Deliverable 2.1 Technology Environment and Regulatory Gap Analysis Report

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Abstract	This report analyses key technological and regulatory gaps related to Europe's low voltage grids. Drawing on insights from leading research projects, it highlights innovation outcomes, while identifying barriers and offering guidance for future research.
Keywords	Technology, Gaps, Energy, Grids, Low Voltage

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Executive Summary

This report provides a focused analysis of emerging technologies and systemic challenges that are shaping the evolution of Europe's electricity distribution networks. As the energy transition accelerates, driven by the widespread integration of renewable energy sources, increasing electrification, and the active participation of consumers, the role of intelligent, flexible, and resilient grid infrastructure is becoming increasingly critical.

Building on the outcomes of key EU-funded projects and project partners' experience, this report explores a core set of technological solutions that support the decentralisation and digitalisation of the energy system. These include tools and platforms for energy planning, energy management and microgrid control, demand-side management, grid monitoring and predictive analytics, and the operation of energy communities. Each technology is assessed in terms of its practical functionality, maturity, and alignment with future grid needs.

Despite considerable progress, the analysis identifies a number of cross-cutting technological challenges. Many solutions face limitations in terms of interoperability, scalability, and integration with existing infrastructure—particularly at the low-voltage level where much of the transformation is now taking place. In several cases, technologies lack the ability to process data in real time, rely on fragmented communication standards, or remain too costly for widespread deployment among smaller users.

In parallel, the report highlights important regulatory barriers that continue to constrain the broader deployment and impact of these innovations. These include the absence of clear mandates for grid observability at the distribution level, limited recognition of new actors such as independent aggregators, and tariff structures that do not adequately reward flexibility or incentivise behavioural change. Furthermore, critical gaps persist in data governance, cybersecurity, and the regulatory treatment of software-based, service-oriented solutions.

The findings underscore the need for modernised policy and regulatory frameworks that can keep pace with technological innovation. There is a growing urgency to align market structures, incentives, and grid operation rules with the realities of a decentralised and data-driven energy system. Ensuring fair access for new market participants, standardising digital interfaces, and embedding flexibility into network planning will be essential to unlocking the full potential of these emerging solutions.

By synthesising insights from leading European research projects, this report offers a knowledge base for policymakers, regulators, grid operators, and innovators. It contributes to ongoing discussions about how to future-proof energy systems and accelerate the delivery of clean, reliable, and inclusive energy across the EU.

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1 Introduction

1.1 Purpose of the document

The purpose of this document is to analyse key technological developments and associated challenges in the transition towards a modern, flexible, and decarbonised energy system. It focuses specifically on the outputs of EU-funded research and innovation projects that address the evolving needs of electricity distribution networks in the face of increasing decentralisation, electrification, and renewable energy integration.

By examining these technologies, including energy management systems, microgrids, demand-side management, grid monitoring, and predictive analytics, the document aims to provide a clear overview of the current state of innovation in smart grid technologies. It highlights not only the technical capabilities of each solution but also the technological gaps, areas for further development, and regulatory barriers that limit their scalability and deployment.

The insights presented are intended to support stakeholders involved in energy research, policy, infrastructure planning, and regulatory design, offering a knowledge base for identifying priorities in project development, regulatory adaptation, and future funding mechanisms.

1.2 Scope of the document

This document focuses on a curated set of key technologies critical to the operation of future-proof, distributed, and consumer-centric energy systems. These include:

- Energy Planning
- Energy Management Systems (EMS) and Microgrid Controllers
- Demand Side Management (DSM) and Demand Response (DR)
- Grid Monitoring and Predictive Analysis
- Energy Communities and Local Market Integration

Each technology is examined through a structured lens, addressing:

- A general overview and its role in the energy transition
- Key components and functionalities
- Technological gaps and areas requiring innovation
- Regulatory gaps hindering adoption and scalability

While the technologies originate from various EU-funded demonstration projects the findings are synthesised in a cross-project, cross-technology format to identify common challenges and systemic needs across the broader energy transition landscape.

1.3 Structure of the document

The rest of the document is organised as follows:

- **Section 2: Methodology**

The methodology of the analysis is presented.

- **Section 3: Technology Analysis**

  Each selected technology is introduced and assessed in terms of function, use cases, key components, and its relevance to current and future energy system needs.

- **Section 4: Technological Gaps and Areas for Innovation**

  This section identifies limitations in current deployments or maturity levels of each technology and outlines priority areas for further R&D, including integration challenges, scalability, and cost barriers.

- **Section 5: Regulatory Gaps**

  An overview of regulatory and policy challenges that limit the adoption, interoperability, or economic viability of the technologies. This includes analysis of issues such as data governance, market access, pricing mechanisms, cybersecurity, and incentive structures.

- **Section 6: Conclusions and Recommendations**

  The final section summarises key cross-cutting issues and offers recommendations for policymakers, regulators, and technology developers to support the effective integration of these technologies into future energy systems.

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2 Methodology

This Technology Environment and Regulatory Gap Analysis was conducted using a structured, multi-phase approach that synthesizes information on current technologies, relevant European projects, and existing regulatory frameworks. The methodology ensures that both technical and regulatory dimensions are critically assessed to identify gaps and areas for innovation. Figure 1 below outlines the overall research flow.

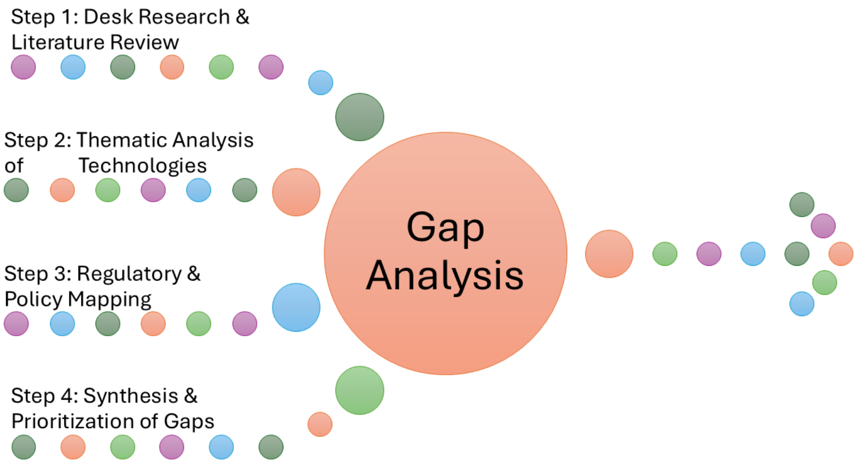

Figure 1: Methodology for the analysis

First, **desk research** provided an initial evidence base, drawing on publicly available deliverables from EU-funded projects, as well as academic publications and industry reports. Emphasis was placed on extracting practical insights related to technologies pertinent to low voltage grids.

Building on these sources, the project team categorized emerging technologies according to their role in decentralized power systems, focusing on (i) **energy system observability and monitoring**, (ii) **management and control**, and (iii) **community and market integration**. This thematic structure allowed for a clearer assessment of how technologies interrelate, the maturity of their components, and their interoperability with existing grid infrastructures.

In parallel, regulatory and policy mapping examined relevant EU directives (such as those under the Clean Energy for All Europeans Package) and national-level regulations. Key policy documents were reviewed to understand how market rules, licensing procedures, tariff structures, and data governance practices align or conflict with the operational needs of advanced energy technologies.

Finally, gaps were synthesized by systematically comparing technical requirements with existing regulatory frameworks. Overlapping issues were consolidated into broader gap statements, which were then prioritized based on impact, urgency, and feasibility. The resulting recommendations address both policy adjustments, such as clearer guidelines for energy community formation and flexible tariff models and technological innovations, including standardized communication protocols and cybersecurity measures. Together, these insights lay the groundwork for future deployment strategies that bridge technical capabilities and supportive regulatory environments, fostering the growth of resilient energy systems.

3 Relevant research areas – technologies

This section presents an overview of key research and innovation activities relevant to the energy transition, focusing on technologies that support grid flexibility, decentralisation, digitalisation, and citizen participation. The purpose is to highlight how different EU-funded and national projects are contributing to the development and demonstration of new technologies and solutions across critical areas such as energy management, demand-side flexibility, smart grids, and energy communities.

The analysis focuses on selected projects which collectively showcase diverse technological approaches and practical implementation experiences. While the projects analysed here are not exhaustive, they provide representative examples of ongoing efforts to advance key technologies and address the operational, regulatory, and social challenges of the evolving energy system. A complete list of projects analysed is presented in deliverable 2.2.

Each project is summarised in terms of its objectives, main outcomes, pilot demonstrations, and the specific technologies it developed or advanced, offering insights into the state-of-the-art and areas for further innovation.

3.1 RE-EMPOWERED H2020

The RE-EMPOWERED project successfully developed and demonstrated innovative tools for comprehensive energy solutions tailored to islanded and isolated communities. These solutions encompassed energy planning (ecoPlanning), facilitating the design of microgrids from the ground up and the enhancement of existing installations to accommodate high-penetration renewable energy systems. Planning decisions were guided by economic and reliability criteria to optimize generation capacity and infrastructure investments.

Building upon proven technologies from previous EU projects, the project advanced Energy Management Systems (ecoEMS, ecoMicrogrid, ecoPlatform) to enable optimal operation of both large and small-scale energy systems, integrating Demand Side Management (DSM) capabilities. Furthermore, energy management tools were designed to leverage synergies with other energy carriers, including electricity, heating, cooling, water, waste, and e-mobility, while considering operational, security, and reserve constraints.

