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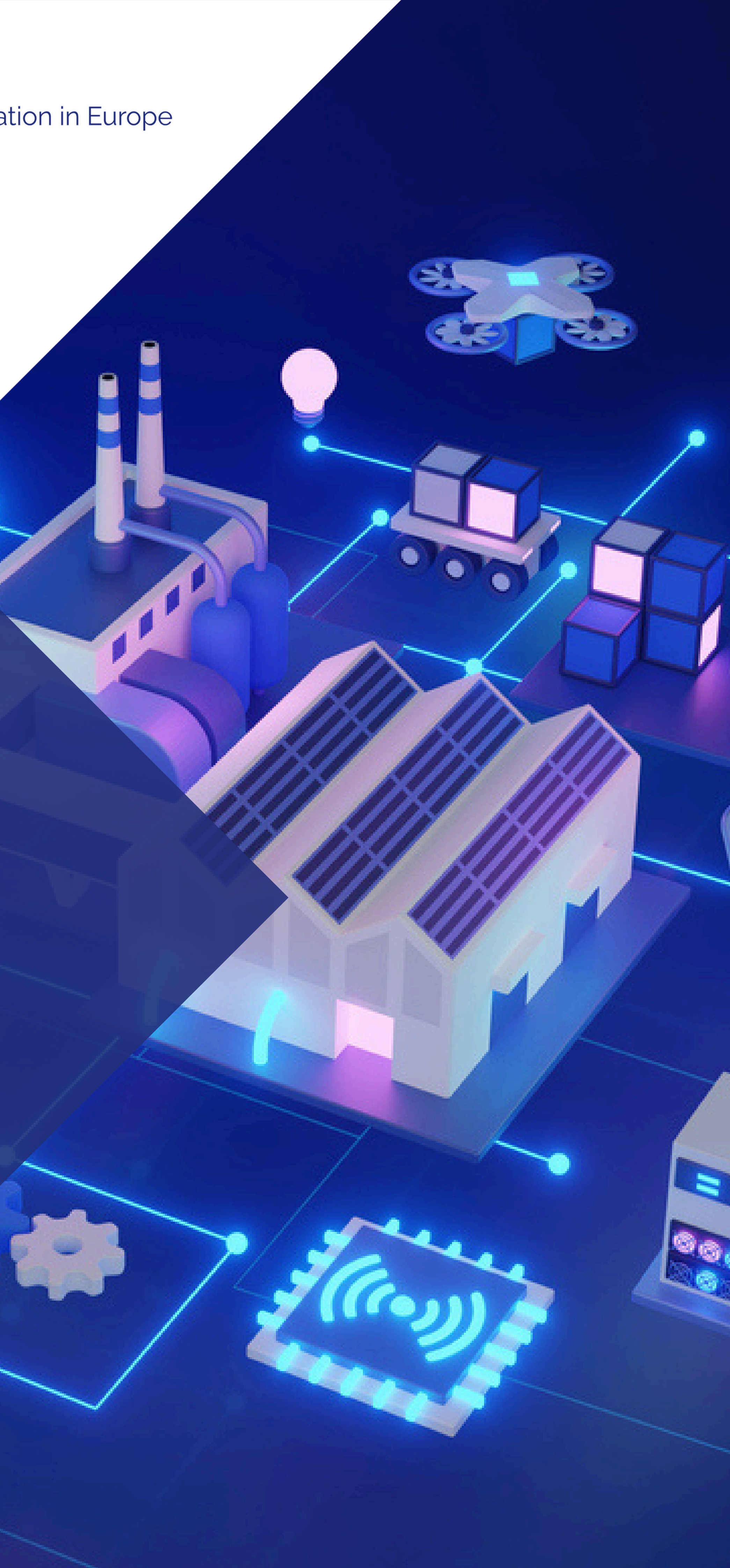

FLEXIBILITY IN THE ENERGY SECTOR

REPORT

May 2025

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Report

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Executive Summary

Flexibility is becoming a cornerstone of modern energy systems for managing variability and uncertainty in demand, supply, and grid availability across different timeframes. While stability has traditionally relied on conventional, dispatchable power plants and large industrial consumers, increased electrification, greater integration of intermittent renewables, and the gradual phase-out of conventional generation create new flexibility challenges.

This report looks at flexibility beyond the power grid to include sectors such as gas and bioenergy. It analyses technical and operational strategies, highlights the enabling role of digitalisation, and assesses market mechanisms and regulatory frameworks that facilitate system-wide flexibility. Additionally, it maps regional differences across Europe, explores innovative business models, and offers policy recommendations for increasing flexibility in the energy system.

