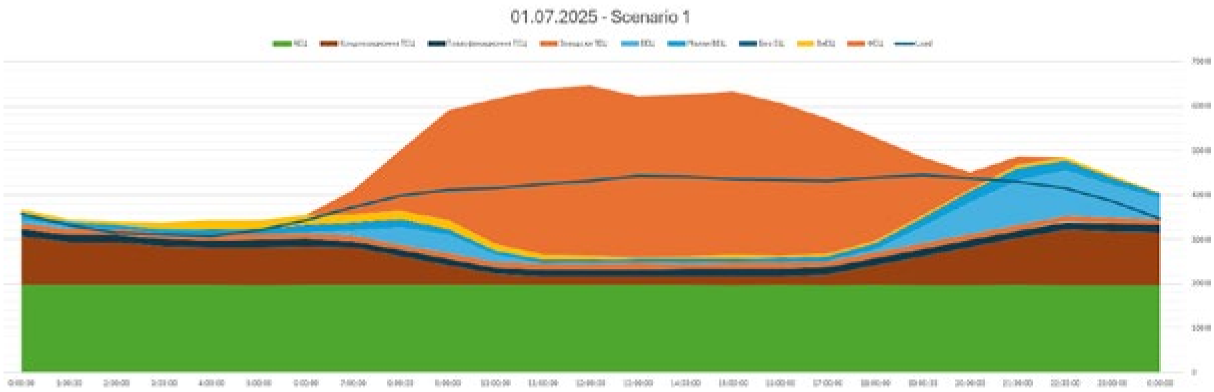


Figure 9 Electricity generation for 24 hours in summer (Scenario1)

The system's structural inflexibility reflects the dominance of baseload capacity. The following technical constraints are applied consistently across all scenarios:

- Minimum output of condensing thermal power plants: 460 MW
- Maximum ramp rate for thermal generation: 200 MW/hour

These constraints represent real operational limits of the existing Bulgarian thermal fleet and define the ceiling on how rapidly the system can respond to changes in renewable output.

6.2. Scenario 1: +30% Solar PV Capacity

In this scenario, installed solar photovoltaic capacity is increased by 30% above the baseline. PV output is curtailed to the level required after thermal generation has been reduced to its minimum operating threshold.

Results:

- Curtailed solar energy (irrecoverable surplus): 0.43 TWh/year
- Flexible energy deficit (primarily evening hours): 160.7 GWh/year

The evening deficit arises from two compounding factors: the slow ramp-down rate of thermal plants and the sharp decline in solar output after mid-afternoon. This pattern is already present in the baseline scenario, where evening deficits are currently compensated by hydropower. As the solar share grows, the amplitude and frequency of these evening shortfalls increase, placing additional pressure on hydro reserves.

6.3. Scenario 2: +50% Solar PV Capacity

With solar capacity increased by 50% and the same operational constraints applied:

- Curtailed solar energy: 1.6 TWh/year
- Flexible energy deficit: 117.7 GWh/year

With 50% more installed PV capacity, curtailed solar energy rises to 1.6 TWh/year – nearly four times the surplus recorded in Scenario 1 – while the flexible energy deficit falls to 117.7 GWh/year. This pattern reveals a non-linear dynamic: as installed PV capacity crosses a critical threshold, curtailment begins to grow disproportionately while the reduction in the evening deficit slows. The roughly 27% improvement in the flexibility deficit relative to Scenario 1 reflects better coverage of the demand curve during low-efficiency generation periods, but the improvement curve is approaching saturation. Further increases in installed PV capacity, without accompanying flexibility measures, will not deliver proportionate system benefits – and will instead generate growing volumes of curtailed generation that destroy economic value without improving system balance. This saturation effect is independently confirmed by the growing number of hours with negative electricity prices on leading European exchanges, a structural indicator of generation surplus during peak solar periods.

The charts below present the aggregated scenario results: Figure 9 shows the combined effect of increasing solar capacity on system surplus and deficit across all scenarios, while Figure 10 illustrates how the achievable PV share in the generation mix grows - and progressively saturates - as installed PV capacity increases.