To further optimize energy systems, the project developed and validated Demand Response (ecoDR) tools, implementing behavioral demand response techniques. These demonstrated the benefits of load management, enhancing system flexibility and ensuring more efficient use of energy infrastructure and resources. From a citizen engagement perspective, the project promoted a culture of energy efficiency and self-sufficiency, fostering an autonomous energy supply mindset where applicable.

A strong emphasis was placed on consumer-driven approaches, including dynamic pricing and the establishment of local energy communities. These efforts were supported through community training programs, empowering citizens to actively participate in energy generation and management. To facilitate this engagement, a specialized tool (ecoCommunity) was developed and deployed, encouraging direct citizen involvement in local energy ecosystems.

The project's innovations were successfully demonstrated across four pilot sites with weak or non-existent grid infrastructure—two in Europe (Denmark and Greece) and two in India. Alongside energy management solutions, hardware innovations were also deployed on a smaller scale to address specific local challenges. These included custom converters, electric vehicles and boats, cycloneresistant PV systems, and locally manufactured wind turbines, tailored to the unique needs of each demonstration site.

The RE-EMPOWERED project has significantly contributed to the advancement of sustainable, autonomous energy solutions for isolated communities, paving the way for future developments in resilient and community-driven energy systems.

Relevant technologies:

- Energy Planning
- Energy Management
- Microgrids
- Demand side management
- Co optimization of energy vectors

3.2 COMPILE H2020 project

The COMPILE project, funded under the Horizon 2020 program, aimed to demonstrate the potential of energy islands in decarbonizing energy supply, fostering community development, and generating environmental and socioeconomic benefits. Focusing on the empowerment of local energy systems, COMPILE facilitated the transition from centralized structures to flexible, secure, and decentralized networks.

A key aspect of the project was the optimal integration and control of various energy vectors, storage solutions, and electromobility options to maximize decarbonization and energy savings. Building upon technologies from previous EU projects, COMPILE developed a suite of tools, including GridRule, HomeRule, EVrule, ComPilot, COOLkit, and the Value Tool. These tools were designed to enhance energy management at both community and individual levels, incorporating demand-side management capabilities and promoting interoperability among different energy systems.

The project placed significant emphasis on fostering the creation of energy communities, considering positive effects on the local economy and user acceptance, including vulnerable groups. Through community training programs and the development of support tools like COOLkit, COMPILE empowered citizens to actively participate in energy generation and management, promoting a culture of energy efficiency and self-sufficiency.

COMPILE's innovations were successfully demonstrated across five pilot sites: Luče (Slovenia), Crevillent (Spain), Križevci (Croatia), Lisbon (Portugal), and Rafina (Greece). These sites showcased the practical implementation of the project's tools and approaches in diverse settings, addressing specific local challenges and demonstrating the benefits of cooperative energy solutions.

The COMPILE project has significantly contributed to the advancement of sustainable, autonomous energy solutions for local communities, paving the way for future developments in resilient and community-driven energy systems.

Relevant technologies:

- Energy Communities – Enabling the creation and operation of local energy communities to foster decentralized and cooperative energy management.
- Energy Management Systems – Optimizing the integration of distributed energy resources, storage, and demand-side flexibility.

- Microgrids & Islanding – Facilitating self-sufficient local energy networks that can operate independently from the main grid when needed.
- Electromobility Integration – Incorporating electric vehicles (EVs) as flexible energy assets within local energy systems.
- Grid Flexibility & Optimization – Enhancing grid resilience through tools like GridRule and HomeRule, which manage power flows and energy storage efficiently.

3.3 WeForming (Horizon Europe)

The WeForming project is funded under the EU Horizon Europe programme and it focuses on the development and deployment of Intelligent Grid-Forming Buildings (iGFBs). iGFBs are smart buildings capable of communicating internally and externally – with other buildings and energy stakeholders, to enable more efficient, cooperative energy management. These smart buildings of the future are viewed as active participants in the energy system, contributing to flexibility, resilience, and sustainability.

To achieve this, WeForming integrates AI-based models and digital twins for the optimal use of energy resources within and across buildings. This data-driven approach enhances energy efficiency, reduces operational costs, and minimizes energy waste by enabling predictive and adaptive control strategies.

A key objective of the project is the development of standardized architecture for data sharing and communication. A dedicated middleware layer is being created to ensure interoperability between diverse systems and stakeholders, aligned with major European standards and frameworks such as EDS, IDSA, IEGSA, and FIWARE.

In addition to the technical components, the project also focuses on the development and validation of viable business models for the operation of iGFBs and the services they can offer. This includes the creation of an application that facilitates service exchange, which consists of allowing each iGFB to publish its needs or capabilities and interact with others accordingly.

The WeForming developments are currently being demonstrated at six pilot sites across Europe, each representing different energy contexts and challenges: Luxembourg (multi-energy district with EV fleet), Portugal (commercial building with on-site generation and storage), Croatia (grid-interactive district with seasonal demand fluctuations), Belgium (residential area with power-to-heat-to-power and thermal storage systems), Spain (rural energy community), and Germany (smart district driven by market signals).

Still ongoing, the WeForming project aims to demonstrate that intelligent, interoperable, and market-responsive buildings can play a central role in the energy transition by supporting a more flexible, sustainable, and community-driven energy system.

Relevant technologies:

- Smart Buildings
- AI-based Energy Optimization
- Digital Twins for Smart Buildings
- Energy Communities
- Co-optimization of Energy Vectors
- Demand Side Management

- Energy Management Systems

3.4 REANIMATION (National Recovery and Resilience Plan 2021- 2026)

REANIMATION is a national research ongoing project that focuses on household flexibility provision for grid stability support through their electricity market participation. In the project, an automated system for two-way interaction between households and aggregators is developed. It enables optimal scheduling of household appliances in response to market signals while preserving user comfort.

The solution integrates demand and price forecasting, together with optimization algorithms to schedule appliance usage per household and to aggregate households' flexibility for trading in day-ahead, intraday, and reserve markets. Aside from that, in order to test the scalability and coordination strategies of the developed solution, a simulator of virtual households is being developed. The aim of the project is to reach high technology readiness levels (TRL 7-8).

Alongside the control software, both the aggregator and households are equipped with a performance monitoring system. A web platform and real-time appliance control are available to the aggregator, while households receive monthly energy performance reports. Solution testing is being conducted in both a lab environment and real-world settings, precisely in energy-poor households equipped with smart and energy-efficient devices obtained through this project. The whole solution developed within this project prioritizes user comfort, ease of use, and financial benefits, ensuring profitability for both households and aggregators.

Relevant technologies:

- AI-based Forecasting Models
- Optimization Algorithms
- Distributed Control
- Demand Response
- Digital Twins
- Smart Home Integration
- Electricity Markets Participation
- Flexibility Provision

3.5 DINGO (European Regional Development Fund)

DIstributioN Grid Optimization (DINGO) is a project funded by the European Regional Development Fund that focuses on increasing the observability of low voltage distribution networks. The goals of the project were achieved by the installation of new metering devices in a network but also by exploiting the potential of already existing ones. Several tools were developed to achieve the main goal of the project, which was creating a network's digital twin. This is a prerequisite for different analyses of a network, enabling integration of RES and accelerating energy transition.

Developed tools were oriented on data processing – editing data from the Geographic Information System needed to create a mathematical representation of the network and the set of AI/ML tools for identifying the phase connectivity of end-users, distributing aggregated consumption amongst three phases and forecasting network losses. This set enables the creation of a more accurate digital twin of the network by using real-world data and minimizing assumptions.

Following the creation of the network's digital twin, different analyses were performed to show the importance of developed tools, ranging from basic power flow analyses, investigating the impact of

RES on current-voltage conditions in LV networks, to more advanced calculations applying optimization techniques such as the calculation of network's hosting capacity or flexibility provision.

The pilot location included several LV networks that are part of the Croatian distribution system. All pilot locations were, to some extent, equipped with smart meters, and their topology was a part of the geographic information system. The DINGO project has not only contributed to the development of new tools but helped better understand the shortcomings of current metering systems installed in distribution networks and raised the awareness of the system operators to observe a larger set of measurements needed to perform different analyses.

Relevant technologies:

- Digital Twins
- Grid Monitoring
- Grid Planning and Operation
- RES integration

3.6 FLEXIGRID (H2020)

FLEXIGRID was funded under the H2020 programme, with the aim to improve the distribution grid operation making it more flexible, reliable and cost-efficient, through the development of hardware (HW) and software (SW) modules. The FLEXIGRID project aimed to enhance grid flexibility, security, and efficiency to support the integration of renewable energy sources and the decarbonization of the energy system. It achieved this by developing smart grid technologies, improving observability and control, ensuring interoperability across European distribution systems, and conducting real-world demonstrations in four countries. Additionally, it addressed regulatory challenges, promoted stakeholder engagement, and laid the groundwork for the exploitation and replication of its innovations across Europe.

The FLEXIGRID project successfully completed pilot demonstrations across Spain, Greece, Croatia, and Italy, validating key technologies such as self-healing algorithms, flexibility solutions, and islanded grid operation. All developed technologies were integrated into an open-source platform to ensure interoperability, while project impact, replicability potential, and regulatory barriers were analysed to inform policy recommendations. Additionally, a cost-benefit analysis methodology was defined, business strategies were finalized, and the project's results were widely disseminated through scientific publications, workshops and other activities.