This report distinguishes itself through three key analytical strengths. First, it adopts a **case study approach** that anchors theoretical concepts in real-world examples, addressing gaps identified in ACER's 2025 'Public consultation on prioritising the removal of barriers to electricity demand response,' which specifically called for illustrative cases. Second, it employs **textual analysis with embedding techniques** to characterise flexibility concepts within regulatory and policy documents, providing deeper insights than traditional definitional approaches. Third, the framework applies a **whole-energy system perspective** which encompasses all energy vectors, including heating, transport, and industry, offering a more holistic view of energy challenges and solutions. Together, these distinctive methodological elements provide an integrated understanding of flexibility in complex energy systems.

Chapter 1: Defining Flexibility in the Energy System

Chapter 1 presents the report's context, defining flexibility as the ability to manage variability and uncertainty in demand, supply, and grid availability across multiple timeframes. It outlines how flexibility encompasses both technical components (technologies providing key attributes) and operational aspects (how these technologies interact under regulatory frameworks).

This chapter highlights that flexibility requirements in European energy systems are expected to double by 2030 and triple by 2050, initially driven by the growing integration of renewable energy sources and later intensified by widespread electrification. It further discusses measurement approaches, including ENTSO-E's duration indicators, and identifies signs of limited system flexibility, such as frequency deviations, renewable curtailment, and price volatility.

Finally, it expands the traditional scope of flexibility beyond the electricity sector to adopt a whole-energy system perspective that includes gas industries and bioenergy. This approach acknowledges that both sources of variability and potential solutions span multiple sectors within the context of decarbonisation.

Chapter 2: Different Technologies, Different Contribution to Flexibility

Chapter 2 explores technological solutions that enhance energy system flexibility in the context of the ongoing phase-out of conventional power plants driven by decarbonisation initiatives. On the supply side, this chapter highlights how low-carbon gases (biomethane and hydrogen) can replace natural gas as flexible resources, while maintaining compatibility with existing infrastructure. It analyses energy storage solutions, particularly Battery Energy Storage Systems (BESS), which have become more affordable and accessible due to the falling cost of lithium-ion batteries. This chapter also examines hydropower as a benchmark flexible technology, highlighting its role in providing reliable backup power, cost-effective storage, and immediate generation capabilities.

On the demand side, this chapter explores flexibility across residential, commercial, industrial, and agricultural sectors. It analyses how electrification in heating (via heat pumps) and transportation (via electric vehicles with smart charging) is converting passive consumers into active participants in grid management. Furthermore, it investigates industrial decarbonisation, illustrating how energy-intensive processes are adapting to provide flexibility, especially through the electrification of challenging sectors such as steel production. Additionally, this chapter underscores the rising importance of data centres as significant electricity consumers capable of offering flexibility through load shifting, battery storage, and waste heat recovery. The chapter concludes with a comprehensive matrix mapping various flexibility options according to their duration capabilities and contributions to the green transition.

Chapter 3: Market and Regulatory Enablers of Flexibility

Chapter 3 analyses the enablers of flexibility in the energy system, focusing on how different actors and mechanisms support the integration of renewable energy sources. It explores key enablers such as energy grids, emphasising cooperation between TSOs and DSOs; aggregators who manage distributed resources through various contract types; local flexibility markets that facilitate the participation of distributed energy resources; collective self-consumption through prosumer networks and energy communities; and digitalisation, which enhances system optimisation across multiple timeframes. The chapter also reviews the regulatory framework underpinning flexibility, highlighting how EU legislation, such as the Clean Energy Package, the Electricity Market Design Reform, and the Gas and Hydrogen Market Package, has laid the foundation for flexibility mechanisms.

The textual analysis focusing on flexibility serves as a key analytical tool in this chapter. It uncovers interesting patterns in which flexibility is conceptualised across regulatory and policy documents. Using embedding techniques, the analysis categorises flexibility-related keywords into five conceptual groups: demand-side flexibility, supply-side flexibility, market mechanisms, flexibility assessment, and system flexibility. The evidence indicates that flexibility assessment and system flexibility dominate discussions in the analysed documents, while market mechanisms receive less attention. Notably, methodology-focused documents like the ENTSO Methodology Report emphasise assessment needs, while market-oriented regulations distribute attention more evenly across flexibility concepts. Recent policy documents — notably the Action Plan for Affordable Energy (COM/2025/79) presented by the European Commission (EC) as part of the Clean Industrial Deal — place greater emphasis on flexibility than previous texts, reflecting its growing importance in energy policy.

Chapter 4: Remaining Flexibility Issues

Chapter 4 highlights that, although EU policy broadly recognises the need for flexibility, significant implementation challenges remain due to structural and economic barriers. It presents practical flexibility solutions across five categories, illustrated with international case studies.