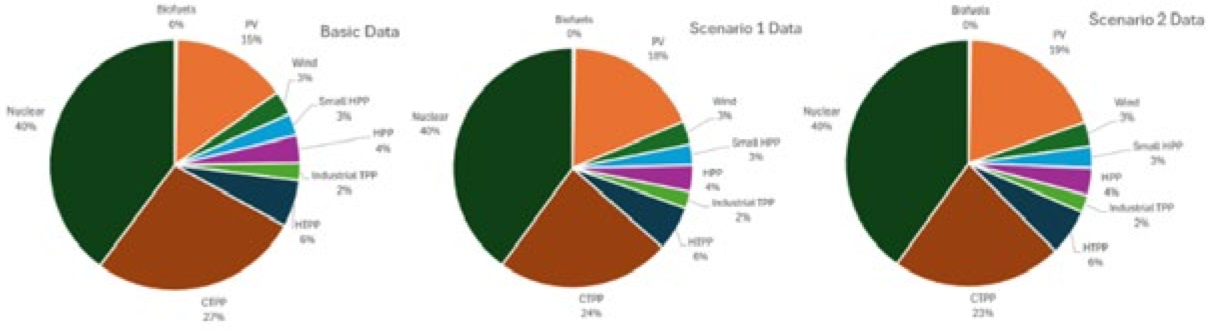


Figure 10 Aggregated data for the scenarios

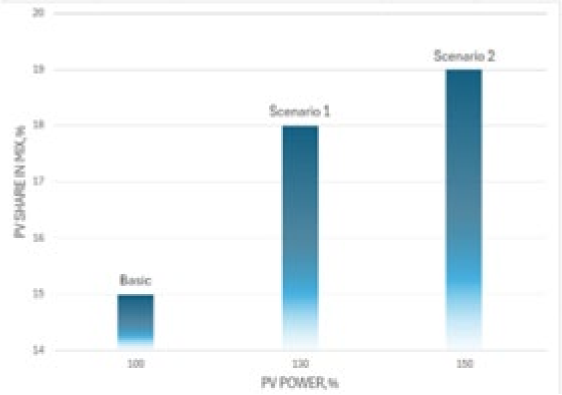
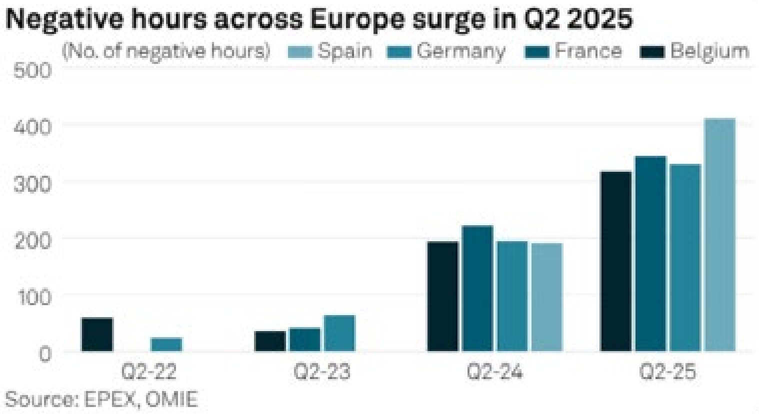


Figure 11 Possible PV share in mix increase depending on increasing of installed PV power

The flexible energy deficit is attributable to two compounding factors: the slow ramp-down rate of thermal power plants and the sharp decline in solar output during the afternoon hours, which is further exacerbated by variable weather conditions. As the figures show, this pattern is already present in the baseline scenario, where evening deficits are currently offset by hydropower dispatch. The saturation of the improvement curve in Figure 11 delivers a clear signal: beyond a certain threshold, expanding installed renewable capacity without accompanying flexibility measures yields no significant additional benefit to the system. This conclusion is independently corroborated by the growing number of hours with negative electricity prices recorded on leading European power exchanges, shown in Figure 12.