The FLEXIGRID project developed and implemented nine innovative solutions—four hardware, four software, and one open-source platform—across eight use cases in four European pilot sites. These solutions significantly improved grid stability and flexibility, with major reductions in outage durations (e.g., up to 59.72% drop in CAIDI in Italy) and increased system resilience. Enhanced observability and control led to reduced curtailment and improved forecasting accuracy across all sites. The project also minimized the need for infrastructure reinforcements through efficient peak load and voltage management, while successfully preparing the grid for future energy demands with high performance indicators (SERI and SMRI up to 99.9%). Additionally, the solutions contributed to measurable CO_2 emissions reductions by improving the integration of renewable energy and reducing reliance on conventional power sources.

Relevant Technologies:

- Demand Side Management
- RES integration
- Observability, controllability and automation

- Congestion Management

3.7 STREAM (HE)

The STREAM project, funded under the Horizon Europe programme, aims to create a robust flexibility ecosystem focused on the LV side of the electricity network. STREAM addresses the growing need for more dynamic, decentralised, and market-based management of flexibility resources in support of grid stability and energy transition goals.

To achieve this, STREAM aims to develop tools enabling the coordination of distributed flexibility. These include sGRID intended for DSOs to increase the observability of the grid, sPLAN for decision support in comparing grid reinforcement with flexibility measures, sMART for local flexibility market operation, sDATA for secure data exchange, sENC for energy community aggregation and market participation and sFLEX for flexibility asset management among medium to large prosumers. Together, these tools form the backbone of the STREAM ecosystem, connecting devices, data, stakeholders, and local markets.

The project is centred around four pilot sites located in Spain, Italy, Finland, and Slovenia. Each pilot focuses on a different aspect of the flexibility value chain. By strengthening the role of distributed flexibility in LV networks, STREAM supports the development of more resilient, efficient, and user-centred energy systems, while addressing regulatory, technical, and market barriers to flexibility deployment.

Relevant Technologies:

- Local Flexibility Markets
- Flexibility Asset Management
- Secure Data Exchange
- Grid Observability and Planning Tools

4 Gaps Analysis – Technologies and Innovation

Energy transition projects and research initiatives in Europe usually focus on enhancing the resilience, efficiency, and sustainability of energy systems. The technologies developed in these projects can be categorized into three main areas based on their role in transforming energy systems:

- **Energy System Observability & Monitoring** – Tools and platforms that provide real-time data, predictive analytics, and situational awareness for improved energy system visibility.
    - Energy Planning – Supporting infrastructure investments, renewable energy integration, and resilience strategies.
    - Grid Monitoring & Predictive Analytics – Providing real-time data, forecasting, and anomaly detection for enhanced decision-making.
- **Management & Control** – Advanced energy management systems, demand-side solutions, and optimization techniques that enable the efficient operation of distributed energy resources.
    - Energy Management Systems (EMS) – Optimizing the coordination of energy resources, including generation, consumption, and storage.
    - Demand Side Management (DSM) – Enabling flexible energy consumption through smart pricing, automation, and behavioral incentives.
    - Microgrids & Islanding Capabilities – Allowing local energy systems to operate autonomously while integrating high shares of renewables.
    - Electromobility & Storage Integration – Utilizing EVs, batteries, and hybrid storage systems as flexible grid assets.
- **Community & Market Integration** – Solutions that promote citizen engagement, energy-sharing models, and the development of local energy markets to foster active participation in the energy transition.
    - Energy Communities & Peer-to-Peer Trading – Establishing collaborative local energy networks and decentralized market models.
    - Citizen Engagement & Capacity Building – Empowering individuals and organizations through education, participation, and digital tools.
    - Local Flexibility Markets – Investigates the designs enabling the utilization of small-scale flexibility.

This classification ensures a comprehensive approach to understanding the impact of energy innovation projects, addressing both technical advancements and societal engagement in decentralized energy systems.

4.1 Energy System Observability & Monitoring

4.1.1 Energy planning

Energy planning refers to the strategic process of designing, modelling, and optimizing energy systems to ensure that they meet the needs of society while minimizing environmental impact, reducing costs, and enhancing resilience. Effective energy planning involves forecasting energy demand, identifying renewable energy potentials, evaluating infrastructure requirements, and determining the optimal mix of energy sources and technologies. The goal is to create a comprehensive roadmap for transitioning toward a sustainable, low-carbon energy system that is resilient to future challenges such as climate change, fluctuating energy prices, and growing demand for electricity.

Energy planning is essential at both the local (community-level) and national or regional scales, allowing stakeholders to make informed decisions regarding energy generation, distribution, and consumption. Advanced simulation models and optimization tools are increasingly being used to evaluate different energy scenarios, considering factors like economic viability, environmental impact, social acceptance, and grid reliability. As energy systems become more decentralized, the complexity of planning increases, as it must account for distributed energy resources (DERs), microgrids, demand response, and the integration of renewables into existing grids.

Key components of energy planning include:

- **Demand Forecasting** – Predicting future energy needs based on factors such as population growth, technological trends, and climate conditions.
- **Energy System Modelling** – Using simulation tools to model different energy generation and distribution scenarios, considering available resources, infrastructure, and policy goals.
- **Renewable Energy Integration** – Evaluating the potential for integrating renewable energy sources like solar, wind, hydro, and bioenergy, while balancing intermittent generation with grid stability.
- **Infrastructure Design** – Determining the required infrastructure (e.g., transmission lines, energy storage systems, microgrids) to support the chosen energy mix and ensure supply reliability.
- **Optimization Techniques** – Identifying cost-effective and efficient energy solutions that maximize resource use while minimizing environmental impact.
- **Stakeholder Engagement** – Involving local communities, industry players, policymakers, and consumers in the decision-making process to ensure broad support and successful implementation of energy strategies.

4.1.1.1 Technological Gaps and Areas for Innovation

While energy planning tools and methodologies have advanced in recent years, several technological gaps still exist that hinder the full potential of energy planning processes. These include:

- **Integration of DERs** – Current planning tools often struggle to fully account for the role of DERs, such as solar panels, batteries, and electric vehicles, in system-wide optimization. There is a need **for advanced modelling** that integrates these decentralized resources and accounts for their variability and flexibility.
- **Real-time Data & Dynamic Modelling** – Many energy planning tools are based on historical data and static models, which may not accurately reflect real-time system changes or future uncertainties. The development of dynamic, real-time energy system models that can adapt to shifting demand, renewable generation, and grid conditions is critical.
- **Scalability and Complexity** – Energy planning for large, interconnected systems often involves complex mathematical models and simulations that are difficult to scale for smaller regions, communities, or local microgrids. Simplified, scalable planning tools are needed to make energy planning accessible at the community level and in diverse geographical contexts.
- **Cost-benefit Analysis for Renewable Integration** – The economic case for integrating renewable energy into existing grids is still a challenge due to the intermittent nature of

renewables and the high upfront costs of infrastructure. Advanced economic modelling that accurately reflects the long-term benefits of renewable integration, considering both direct and indirect costs (e.g., health benefits, environmental costs), is necessary.

- **Stakeholder and Policy Alignment** – Effective energy planning requires multi-stakeholder collaboration across government agencies, private industry, and communities. Tools that facilitate collaborative decision-making and policy alignment, incorporating local preferences and diverse interests, are still lacking in many regions.

- **Climate and Resilience Planning** – As the impacts of climate change become more pronounced, energy planning must incorporate climate resilience strategies, ensuring that energy systems can withstand extreme weather events, natural disasters, and other climate-related disruptions. Resilience modelling tools that simulate these scenarios are a key area for development.

- **Integrated Energy and Environmental Planning** – Often, energy planning is carried out in isolation from broader environmental and land-use planning**.** Holistic models that integrate energy, environmental, and social considerations are needed to align long-term sustainability goals across sectors.

4.1.2 Grid Monitoring & Predictive Analysis

Grid monitoring and predictive analysis refer to the suite of technologies and methodologies used to observe, assess, and forecast the behavior of electricity distribution and transmission systems in real time or near-real time. These technologies aim to ensure the reliability, stability, and efficiency of power systems—especially in the context of increasing decentralisation, electrification, and renewable energy integration.

Modern grids are becoming more dynamic and complex, with bidirectional energy flows, DERs, and prosumers. This evolution requires enhanced situational awareness through real-time data collection, advanced analytics, and forecasting techniques. Grid monitoring involves the deployment of sensors, smart meters, phasor measurement units (PMUs), and IoT devices to collect operational data. The predictive analysis applies machine learning (ML), artificial intelligence (AI), and statistical models to identify patterns, detect anomalies, and anticipate system behavior such as voltage instabilities, congestion, or equipment failures.

By combining real-time visibility with predictive insights, operators can move from reactive to proactive grid management, improving resilience, reducing outages, and optimizing grid performance under variable conditions.

Key Components

- **Sensing and Measurement Infrastructure**: Devices such as PMUs, smart meters, voltage sensors, current transformers, and fault indicators deployed across the grid to capture high-resolution operational data.

- **Data Communication Networks**: Secure, high-speed infrastructure for transmitting data from edge devices to control centers or cloud-based platforms.

- **Data Management Platforms**: Systems for collecting, storing, cleaning, and processing large volumes of grid data, ensuring data quality and integrity.

- **Forecasting Tools**: Algorithms that predict short-term and long-term grid states based on consumption trends, weather forecasts, renewable energy generation, and historical data.

- **Anomaly Detection and Predictive Maintenance**: AI-based tools that identify unusual grid behavior, potential equipment failures, or cyber threats before they result in outages.
- **Visualization Dashboards**: Operator-facing tools that present real-time grid status, key metrics, alerts, and trends in an intuitive format for rapid decision-making.