For generation flexibility, it covers the cases of Denmark's reforms requiring CHP plants to decouple heat and electricity production, and Germany's integration of biogas plants into virtual power plants. Storage solutions are illustrated through California's vehicle-to-grid programs, Australia's community battery initiatives, and Germany's REFHYNE project, which uses green hydrogen for grid services. Demand-side flexibility is examined through Sweden's successful implementation of dynamic pricing and Italy's comprehensive smart meter rollout program, which enables consumer participation in flexibility markets.

This chapter also explores transmission and distribution solutions, such as Australia's Dynamic Operating Envelopes, which enable greater renewable energy integration, and Sweden's sthlmflex project, which demonstrates effective coordination between TSOs and DSOs. System-level integration is illustrated by Hydro-Québec's dual-energy program, which aligns electricity and gas systems, and by the UK's new Flexibility Market Asset Registration system, designed to streamline aggregator participation.

Chapter 5: Flexibility in Europe and Regional Differences

Chapter 5 examines the implementation of flexibility across European countries, selecting a set of examples that showcase national approaches tailored to specific system needs and policy priorities.

The United Kingdom is highlighted for its multidimensional flexibility strategy, which includes institutional reforms such as the Future System Operator, gas system decarbonisation initiatives, digital platform development (Flexible Power, Piclo Flex, and Piclo Mission Innovation), integration of electric vehicles through vehicle-to-grid technologies, and the establishment of a national Flexibility Market Asset Registration system.

Spain's approach focuses on dynamic and localised flexibility, bolstered by regulatory reforms for grid access, smart meter deployment, distributed flexibility initiatives through the IREMEL project, and the growth of energy communities that enable collective self-consumption and local renewable generation.

Italy shows consumer-driven flexibility through sector coupling via its UVAM framework for aggregators, market platforms for flexibility trading, and initiatives linking electricity with heating and transportation sectors.

The Nordic region's integrated ‘flexibility-first’ approach is also discussed, characterised by extensive hydropower use, the Nord Pool market for cross-border balancing, innovative platforms like NODES, effective TSO-DSO coordination through initiatives like sthlmflex, advanced sector coupling, and the successful implementation of dynamic pricing models in Sweden.

This chapter concludes by examining cross-European cooperation mechanisms that enhance flexibility. These include the blockchain-based Equigy platform developed by five transmission system operators, the GOPACS platform for coordinated congestioning aggregators. It also highlights the significant variation in flexibility market development across Europe. The UK stands out for its leadership in prosumer market access, while Spain and Italy occupy a middle tier, and countries like Croatia are still in earlier stages of development. This variation underscores how national contexts shape the design and implementation of flexibility strategies.

Chapter 6. Options and Recommendations

Chapter 6 examines the key uncertainties and trade-offs in energy system flexibility planning. It highlights technological uncertainties related to optimal flexibility solutions, the tension between short-term price signals and long-term investment certainty, challenges of centralisation versus decentralisation, obstacles in realising the potential of digitalisation, and geopolitical complications that affect supply chains.

This chapter reviews recommendations from recent high-quality reports, identifying a quasi-consensus on implementing existing EU regulations rather than creating new legislation, removing barriers to flexibility solutions, conducting thorough flexibility needs assessments, and addressing cross-border integration. It acknowledges uneven progress across Member States in smart meter deployment, dynamic pricing adoption, and demand-side resource participation.

The policy recommendations are organised along two dimensions: the level of uncertainty (Low Uncertainty-LU vs. Adaptive Approach-AA) and the required structural change (Low-LS vs. High-HS). The following provides a concise overview of the key recommendations.

1. **Ensure an integrated, whole-system approach to flexibility planning across energy carriers [LU-LS].** Coordinate electricity, gas, and heat sectors to enhance system flexibility, building on existing EU strategies with a stronger focus on integration.
2. **Enable effective price signals at different levels [LU-HS]**. Use dynamic pricing and adaptive tariffs to drive flexible energy use, ensuring fair compensation for flexibility services across all markets.
3. **Accelerate demand response, aggregation, and DER participation [LU-HS]**. Remove barriers for small-scale resources and promote aggregation to fully leverage demand response in flexibility markets.
4. **Boost digitalisation at key nodes for flexibility [LU-HS].** Expand smart grids and data systems to enable real-time supply-demand adjustments, ensuring scalability and consumer participation.
5. **Keep options open for new technologies [AA-LS].** Support pilots and regulatory sandboxes to test emerging flexibility solutions, avoiding early technology lock-ins.
6. **Adaptive regulation for hydrogen integration [AA-HS].** Promote hydrogen's role in flexibility through adaptive policies, continuous R&D, and pilot projects to guide future strategies.