Source: EPEX, OMIE

Figure 12 Days with negative prices of the electricity[54]

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[54] S&P Global Commodity Insights. (2025). *Negative Hourly Power Prices in Europe to Dissipate amid Summer Bullishness*.

6.4. Scenario 3: BESS + Demand-Side Response (DSR)

Scenarios 1 and 2 demonstrate that expanding renewable capacity in isolation is insufficient. The scenario analysis points to three complementary pathways that must be combined to resolve the flexibility gap:

Table 5 COMPLEMENTARY FLEXIBILITY PATHWAYS AND THEIR DIGITAL INFRASTRUCTURE REQUIREMENTS

PATHWAY	MECHANISM	KEY REQUIREMENT
1 **Additional hydropower**	Dispatch hydro capacity to cover evening deficits currently compensated at baseline	Real-time data exchange; coordinated dispatch with TSO
2 **Battery storage (BESS)**	Charge during midday solar surplus; discharge during evening peak. Required capacity in Scenario 1: ~1.5 GWh	Digital control and forecasting systems; grid-forming capability
3 **Demand-side response (DSR)**	Shift industrial and domestic loads to periods of maximum solar output through price signals and automated controls	Advanced metering; aggregator platforms; customer engagement

All three pathways depend critically on digital infrastructure: real-time data transmission, automated dispatch signals and aggregation platforms. The combination of BESS and DSR is the most cost-effective approach for the 2026-2029 horizon, particularly as battery costs continue to decline and the regulatory framework for aggregators matures under Regulation EU/2019/943.

The saturation of the improvement curve between Scenario 1 and Scenario 2 carries a clear investment signal: every euro invested in new renewable capacity beyond a certain threshold must be matched by investment in flexibility- BESS, DSR programmes and the digital infrastructure that enables them. Without this, a growing share of new renewable generation will be curtailed, destroying both economic value and system credibility. The 2026-2029 investment cycle represents the critical window for Bulgaria to make these complementary investments before the saturation effect becomes an operational and financial problem.

7. RECOMMENDATIONS TO IMPROVE ELECTRICITY SYSTEM FLEXIBILITY IN BULGARIA

Bulgaria's electricity system is at a structural inflection point. The scenario analysis in this report confirms that expanding renewable capacity without accompanying flexibility investment yields rapidly diminishing returns – and the daily generation profile already demonstrates that the flexibility gap is not a future concern but a present operational reality. The recommendations below are grounded in the analysis across all preceding chapters and are aligned with the latest guidance from the JRC DSO Observatory 2024, CERRE's Flexibility in the Energy Sector report (2025) and the EU Action Plan on Digitalising the Energy System. They are structured by actor, with clear time horizons and links to available funding instruments.

For Regulators and Policymakers

Mandate a single interoperable metering communication standard. The most consequential single policy decision available to Bulgarian regulators is to mandate a national communication standard – whether DLMS/COSEM or an equivalent – as a condition for all new smart meter deployments by DSOs. Romania has already taken this decision under its Recovery and Resilience Plan, and the JRC DSO Observatory 2024 explicitly identifies the acceleration of smart meter deployment and the standardisation of data-sharing mechanisms as necessary conditions for market innovation and consumer participation. Without this decision, Bulgaria will continue to operate three incompatible systems, making national-scale flexibility services commercially unattractive for aggregators. Every year of delay makes retrofitting standardisation more expensive. The experience of leading EU countries is unambiguous on this point: mandating a standard from the outset of any new metering deployment is far less expensive than retrofitting standardisation after fragmented rollout.

Complete NIS2 transposition and designate the Network Code competent authority. The Directive has been in force since October 2024 and its obligations apply to Bulgarian energy operators regardless of the state of national transposition. The designation of a competent authority under the Network Code on Cybersecurity (C/2024/1366) was required by 13 December 2024. This delay creates legal uncertainty that is already slowing investment decisions and exposes operators to the risk of sanctions of up to €10 million. Crucially, the cybersecurity architecture must be built into the communication standard from the beginning, not added afterwards. The German Smart Meter Gateway model, despite its delays, provides the right security architecture – even if its rollout timeline should be treated as a cautionary tale rather than a model to replicate.