4.1.2.1 Technological Gaps and Areas for Innovation

Despite recent advances, several **technological challenges** remain:

- **Data Granularity and Latency**: In many systems, sensing infrastructure does not yet offer sufficient temporal or spatial resolution to capture fine-grained variations in grid conditions, especially at the LV level.
- **Interoperability and Standardisation**: Diverse hardware and software systems used by utilities often lack common standards, making integration difficult and limiting cross-vendor compatibility.
- **Edge Processing and AI at the Grid Edge**: Most predictive analysis still relies on centralized computing. There is a growing need for **distributed intelligence**—processing data at or near the source using edge computing and lightweight ML models.
- **Scalability of Predictive Models**: AI/ML models need to be trained and adapted to specific grid topologies and operating environments, which limits generalizability across different networks.
- **Cybersecurity**: As grid monitoring becomes more data-intensive and reliant on communication networks, ensuring **data privacy, integrity, and protection** against cyber threats is a growing concern.
- **Low-Cost Deployment for LV Grids**: Monitoring solutions are still expensive and primarily deployed in transmission and MV networks. Affordable, plug-and-play solutions are needed for LV grids, where most RES and prosumers are connected.

4.2 Management and control

4.2.1 Microgrids

Microgrids (MGs) are distribution networks formed by clusters of DERs, including distributed generators (DGs), controllable loads, and storage devices. They can operate in a controlled and coordinated manner, either while connected to the main power network or in islanded mode. The coordination of DERs can be achieved through various methods, ranging from decentralized approaches—where local controllers make independent decisions without communication—to centralized control, where a single entity makes decisions for the entire system.

According to IEEE Standard 2030.7, a microgrid is defined as:

"A group of interconnected loads and distributed energy resources with clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid and can connect and disconnect from the grid to enable it to operate in both grid-connected or island modes."

The key feature distinguishing microgrids from conventional distribution networks with DERs is their controllability as a unified system. However, this characteristic introduces significant technical challenges, particularly when operating in islanded mode. The high presence of power electronic loads

(PEL) interfacing DERs increases control complexities. The lack of inertia, short distribution lines, and limited fault contributions from PEL-interfaced DERs complicate frequency and voltage control, protection, and safety measures. Innovative solutions are required to address these challenges.

Additionally, MGs, being distributed systems covering limited geographical areas, often lack the computing and communication facilities available in traditional power systems, such as dedicated control rooms and system operators. Thus, any applied solutions must be cost-effective while ensuring efficiency. These include:

- DERs: Renewable energy sources like solar PV, wind, and biomass, along with conventional generation methods such as diesel generators and CHP.
- Energy Storage Systems (ESS): Batteries, pumped hydro storage, and flywheels that enable energy balancing and grid stability.
- Microgrid Controllers: Advanced control systems that manage energy flow, optimize loads, and enable seamless islanding (disconnection from the main grid during outages).
- Smart Meters and IoT Solutions: Real-time data monitoring and communication tools that enhance demand-side management and operational efficiency.
- Demand Response Mechanisms: Automated systems that adjust energy consumption in response to grid conditions, improving overall efficiency.
- Blockchain and Peer-to-Peer Energy Trading: Emerging solutions that enable decentralized energy transactions within microgrid networks.

4.2.1.1 Technological Gaps and Areas for Innovation

To fully unlock the potential of microgrids, technological advancements are needed in several key areas. These include:

- **Advanced Control and Optimization:** Developing more robust decentralized control mechanisms, real-time grid stability solutions, and seamless transitioning between grid-connected and island modes.
- **Energy Storage Innovations**: Improving battery technologies, hybrid storage systems, and sustainable recycling solutions for energy storage.
- **Power Electronics and Grid Interface:** Enhancing high-power inverters, grid-forming inverters, and solutions for improved voltage and frequency stability.
- **Cybersecurity and Data Management:** Strengthening microgrid cybersecurity frameworks, standardizing data governance, and leveraging edge computing for real-time decision-making.
- **Economic and Market Mechanisms**: Introducing peer-to-peer energy trading, dynamic pricing models, and virtual power plants (VPPs) to improve microgrid financial viability.
- **Resilience and Disaster Recovery**: Advancing black-start capabilities, climate-resilient infrastructure, and adaptive grid architectures to withstand extreme weather events.

4.2.2 Digital Twin – Grid Modelling

Digital twins in the electricity sector refer to virtual representations of physical grid assets or entire distribution systems, constructed using real-time or historical data, network topologies, and physical parameters. In the context of DSOs, digital twins serve as a planning and operational tool to simulate, analyse, and optimise the behaviour of LV grids under different conditions. These models can be static (used in planning) or dynamic (used in operational decision-making), and their resolution can range from single-line approximations to full three-phase unbalanced grid representations.

A digital twin of the distribution grid enables DSOs to perform scenario-based analyses for future DER integration, investment planning, and operational reliability. The model incorporates data from smart meters, IoT sensors, GIS, SCADA systems, and asset management databases, creating a data-rich environment for simulation and forecasting. The application of digital twins in LV grid planning supports more informed and evidence-based decision-making by simulating the integration of technologies such as PV systems, HPs, EVs and storage units. It allows DSOs to assess thermal limits, voltage deviations, hosting capacity, and the impact of local flexibility under various future scenarios. When coupled with optimisation algorithms, digital twins can also evaluate the cost-benefit ratio between conventional reinforcement and flexibility-based solutions.

Key Components and Supporting Technologies of Grid Modelling include:

- **Grid Modelling Engines**: Power flow solvers and simulation tools (e.g., OpenDSS, PowerFactory) capable of three-phase, time-series, and probabilistic analysis.
- **Data Integration Platforms**: Systems that aggregate and harmonise input from smart meters, IoT devices, GIS, and asset registries.
- **Forecasting and Analytics**: Machine learning and statistical tools for predicting demand, generation, EV charging profiles, and asset failures.
- **Scenario Simulation Tools**: Software layers that allow DSOs to model different DER growth trajectories, technology adoption rates, and investment options over 10–20-year horizon.
- **Visualisation and Decision Support Dashboards**: Interfaces that allow grid planners to explore trade-offs, visualise risks, and compare reinforcement versus flexibility options.

4.2.2.1 Technological Gaps and Areas for Innovation

While the use of digital twins in DSO planning is steadily increasing, several important challenges still need to be addressed:

- **Data Availability and Quality** remains a limiting factor. In many low-voltage (LV) networks, monitoring infrastructure is either insufficient or unevenly deployed, which restricts the granularity and accuracy of digital models. Although the rollout of smart meters is progressing across Europe, access to high-resolution operational data varies considerably between countries and regions.
- **Model Interoperability**: The lack of standardised data formats and interfaces complicates the integration of digital twins with grid modelling tools, SCADA systems, and planning platforms. Efforts to promote standards such as the Common Information Model are underway, but widespread adoption is still limited.
- **Scalability**: Running detailed, time-series simulations across large network areas demands substantial computational resources, alongside the development of more advanced optimisation techniques to maintain performance and responsiveness.
- **DER Modelling Complexity**: Accurately representing the behaviour of flexible resources such as EV chargers or HP load shifting is challenging, due to the stochastic nature of the process.
- **Cybersecurity and Data Governance**: As digital twins become more reliant on sensitive operational and customer data, ensuring secure data exchange and compliance with regulatory frameworks, including GDPR, is essential.

4.2.3 Demand side management

Demand Side Management (DSM) refers to the strategies and technologies aimed at optimizing and shifting energy consumption patterns from consumers in response to grid conditions, energy pricing, and other incentives. The primary goal of DSM is to reduce peak demand, balance energy usage, and enhance overall grid stability, while maximizing the efficiency of energy resources. DSM can be implemented at the level of individual consumers, businesses, or entire communities and plays a critical role in facilitating the integration of renewable energy sources (RES) and reducing reliance on fossil fuel-based generation.

With the growing importance of renewable energy integration, DSM is becoming increasingly essential to balance variable generation (such as wind and solar) and grid demand. It provides a flexible tool for consumers to actively participate in energy system operations, encouraging more efficient energy use through smart meters, automation, dynamic pricing, and incentive programs. DSM encompasses a range of technologies and strategies, from simple load-shifting techniques to more complex behavioral interventions and advanced control systems that can respond in real-time to grid needs.

Key components of Demand Side Management include:

- **Smart Meters & IoT Devices** – Devices that collect real-time data on energy consumption and enable more accurate, dynamic pricing.
- **Automation & Control Systems** – Smart appliances, heating/cooling systems, and energy management platforms that automatically adjust energy consumption based on signals from the grid.
- **Demand Response Programs** – Voluntary programs where consumers reduce their energy usage during peak demand periods in exchange for financial incentives or lower energy rates.
- **Dynamic Pricing & Time-of-Use Tariffs** – Flexible pricing models that incentivize consumers to shift their energy use to off-peak hours, lowering costs for both consumers and the grid.
- **Consumer Engagement Platforms** – Tools that encourage users to actively participate in DSM programs through gamification, feedback, and rewards systems.