Develop a structured national investment roadmap for distribution digitalisation. What is missing in Bulgaria is a coherent national roadmap that sequences the available funding instruments – RRF, Horizon Europe and CEF – identifies the communication infrastructure investments that unlock the largest flexibility value, and provides DSOs with the regulatory certainty needed to commit long-term capital to grid modernisation. Without this sequencing, individual projects will continue to be developed in isolation, and the systemic gap between transmission and distribution digitalisation will widen. The roadmap should also address local flexibility markets, providing DSOs with a clear framework to procure local grid services from aggregators independently of the central balancing market – a mechanism that only 15% of EU countries currently incentivise, despite its growing importance as identified by the JRC DSO Observatory 2024.

Develop sector-specific data governance guidance. The question of who owns the data generated by a smart meter – the customer, the DSO, the aggregator or the platform operator – is not yet consistently resolved in Bulgaria. Implementing Regulation (EU) 2023/1162 introduces requirements for interoperability and non-discriminatory access to metering data, but national implementation requires concrete guidance. CERRE (2025) identifies regulatory uncertainty around data rights as a systemic barrier to flexibility market development across the EU. Until sector-specific guidance is in place, this ambiguity will continue to deter aggregators and platform operators and create legal risk for those that proceed without it.

Simplify aggregator registration and energy community procedures. Regulation (EU) 2019/943 provides the legal basis for aggregator participation in balancing markets, but national implementation remains incomplete. Registration procedures for aggregators must be simplified to the point where they are accessible without dedicated legal and technical resources. Energy community procedures must be streamlined in line with the requirements of Directives 2018/2001 and 2019/944, removing discriminatory provisions and filling secondary legislation gaps that continue to impede the formation of new communities.

For Transmission System Operators

Accelerate the Digital Transformation of the Electricity Grid project. The project, financed under the Recovery and Resilience Mechanism, is the strategic foundation for SCADA/EMS modernisation and communication infrastructure upgrade. Priority should be given to the components that expand real-time monitoring coverage of distributed generation, improve data exchange with ENTSO-E member TSOs and build the data foundation for a national grid digital twin – building on the TwinEU methodology and ESO's participation in the GRAVITECA project.

Develop an operational AI deployment roadmap compliant with the EU AI Act. ESO's current AI engagement is concentrated in research projects. The EU Strategic Roadmap for Digitalisation and AI in the Energy Sector (2025) places AI-based grid management as a sector-wide priority. ESO should develop an internal transition plan from AI in supporting functions – load and generation forecasting – towards AI in operational functions, including congestion management and BESS dispatch optimisation, with full compliance with the high-risk system requirements of the EU AI Act built into the procurement specifications from the outset.

Evaluate private or dedicated communication networks for critical distribution segments. While ESO's transmission communication infrastructure is modern and extensive, the fragmented distribution layer sits beneath it without adequate connectivity for real-time control. Private or dedicated communication networks – whether licensed spectrum, fibre to substations or a hybrid architecture – should be evaluated for the segments of the distribution network where commercial mobile network reliability is insufficient for the control applications planned. The cost of this infrastructure is significant but is dwarfed by the value of the flexibility services it enables.

For Distribution System Operators

The practical implication of Bulgaria's current communication landscape is that the country is operating a two-speed system: a technically modern, standardised transmission infrastructure at the TSO level, sitting above a fragmented, protocol-diverse distribution layer that was not designed for the flexibility services the energy transition requires. This gap is manageable in the near term – the existing infrastructure is sufficient for market settlement, basic monitoring and the aggregation models that large industrial participants can access. But it will become an active constraint on the pace and depth of the energy transition as the number of distributed renewable installations, prosumers and electric vehicles grows. The strategic choice facing Bulgarian DSOs is not whether to modernise the communication layer, but how to sequence and fund that modernisation.

Develop a common API for aggregator data access across all three territories. The three Bulgarian DSOs operate incompatible systems, making the national flexibility market commercially unattractive. CERRE (2025) identifies fragmented data interfaces as a primary systemic barrier to aggregators across Europe. Regardless of the regulatory decision on the metering standard, DSOs should immediately collaborate on a common API allowing aggregators to access standardised data across all three networks. The Dutch P1 port model demonstrates that this is technically and commercially achievable within a short timeframe.

Implement NIS2-aligned cybersecurity measures immediately. Regardless of the state of national transposition, NIS2 obligations apply. The concrete near-term steps are: a documented risk assessment process covering OT/IT convergence by IEC 62443; cybersecurity requirements embedded contractually in technology supplier agreements; and incident reporting procedures capable of delivering notification to the competent authority within 24 hours of detection. The cost of retrofitting security onto legacy OT infrastructure is significantly higher than building it in from the outset – acting now avoids the larger cost later.

Prioritise AMI deployment in underserved territories. The threefold variation in smart meter penetration across the three DSO territories – from approximately 15% to 75% – means that operational opportunities for practitioners, aggregators and prosumers vary fundamentally by location. ERN West and ENERGO-PRO should accelerate AMI deployment programmes as the single most impactful investment in unlocking flexibility in their territories, using RRF co-financing where available.

For Industrial Consumers and Aggregators

Design demand response programmes starting in EVN territory. For practitioners designing flexibility programmes, aggregation platforms or demand response services in Bulgaria today, the communication constraint is real and must be treated as a planning variable rather than an assumption. Services that depend on sub-minute response times should be designed around the DSO territories and connection points where cellular connectivity is reliable and data collection is already at 15-minute or better granularity – in practice, this means starting in EVN territory and in industrial rather than residential segments. The infrastructure modernisation required to extend these services to the full national grid is a medium-term investment; in the near term, the commercially viable market is narrower than the regulatory framework suggests.

Invest in AI-based forecasting on existing data. Existing SCADA and smart meter data are sufficient to develop AI models for generation and consumption forecasting, balancing market participation optimisation and imbalance cost reduction. These applications fall below the high-risk threshold of the EU AI Act and can be deployed without full conformity assessment procedures – making them the fastest and lowest-risk entry point for AI in the Bulgarian energy sector.

Engage with the BESS investment pipeline. The scenario analysis confirms a need for approximately 1.5 GWh of battery storage capacity to compensate the evening flexibility deficit under a moderate solar growth scenario. The 2026–2029 window offers declining battery costs, maturing regulation and a clear system need. Horizon Europe and RRF provide accessible co-financing instruments for demonstration and commercial BESS projects.

For Municipalities and Energy Communities

Use the European Energy Communities Facility and ENERCOM for co-financing and technical support. Both initiatives, funded under the LIFE Programme and active through 2028, offer technical and financial assistance that would be difficult to assemble independently. Priority should go to projects combining generation, storage and demand management – not solar-only installations – as these deliver the greatest system value and the strongest long-term financial case for community members.

Design energy communities with flexibility market participation from the outset. The experience of the Netherlands and Greece shows that communities designed solely for self-consumption scale poorly. Communities designed with aggregator-mediated participation in balancing and local flexibility markets from the start generate additional revenue streams and strengthen the system value of their renewable generation. CERRE (2025) identifies collective self-consumption as a significantly underutilised flexibility resource across most EU markets. The regulatory framework in Bulgaria is in place; the design choices made today by municipalities and community developers will determine whether that potential is realised.

The core message of this report's recommendations is straightforward: the regulatory framework, the funding instruments and the proven technology are all available. What has been missing is the sequencing – a national investment roadmap that coordinates the actions of regulators, operators and market participants around a shared timeline and a shared understanding of which investments unlock the greatest flexibility value. The 2026–2029 window is the critical period in which these decisions must be made. The system itself is already sending the investment signals, every day, in the evening price spikes, the curtailed solar output and the saturation of the renewable capacity curve. The question is whether practitioners, regulators and policymakers will act on them in time.

SOFIA UNIVERSITY „ST. KLIMENT OHRIDSKI“, 2026

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