4.2.3.1 Technological Gaps and Areas for Innovation

While DSM has demonstrated significant potential, several technological and operational gaps need to be addressed to maximize its effectiveness:

- **Interoperability & Integration** – DSM solutions often rely on multiple devices, platforms, and communication standards. A lack of interoperability between smart meters, appliances, and energy management systems makes it difficult to achieve seamless integration across various technologies. Standardization of communication protocols is needed to enable the smooth interaction of devices from different manufacturers.
- **Real-time Grid Communication & Control** – DSM requires rapid communication between consumers and grid operators to enable real-time adjustments. Current communication networks are sometimes insufficient to support the instantaneous, bidirectional data flow required for optimal DSM performance. Improving communication latency and data transmission speeds is essential.
- **Consumer Behaviour Modelling & Incentives** – **Behavioural economics** and psychological factors play a significant role in the effectiveness of DSM. More research is needed to develop advanced models that accurately predict consumer responses to price signals, incentives, and demand response events. This includes better understanding of consumer preferences and willingness to participate in demand response programs.
- **Data Privacy & Security** – As DSM systems rely on large amounts of consumer data, particularly through smart meters and IoT devices, ensuring cybersecurity and data privacy is

critical. Current systems may not fully meet the standards needed to protect sensitive user data.

- **Grid Flexibility & Energy Storage** – While DSM can shift demand, it is also crucial to address energy storage solutions to smooth the integration of renewable energy. Improvements in battery storage, demand-side storage, and virtual power plants (VPPs) are needed to complement DSM in creating a more flexible and resilient energy system.

- **Scalable and Affordable Solutions** – The cost of implementing DSM solutions—particularly for residential and small-scale applications—can be a barrier. Lower-cost, scalable DSM technologies that are accessible for a wide range of consumers, including low-income and vulnerable groups, are crucial for achieving widespread adoption.

4.3 Community & Market Integration

4.3.1 Energy communities

Energy communities (ECs) are decentralized energy systems where groups of prosumers, consumers, and local stakeholders collaborate to generate, store, and share energy. These communities enable a shift from centralized power generation to localized energy ecosystems, fostering resilience, energy independence, and economic benefits. Energy communities can take various forms, including citizen-led cooperatives, municipal initiatives, and peer-to-peer (P2P) trading networks.

The Clean Energy for All Europeans Package defines energy communities as entities that allow active consumer participation in the energy system while prioritizing social and environmental benefits over financial profit. These communities are essential for integrating RES, increasing local energy self-sufficiency, and promoting sustainable energy consumption practices.

Unlike traditional utility-based energy supply models, energy communities emphasize collective decision-making, decentralized governance, and local energy market participation. However, the implementation of ECs presents challenges related to regulatory compliance, grid integration, economic sustainability, and technological infrastructure. Addressing these challenges requires innovative tools and mechanisms that facilitate seamless energy sharing, demand-side flexibility, and efficient management of distributed resources.

Key components of energy communities include:

- **Local Renewable Energy Generation** – Solar PV, wind, biomass, and other decentralized energy sources owned and managed by the community.

- **Energy Storage Solutions** – Battery storage systems that enhance energy autonomy and optimize energy use.

- **Peer-to-Peer Energy Trading Platforms** – Blockchain-based or digital marketplaces that enable secure and transparent energy exchanges between members.

- **Demand Response & Flexibility Mechanisms** – Smart systems that adjust consumption patterns to optimize grid stability and efficiency.

- **Community Energy Management Systems (CEMS)** – Advanced software and IoT-based solutions that monitor, optimize, and balance local energy flows.

- **Regulatory & Market Integration Tools** – Frameworks that align EC operations with national and EU energy policies, ensuring economic viability and scalability.

4.3.1.1 Technological Gaps and Areas for Innovation

For energy communities to thrive, several technological advancements are required to enhance their effectiveness and scalability:

- **Scalable Digital Energy Platforms** – Development of interoperable and user-friendly platforms that support real-time energy tracking, dynamic pricing, and automated trading.
- **Advanced Energy Sharing & P2P Marketplaces** – Blockchain and AI-powered systems to facilitate secure, transparent, and cost-effective energy transactions.
- **Enhanced Community Energy Storage Solutions** – Scalable and cost-effective storage technologies to improve local energy autonomy and grid interaction.
- **Smart Contracts & Regulatory Compliance Tools** – Automated contract execution mechanisms that simplify market participation while ensuring legal compliance.
- **Cybersecurity & Data Privacy Measures** – Strengthening protection for energy data, ensuring trust in decentralized energy transactions.
- **Social & Behavioural Innovation** – Strategies and incentives to engage citizens, increase participation, and ensure fair energy distribution within the community.

4.3.2 Citizen engagement & capacity building

Citizen engagement and capacity building are central to the success of energy communities (ECs), enabling a shift from passive energy consumption to active, participatory roles in the energy system. In this new paradigm, individuals and communities do not merely receive energy—they generate, store, share, and manage it. This transformation requires more than physical infrastructure; it hinges on social innovation, digital tools, and the ability to build trust and competence among users.

The Clean Energy for All Europeans Package defines energy communities as inclusive structures that empower citizens to take ownership of energy generation and management while delivering social and environmental benefits. Realising this vision means equipping communities with the knowledge, tools, and institutional frameworks necessary for sustained participation. This includes facilitating access to data, ensuring digital literacy, and providing clear, intuitive interfaces that support meaningful decision-making.

Digital tools are pivotal in enabling citizen engagement at scale. They serve as bridges between technical complexity and user action, supporting everything from real-time energy monitoring to voting on community investments or participating in local energy markets. However, their full potential is yet to be realised, particularly among vulnerable groups or in regions with lower digital readiness.

Key Components

- **Community Energy Platforms and Dashboards** – User-friendly interfaces that allow citizens to track energy production, consumption, and costs in real time, often with visual feedback to support behavioural change.

- **Digital Participation Tools** – Applications enabling democratic decision-making in community energy governance, such as participatory budgeting, digital voting, or collaborative project design.
- **Gamification and Incentive Mechanisms** – Engagement strategies using game design elements (points, badges, leaderboards) to encourage behavioural change and sustained interaction with energy systems.
- **Training and Digital Literacy Campaigns** – Online and in-person programs that educate users on energy concepts, digital tools, and their rights and roles within energy communities.
- **Mobile Apps for Peer-to-Peer Trading and Demand Response** – Applications that allow users to easily buy, sell, or shift energy within the community based on preferences, pricing, or grid conditions.
- **Feedback and Behavioural Nudging Tools** – Data-driven notifications and insights that promote energy-efficient behaviours or signal optimal times for consumption or generation.

4.3.2.1 Technological Gaps and Areas for Innovation

Although several digital engagement tools have been piloted, challenges remain in scaling them, ensuring inclusivity, and integrating them seamlessly into daily life. Key gaps include:

- **Low Accessibility and Digital Inclusion** – Many tools are not designed with accessibility in mind, leaving behind older adults, digitally unskilled users, or those with limited internet access.
- **Lack of Interoperability and Standards** – Community platforms often operate in isolation, unable to exchange data or integrate with grid-level systems or broader energy market platforms.
- **Limited Personalisation and Adaptivity** – Current engagement tools lack the ability to tailor content and feedback based on individual user profiles, preferences, or learning styles.
- **Short-Term Engagement Cycles** – Many initiatives experience a drop in user participation over time due to lack of tangible benefits, complexity, or loss of novelty.
- **Trust and Data Protection Issues** – Citizens may hesitate to participate actively due to concerns over how their energy usage data is collected, stored, and used.

To address these, innovation is needed in co-designing digital platforms with users, developing modular, interoperable toolkits, and incorporating AI and behavioural science to deliver personalised, adaptive, and rewarding engagement experiences.

4.3.3 Local Flexibility Markets

Local flexibility markets (LFMs) have emerged as a key mechanism to address the increasing variability and decentralisation of electricity systems. By enabling the procurement of flexibility services from DERs, energy communities, SMEs, and households, DSOs can manage congestion, voltage issues, and grid reinforcement costs more efficiently. LFMs are designed to unlock these resources at the local level, supporting system operation without the need for large-scale network upgrades.

While the primary focus of LFMs is currently on meeting DSO operational needs, the increasing interaction between distribution and transmission networks introduces new challenges related to the coordination between DSOs and TSOs. Establishing clear priority rules for the dispatch of flexibility services across grid levels is an emerging issue that will become more prominent as LFMs mature.

The establishment of local flexibility markets typically involves several elements:

- **Flexibility Resources**: Residential, commercial, and industrial assets capable of adjusting consumption or generation in response to grid needs.
- **Market Roles**: Flexibility providers (consumers or aggregators) offer services to DSOs based on predefined requirements.
- **Market Mechanisms and Procurement Processes**: Flexibility is typically procured through local market mechanisms, including calls for flexibility, direct contracts, or dynamic platforms that match supply and demand at short notice.
- **Digital Infrastructure and Platforms**: Reliable digital platforms are needed to support registration, bidding, activation, and settlement processes. Real-time or near-real-time communication capabilities are important for time-sensitive services.
- **Technical Requirements**: Measurement and verification processes, baseline definition methodologies, and near-real-time communication are essential to ensure that procured flexibility delivers the intended impact on the grid.
- **Access and Inclusiveness**: Ensuring that small actors, including individual prosumers and SMEs, can access the market without prohibitive technical or administrative barriers is essential for unlocking the full potential of distributed flexibility.

4.3.3.1 Technological Gaps and Areas for Innovation

Several ongoing technological challenges remain that limit the full potential of LFMs. These challenges are not only technical but also relate to participation rules, market design, and system coordination. The main issues are outlined below:

- **Baseline Definition and Verification**: Establishing accurate and fair baselines remains a major difficulty, particularly for small and variable loads. Without reliable reference points, verifying flexibility delivery is complex and often contested, limiting trust in the market.
- **Lack of Standardised Flexibility Products and Processes**: Different DSOs and regions define flexibility services in different ways, using varied performance criteria and verification rules. This fragmentation prevents scaling solutions across regions and increases complexity for participants.
- **Barriers for SMEs and Citizen Participation**: The technical and administrative effort required to participate in local flexibility markets is often too high for smaller actors. Inadequate aggregation services, lack of standardised contracts, and limited digital access further restrict their involvement.
- **Coordination Challenges Between DSOs and TSOs**: Flexibility services may be valuable to both DSOs and TSOs, but there are currently no widely established frameworks for coordination. Without clear rules on priority and responsibility, conflicts could arise during simultaneous activation requests.
- **Limited Availability of Digital Infrastructure**: Many smaller flexibility providers, especially residential users and SMEs, do not have access to real-time metering, control devices, or user-friendly platforms that would allow them to participate efficiently.
- **Scalability and Automation Issues**: Current platforms and market designs are often pilot-specific and manually operated. To reach broader deployment, automation of bidding, activation, and settlement processes is needed, together with scalable ICT solutions.
- **Data Governance and Privacy Concerns**: Flexibility provision requires sharing operational data such as consumption patterns and device availability. Without clear rules on data ownership, privacy, and security, participants may hesitate to engage.

- **Performance Uncertainty**: Variability in how flexibility resources respond to activation signals can lead to operational risks for DSOs. There is a need for better forecasting models, asset prequalification processes, and performance guarantees to make flexibility a reliable resource.

5 Regulatory gaps

The transition toward a more decentralized, resilient, and sustainable energy system is driven by innovations in microgrids, energy communities, demand-side management, flexibility markets, and digital energy platforms. However, existing regulatory frameworks were largely designed for centralized power systems, creating misalignment between policy, market structures, and emerging energy technologies. As a result, regulatory gaps pose significant challenges to the adoption, scalability, and financial viability of these innovations.

Key barriers include unclear legal definitions, restrictions on market participation, rigid grid access rules, and outdated tariff structures that do not reflect the dynamic and distributed nature of modern energy systems. Additionally, financial, data governance, and cybersecurity concerns add complexity to deploying innovative solutions. Without regulatory adaptation, these challenges could hinder the integration of renewable energy, limit consumer participation, and slow the development of flexible and intelligent energy systems.

Addressing these gaps requires policy adjustments, harmonized regulations across jurisdictions, and the creation of supportive mechanisms for new business models such as peer-to-peer energy trading, virtual power plants, and decentralized energy markets. This section explores the key regulatory challenges and identifies areas where innovation in policy and market design is needed to accelerate the energy transition.

5.1 Energy planning

Energy planning involves various stakeholders, including governments, energy producers, consumers, and regulators. Despite significant advancements in energy planning technologies and methodologies, regulatory frameworks often struggle to keep pace with these changes. The gaps in regulation present challenges for effectively transitioning to more sustainable, decentralized, and resilient energy systems. These regulatory gaps often stem from outdated policies, the complexity of integrating renewable energy and distributed resources, and the need for harmonization between national and local regulations. Regulatory frameworks for energy planning generally include a combination of national and regional policies that define energy infrastructure development, emissions reduction targets, renewable energy integration, and grid modernization efforts. Key components include National and regional policy goals, such as carbon reduction targets, renewable energy obligations, and energy efficiency standards. Also, regulations that define how energy markets function, including rules for pricing, trading, and capacity planning. Policies governing grid expansion, modernization, and the integration of DERs, energy storage, and microgrids are also part of the key components of regulation. Energy Efficiency Standards are also set by regulations that establish energy consumption limits and incentivize efficiency measures across different sectors. Regarding the environment, Laws and guidelines related to emissions, resource conservation, and the environmental impact of energy generation and infrastructure. Last, Regulatory mechanisms that support the financing of energy projects, including subsidies, tax incentives, and public-private partnerships.

There are several regulatory gaps in the energy planning sector that hinder the development of efficient and integrated energy systems. These gaps must be addressed to unlock the full potential of new technologies, optimize grid operations, and accelerate the transition to a more sustainable energy future.

Lack of Integration of DERs into Energy Planning

- Regulatory Gap: Many energy systems and market structures are still built around centralized generation and transmission models, which do not account for the full potential of decentralized resources such as solar, wind, and storage. DERs often face regulatory barriers that limit their integration into the broader energy system.
- Innovation Needed: New regulatory frameworks must support market structures that enable decentralized energy trading, peer-to-peer energy transactions, and integrated grid services such as demand response, energy storage, and vehicle-to-grid systems.

Inadequate Support for Microgrid and Community-Scale Energy Systems

- Regulatory Gap: Microgrids and community-scale energy systems often face regulatory hurdles, including restrictive interconnection standards, barriers to financing, and limited incentives for local energy projects. In many jurisdictions, there is a lack of clarity on how microgrids should be integrated into the larger grid.
- Innovation Needed: Policymakers need to create clear guidelines and standards for microgrid development, integration with the grid, and autonomous operation. Standardization of interconnection procedures, financial support mechanisms, and clarification of ownership models (e.g., community ownership versus private-sector investment) are crucial.

Limited Frameworks for Renewable Energy Integration

- Regulatory Gap: Despite the growing use of renewable energy, many regulatory frameworks are not yet fully adapted to support large-scale renewable integration. Issues such as curtailment, grid stability, and balancing intermittent renewable generation with demand are not sufficiently addressed.
- Innovation Needed: Incentives and regulations are needed to facilitate the integration of advanced energy storage solutions, grid flexibility, and smart grid technologies that can better manage variable renewable resources. This includes introducing dynamic pricing models to reflect the value of renewable energy at different times of day and the need for grid stabilization services.

Inconsistent Regulatory Approaches Across Regions

- Regulatory Gap: Regulatory frameworks for energy planning vary significantly across regions, which can create challenges for cross-border energy trading and the implementation of cohesive policies that drive regional or national energy transitions.
- Innovation Needed: There is a need for regional harmonization of energy policies and market rules to enable seamless integration of renewable energy across borders, improve energy security, and facilitate the development of regional energy markets.

Barriers to Data Sharing and Transparency

- Regulatory Gap: Energy planning often relies on data-driven models and real-time information to forecast demand, optimize energy generation, and manage grid operations. However, regulatory barriers related to data privacy, data access, and data ownership hinder the effective use of data across the energy sector.
- Innovation Needed: Regulators must develop frameworks that promote data sharing among utilities, service providers, and consumers while protecting privacy. This can include open data standards, smart grid data access regulations, and real-time data transparency mechanisms to improve decision-making and operational efficiency.

Inflexible Pricing and Incentive Structures

- Regulatory Gap: Traditional energy pricing structures are often outdated and do not reflect the true costs and benefits of integrating renewable energy, energy storage, and demand-side management. The lack of flexible pricing models hinders the participation of new market players and impedes the adoption of innovative technologies.
- Innovation Needed: Dynamic pricing and market-based incentive structures are needed to encourage investment in low-carbon technologies. This includes revisiting capacity markets, demand response programs, and the introduction of carbon pricing to create economic signals that promote sustainable energy solutions.

Slow Adoption of Climate Resilience Standards

- Regulatory Gap: Climate change is increasing the vulnerability of energy infrastructure to extreme weather events, yet many regulatory frameworks have not adequately integrated climate resilience standards into energy planning processes. As a result, energy systems remain highly susceptible to disruptions.
- Innovation Needed: Regulators need to develop resilience standards for energy infrastructure, including climate adaptation plans for critical grid components, emergency response strategies, and supply chain resilience measures.

Inadequate Incentives for Energy Efficiency and Demand-side Management (DSM)

- Regulatory Gap: While energy efficiency is crucial for reducing overall demand, existing regulations often lack strong incentives for the widespread adoption of demand-side management measures, such as real-time energy monitoring, energy-efficient appliances, and load shifting.
- Innovation Needed: Policymakers should introduce financial incentives, tax rebates, and subsidies for energy efficiency upgrades. Additionally, regulatory frameworks should better integrate DSM strategies with smart grid capabilities, enabling more precise and effective demand management.

5.2 Grid Monitoring & Predictive Analysis

As the energy system becomes more decentralized and data-driven, the need for robust grid observability and predictive capabilities becomes critical. However, current regulatory frameworks across Europe and other regions are often not yet fully aligned with the technical and operational requirements of modern, digitalized grid systems. Several regulatory gaps hinder the scaling, integration, and full utilization of grid monitoring and predictive analytics solutions:

1. Absence of Mandatory LV Grid Monitoring and Visibility Requirements

While regulatory requirements for monitoring exist at the transmission and, to some extent, the medium voltage (MV) level, low voltage (LV) networks—where the majority of DERs, prosumers, and new flexible loads like EVs are connected—remain largely unmonitored.

- Gap: Most DSOs are not obliged to invest in or maintain real-time monitoring systems at the LV level.

- Need: Regulatory mandates and technical standards requiring observability at the LV level, possibly linked to DER hosting capacity.

2. Lack of Standardisation for Data Formats, Interfaces, and Interoperability

Grid monitoring technologies often come from multiple vendors using proprietary formats, leading to data silos and integration challenges.

- Gap: There is no harmonised regulatory framework enforcing common standards for data formats, protocols, or APIs.
- Need: Regulations mandating open standards and interoperability requirements, drawing from EU-wide initiatives like the Common Information Model (CIM) and OpenADR.

3. Ambiguity Around AI and Automated Decision-Making in Grid Operations

AI and ML models are increasingly used to detect grid anomalies, forecast load or generation, and even suggest operational decisions. However, current regulatory frameworks do not define clear guidelines on their deployment, oversight, or auditability.

- Gap: No clear framework for algorithm accountability, explainability, or certification in critical infrastructure contexts.
- Need: Regulatory guidance or certification schemes for AI in operational environments, similar to those emerging in sectors like healthcare and autonomous driving.

4. Weak Cybersecurity and Data Protection Mandates

Grid monitoring systems are increasingly connected via public or semi-public networks, creating potential attack surfaces. However, cybersecurity policies are often generic and not adapted to energy sector specifics, particularly at the DSO or microgrid level.

- Gap: Lack of mandatory cybersecurity frameworks tailored to grid monitoring systems, especially for smaller DSOs or microgrids.
- Need: Stronger alignment with regulations like NIS2, but with specific application to energy systems. This includes encryption standards, authentication protocols, and data access controls.

5. Limited Regulatory Support for Real-Time or Near Real-Time Monitoring

While real-time monitoring can significantly improve grid stability and responsiveness, regulatory models often do not differentiate between static, periodic, and real-time observability in terms of incentives or compliance.

- Gap: No performance-based or output-oriented regulation that rewards faster response times or predictive accuracy.
- Need: Regulatory sandboxes or incentive schemes that reward predictive performance, such as reduced outage durations, avoided curtailment, or higher DER hosting capacity.

6. Inadequate Data Sharing Frameworks

High-quality grid data is valuable for innovators, researchers, aggregators, and third-party service providers. However, most regulatory frameworks do not require DSOs to share data, and when they do, data is often anonymised or aggregated to the point of reduced utility.

- Gap: No regulatory mandates for structured, timely, and standardized data sharing, including live operational data.
- Need: A governance framework balancing data openness, privacy, and security, with mechanisms for accessing anonymised operational data under clear terms.

5.3 Digital Twin – Grid Modelling

Although digital twins are increasingly recognised as a valuable asset for planning and operating distribution grids, **existing regulatory frameworks have not yet been adapted** to support their systematic use. There are currently no formal requirements that oblige DSOs to develop or maintain digital twins as part of their planning obligations or operational practices. As a result, deployment is often driven by pilot projects or innovation initiatives, rather than being integrated into regular grid development strategies.

Interoperability and standardisation also remain a challenge. Regulatory provisions related to data exchange, model compatibility, and communication protocols are either lacking or insufficiently specific. This fragmentation complicates the integration of digital twins across different systems and operators, and increases costs, particularly when combining static planning models with dynamic operational models.

Cybersecurity and data protection are also emerging concerns. Although energy sector cybersecurity regulations are evolving, they do not yet explicitly cover the vulnerabilities introduced by the operation of digital twins, particularly those that rely on live data feeds and cloud-based services. Specific cybersecurity measures, covering both operational resilience and personal data protection, need to be developed for these environments.

There is a **lack of incentives for real-time observability** at the distribution level. Current regulatory frameworks tend to focus on minimum service quality and reliability indicators, without recognising or rewarding the benefits brought by dynamic digital twins in improving flexibility, resilience, or operational efficiency.

5.4 Microgrids

Despite the technological advancements and increasing adoption of microgrids, several regulatory challenges persist:

- Grid Interconnection and Market Participation: Many regulatory frameworks lack clear provisions for microgrid interconnection standards and market participation, limiting their ability to trade surplus energy.
- Ownership and Business Models: The absence of well-defined ownership structures for community microgrids raises legal and operational uncertainties.
- Tariff and Pricing Mechanisms: Existing electricity pricing models do not always account for the benefits of localized energy generation and flexibility services provided by microgrids.

- Licensing and Permitting: Regulatory requirements for microgrid deployment can be complex and vary by jurisdiction, creating administrative hurdles.
- Resilience and Security Standards: There is a need for comprehensive policies addressing cybersecurity and grid resilience to ensure reliable and secure microgrid operations.
- Data Governance and Interoperability: Standardized frameworks for data sharing, interoperability, and privacy remain underdeveloped, hindering the full potential of digitalized microgrids.

5.5 Demand side management

Despite its critical role in enabling flexible, consumer-centric, and renewable-friendly energy systems, the full deployment of Demand Side Management (DSM) across Europe and beyond is constrained by several regulatory and policy barriers. These gaps impact both the economic viability and operational scalability of DSM programs, limiting their contribution to grid flexibility, decarbonisation, and consumer empowerment.

Inconsistent Recognition of Aggregators and Third-Party Service Providers

Aggregators—key enablers of DSM—face regulatory uncertainty or restricted roles in many Member States.

- Gap: Lack of standardized legal recognition of aggregators, particularly independent aggregators (those not tied to a specific supplier).
- Need: EU-wide guidelines (building on the Clean Energy Package) to ensure non-discriminatory market access, transparent baseline methodologies, and appropriate revenue-sharing frameworks between aggregators and suppliers.

Outdated Tariff Structures and Weak Price Signals

Many retail electricity tariffs are still based on flat or static pricing, offering no incentives for consumers to shift demand.

- Gap: Regulatory inertia in mandating time-of-use tariffs, dynamic pricing, or real-time metering in residential and SME markets.
- Need: Regulatory frameworks that support dynamic and locational pricing, encourage adoption of smart meters, and align retail prices with wholesale market signals.

Insufficient Consumer Protection and Incentive Design

While DSM requires active consumer engagement, many regulatory systems fail to balance risk, complexity, and benefit for consumers—especially vulnerable groups.

- Gap: Lack of standards for transparency in contract terms, data usage consent, and equitable access to DSM programs.
- Need: Consumer-focused regulations ensuring informed consent, easy opt-in/opt-out mechanisms, and fair benefit distribution, particularly for low-income households.

Co-funded by the European Union

Weak Data Governance and Access Regulation

Effective DSM depends on real-time access to energy consumption and grid condition data, yet such data is often siloed within utilities or metering providers.

- Gap: No harmonised rules on data access rights, ownership, or interoperability between systems.
- Need: Implementation of data portability and sharing frameworks, aligned with the EU Data Act and GDPR, allowing third-party access with proper safeguards.

Lack of Integrated Planning Between DSM and Network Operators

Distribution System Operators (DSOs) are rarely required to incorporate demand-side flexibility into network planning or grid reinforcement strategies.

- Gap: Regulatory frameworks often focus on supply-side reinforcement rather than incentivising non-wire alternatives like DSM.
- Need: Clear rules and incentives for DSOs to procure DSM services, run flexibility tenders, or factor DSM potential into grid investment planning.

5.6 Energy Communities

Regulatory gaps in energy communities present challenges that hinder their widespread adoption and scalability. These gaps exist across several key areas, including legal recognition, market participation, grid access, financial frameworks, and data governance. Below is an overview of the major regulatory challenges and areas where innovation and policy adjustments are needed:

Legal and Institutional Barriers

- While the Clean Energy for All Europeans Package introduced definitions for energy communities (Citizen Energy Communities - CECs, and Renewable Energy Communities - RECs), national implementations vary significantly across EU member states.
- Unclear legal status and administrative burdens make it difficult for communities to register and operate efficiently.
- Lack of standardized frameworks leads to regulatory fragmentation, creating uncertainty for investors and participants.

Market Participation & Grid Access

- Energy communities often face restrictions in accessing wholesale electricity markets, balancing services, and ancillary grid markets.
- Limited rights to sell excess energy or provide flexibility services to Distribution System Operators (DSOs) and Transmission System Operators (TSOs).
- High connection fees and grid tariffs designed for traditional utilities rather than small-scale community setups.

Economic & Financial Barriers

- Lack of financial incentives (such as tax benefits, grants, or preferential tariffs) for energy communities compared to traditional energy companies.
- Difficulty in securing funding due to high perceived risks, lack of clear business models, and limited access to financing mechanisms.
- Challenges in benefit-sharing models to fairly distribute financial returns among community members.

Data Governance & Digitalization

- Unclear data ownership and privacy regulations when community members share energy usage data on digital platforms.
- Cybersecurity risks in decentralized energy systems, particularly in peer-to-peer (P2P) trading platforms.
- Interoperability issues due to the lack of standardization in energy management systems and digital tools.

Regulatory Support for Innovative Business Models

- Peer-to-peer trading, virtual power plants (VPPs), and demand-side flexibility services lack clear regulatory pathways.
- Smart contracts and blockchain applications in energy sharing face legal uncertainties.
- Self-consumption and energy-sharing models are often limited by outdated net-metering and grid compensation schemes.

5.7 Citizen engagement & capacity building

Despite the growing importance of citizen engagement in energy policy, regulatory frameworks often lack concrete provisions to enable, protect, and promote active consumer participation through digital means:

- Lack of Recognition of Digital Participation Rights – Existing legislation does not always guarantee that citizens within energy communities have structured opportunities for digital engagement in governance or decision-making.
- No Standard for Consumer Data Ownership and Access – Users may not have clear rights over their energy usage data or easy access to it in usable formats, limiting transparency and control.
- Inadequate Support for Inclusive Digital Infrastructure – There is limited regulatory emphasis on ensuring that digital tools used in energy communities are accessible, secure, and inclusive, especially for low-income or vulnerable groups.
- Missing Incentives for Community Engagement Platforms – Most national policies and funding mechanisms prioritise physical infrastructure (e.g., solar panels, batteries) over soft infrastructure like digital platforms, education, and engagement.
- Fragmentation Across Sectors – Energy engagement is often regulated separately from digital policy or data governance, leading to inconsistencies that affect citizen trust and adoption.

Addressing these regulatory gaps will be crucial to support equitable access to energy transitions and to ensure that citizen participation becomes a standard, empowered aspect of energy community operation—not an optional or tokenistic element.

5.8 Local Flexibility markets

A major structural barrier to the development of local flexibility markets is the absence of appropriate **cost recovery mechanisms for DSOs when procuring flexibility services**. Traditional grid investments, such as reinforcing cables or upgrading substations, are added to the Regulated Asset Base and provide a predictable return under existing regulatory models. In contrast, the procurement of flexibility is treated as an operational expense, often without clear provisions for cost recovery or financial incentives. This creates a fundamental bias in favour of capital-intensive solutions, even when procuring local flexibility would be more cost-effective, faster to deploy, and beneficial for consumers and the energy system as a whole. Without regulatory adjustments that allow DSOs to treat flexibility procurement on an equal footing with infrastructure investments, the economic incentives will continue to limit the adoption of flexibility-based solutions, regardless of their technical or social advantages.

Beyond the cost structure, another important regulatory gap is the **absence of a harmonised framework defining how local flexibility markets should operate**. There is a lack of clarity regarding the types of flexibility services that should be procured, the contractual models to be used, and the interaction between flexibility procurement and the regulated tasks of network operation. This uncertainty limits the willingness of DSOs to integrate flexibility systematically into their operational planning.

Coordination between DSOs and TSOs is another regulatory challenge. As both system levels increasingly depend on flexibility resources, it becomes necessary to define clear operational priorities, conflict resolution procedures, and data exchange requirements. Without such frameworks, there is a risk of inefficient activations or even operational conflicts that could undermine system reliability.

6 SMEs and synergies

Small and medium-sized enterprises (SMEs) play a vital role in the successful implementation and potential market uptake of research outcomes in Horizon Europe (HE) and H2020 projects. Their agility, domain-specific expertise, and proximity to market needs make them ideally positioned to contribute to the development, deployment, and commercialisation of innovative energy solutions—especially in areas such as digital tools, control systems, and customer-facing applications.

In practice, EU-funded projects have shown that SMEs can bring significant value when integrated early and meaningfully. In the COMPILE project, for example, SMEs contributed to the development of community energy platforms, energy management tools, and local deployment strategies. In STREAM, SME partners were involved in the creation of data-driven grid monitoring solutions and participated in pilot implementation activities. These cases highlight how SMEs can act as both technology providers and local integrators, bridging the gap between research outputs and market-ready services.

Projects such as COMPILE, X-FLEX, RE-EMPOWERED, FLEXIGRID, WeForming, and DINGO have all demonstrated the added value of SME involvement. In X-FLEX, they contributed to the development of integrated flexibility management tools (e.g., GRIDFLEX and MARKETFLEX), enabling local market participation and demand response integration. The FLEXIGRID project benefited from SME-led innovations that improved LV grid monitoring and interoperability. In WeForming, a consortium of SMEs developed tools for smart, grid-interactive buildings, contributing hardware-software platforms, data analytics, and aggregation services for demand-side flexibility.

In the DINGO project, SMEs were responsible for increasing grid observability by installing advanced metering infrastructure in secondary substations. SMEs also led the integration of multiple software components into a unified product capable of creating digital twins of low-voltage (LV) networks, allowing for real-time monitoring and advanced network analysis. This kind of contribution is critical to enhancing operational awareness and planning capabilities in future smart grids.

Beyond individual tools, SMEs also play broader roles in system innovation and community energy. As highlighted by FER's ongoing collaborations, SMEs are co-developing novel solutions aligned with the energy transition, including tools for the foundation and operation of energy communities, the smart management of electric vehicle (EV) charging infrastructure, and the integration of renewable energy sources into LV networks. These partnerships are not only technical but strategic, often forming the basis for joint project proposals and long-term innovation pipelines.

However, experience from projects involving partners in Widening countries indicates that many SMEs in these regions face structural barriers to participation. A lack of familiarity with EU funding instruments, limited experience navigating complex administrative procedures, and the absence of tailored support mechanisms often discourage engagement—even when project themes align closely with their business interests.

These challenges are compounded by limited human resources within SMEs. When project tasks fall outside their immediate commercial focus or require extensive coordination and reporting, SMEs are unlikely to allocate core staff. This can result in peripheral participation, where involvement is nominal rather than strategic. Conversely, when project activities directly address pressing operational challenges—such as grid digitalisation, demand-side management services, or tools for community energy engagement—SMEs are far more likely to commit resources and actively contribute across technical, testing, and exploitation work packages.

This suggests that two conditions are essential for effective SME engagement, particularly in Widening regions:

Targeted onboarding and capacity-building support: SMEs benefit from early guidance on how to engage in EU-funded projects, including administrative support, matchmaking services, and simplified entry points. National contact points, innovation agencies, and regional clusters can play a pivotal role in this effort, but consortia themselves should also allocate time and resources to help SMEs navigate the project lifecycle.

Strategic alignment with SME business models: Projects should be designed with clear use cases and practical outcomes that match SME capabilities and market ambitions. When SMEs see a direct path from project activities to business opportunities—such as the development of a new service, product, or client base—they are more likely to invest effort and integrate project results into their operations.

To enhance these synergies, future R&I initiatives should ensure that project design is SME-conscious from the outset. This includes involving SMEs in co-design, ensuring that pilot activities have real commercial relevance, and providing support for market replication. Successful examples from projects like RE-EMPOWERED, X-FLEX, and OPENTUNITY show that when SMEs are treated not just as subcontractors but as co-creators, they help accelerate the innovation cycle and ensure that EU-funded research translates into tangible energy transition solutions on the ground.

7 Conclusions

This report demonstrates that significant progress has been made in developing the technological foundations for a flexible, decentralised, and consumer-driven energy system. EU-funded research and innovation projects—such as COMPILE, RE-EMPOWERED, X-FLEX, STREAM, WeForming, FLEXIGRID, and DINGO—have produced a range of innovative tools and solutions that are increasingly mature and field-tested. From advanced energy management systems and grid monitoring platforms to demand-side response tools and digital services for energy communities, these technologies offer clear potential to support the energy transition. However, unlocking this potential at scale requires not only technological innovation but also targeted regulatory reform, market facilitation, and inclusive capacity building.

A consistent message throughout this report is that while innovation is advancing rapidly, its integration into energy systems—particularly at the low-voltage level—remains uneven. Challenges around interoperability, real-time data management, and system-level coordination continue to limit the impact of otherwise well-developed solutions. This is particularly evident in regions where digital infrastructure is underdeveloped or grid planning remains focused on centralised paradigms. For policymakers and grid operators, this signals a need to prioritise investment in the digital backbone of future energy systems, including smart metering, substation automation, and interoperable communication platforms.

Regulatory frameworks have not kept pace with this shift. The existing rules often do not reflect the realities of distributed generation, bi-directional energy flows, and the growing role of prosumers and aggregators. In many jurisdictions, the lack of clear incentives for flexibility, limited access to real-time consumption and grid data, and the absence of standardised participation models for new actors create unnecessary friction. Regulators are encouraged to move towards performance-based models that reward system efficiency and flexibility, and to establish governance frameworks that enable secure data sharing, aggregator participation, and demand-side innovation.

SMEs have proven to be vital drivers of innovation, contributing to the development and deployment of practical, scalable solutions in nearly all the projects reviewed. Their contributions are particularly visible in tool development, digital service platforms, and local deployment strategies. Yet, many SMEs in Widening countries remain underrepresented in EU-funded projects, not due to lack of relevance, but due to structural barriers such as administrative burden, limited support systems, and misalignment with their operational focus. Strengthening national support mechanisms, simplifying engagement processes, and designing projects around realistic SME capacities and commercial interests are critical steps to ensuring their full participation.

Citizen engagement also emerged as an area with untapped potential. While several projects piloted successful tools to involve consumers in energy communities and local energy markets, sustained engagement remains difficult to achieve. Digital tools are often not sufficiently tailored to diverse user groups, and regulatory frameworks rarely include provisions to support inclusive, rights-based digital participation. To realise the full promise of decentralised energy systems, the EU and national authorities must promote citizen-centred design, digital literacy, and fair access to energy data and governance mechanisms.

8 References and acronyms

8.1 Acronyms

Acronyms list	
EU	European Union
EC	European Commission
EMS	Energy Management System
DSM	Demand Side Management
EV	Electric Vehicle
iGFB	Intelligent Grid Forming Buildings
AI	Artificial Intelligence
EDS	European Data Spaces
IDSA	International Data Spaces
IEGSA	Interoperable European Grid Services Architecture
TRL	Technology Readiness Level
RES	Renewable Energy Sources
LV	Low Voltage
HW	Hardware
SW	Software
CAIDI	Customer Average Interruption Duration Index
DER	Distributed Energy Resources
PMU	Phasor measurement Unit
ML	Machine Learning
IoT	Internet of Things
MG	Microgrid

PEL	Power Electronic Load
IEEE	Institute of Electrical and Electronics Engineers
GIS	Geographic Information System
SCADA	Supervisory Control and Data Acquisition
ESS	Energy Storage System
EC	Energy Community
CEMS	Community Energy management System
P2P	Peer to Peer
LFM	Local Flexibility Market
ICT	Information and Communication Technology
API	Application Programming Interface
TSO	Transmission System Operator
CEC	Citizen Energy Community
REC	Renewable Energy Community
SME	SME Small Medium Enterprise