Chapter 7: Conclusion

Chapter 7 provides a conclusive overview and message which reflects the critical role of flexibility in enabling a secure, cost-effective, and decarbonised European energy system. As renewable energy penetration increases and electrification expands across heating, transport, and industry, the need for system-wide flexibility becomes more urgent. While EU legislation broadly supports flexibility through market design and infrastructure measures, significant implementation gaps persist across Member States.

Drawing on international case studies, textual analysis, and a whole-system perspective, the report identifies promising flexibility solutions, from battery storage and digitalisation to aggregators and cross-sector integration. However, many of these remain in early-stage deployment and require further regulatory support, investment signals, and real-world testing to scale effectively.

The report concludes that while the EU policy framework is largely fit for purpose, progress will depend on targeted national action, investment in enabling technologies, and a balanced approach that accelerates proven solutions while adapting to emerging ones. Flexibility is no longer a technical add-on; it is a core enabler of the energy transition.

Chapter 1. Flexibility in the Energy System

1.1. Definition

In energy systems, the concept of flexibility can be explored through multiple dimensions, including the system's ability to adapt, the time scales over which that flexibility is required, and the technological and operational means used to deliver it.

1.1.1. Ability to Adapt

Although the definitions of flexibility differ slightly across academic and grey literature, they tend to converge on the idea that flexibility refers to a system's ability to adapt to both expected and unexpected changes over a given period.

IRENA (2018) defines flexibility as the '*ability of a power system to reliably and cost-effectively manage the variability and uncertainty of demand and supply across all relevant time scales.'*

Similarly, ENTSO-E (2024) describes flexibility as '*the ability of a power system to effectively manage the variability and uncertainty of electricity demand, supply, and grid availability across a range of timeframes, from seconds to years.'* ENTSO-E further clarifies that flexibility should be understood in relation to adequacy. '*Adequacy refers to the power system's capacity to meet peak demand at all times, ensuring sufficient generation resources to maintain reliable supply under both expected and unexpected conditions. By contrast, flexibility is the system's ability to adjust dynamically to variability in supply and demand. This includes the capability to respond to rapid changes in consumption and generation, manage renewable energy variability, and maintain grid stability'* (ENTSO-E, 2024, p. 6).

A similar definition is found in the EEA and ACER joint study on flexibility solutions, where flexibility is described as the '*ability to manage, with all its connected resources, the variability and uncertainty of electricity generation and consumption patterns across relevant time frames'* (EEA & ACER, 2023). Likewise, the National Energy System Operator (NESO) in the UK defines flexibility more concisely as '*the ability to adjust supply and demand to achieve that energy balance'* (NESO, 2020).

1.1.2. Relevant Time Scales

The relevant time scales for flexibility span from seconds to hours and days, to months and years (IRENA, 2018). In the very short run, the objective of the system is to balance fast and unpredictable changes using operating reserves and inertia. In the short run – real-time, intraday, and day-ahead – the challenge is to balance forecast errors in load and generation and variability in net load. In the long run, spanning months to years, the goal is to balance seasonal or multi-year energy availability through scheduling (for hydro, gas, or hydrogen resources) and strategic investments, addressing broader energy security concerns.

The extent to which an energy system is flexible depends on its ability to meet several key objectives in a cost-effective and reliable manner across all time scales (IRENA, 2018). These objectives include: i) meeting peak loads and net loads at all times; ii) maintaining system balance through adequate ramp capability, fast-starting capacity, and operation during low net loads; iii) ensuring sufficient storage (electricity or gas) to manage both high and low levels of variable renewable energy (VRE) generation, as well as periods of high demand via generation or direct heat generation; iv) enabling demand response to supply variation; v) reacting to events that destabilise the power system with adequate ancillary services; vi) ensuring that market design does not prevent flexibility due to inefficiencies.

1.1.3. Technical and Operational Approaches

Following IRENA (2018) and Cochran et al. (2014), flexibility in power systems can be understood on two levels: technical and operational.

Technical flexibility refers to the availability of technologies capable of providing key flexibility attributes. These include the ability of supply (or demand) to respond to changes in demand (or supply) rapidly, the use of storage to balance mismatches between supply and demand across different time scales, and the capability of the grid to deliver the least-cost supply to demand across various locations and times.

Operational flexibility, on the other hand, relates to how these technologies interact and how the energy system is managed. It is mostly shaped by regulatory frameworks and market rules. A power system needs operational flexibility to make effective use of technical flexibility. This may involve mechanisms such as capacity markets and wholesale market designs with finer spatial and temporal granularity to provide clearer price signals and encourage investment in flexible resources.

Box 1: From Capacity to Flexibility

Capacity markets play a key role in ensuring long-term system adequacy, particularly by supporting the development of storage. However, the distinction between short-term system security and long-term adequacy is often blurred. While short-term measures address immediate operational needs, they can also have structural implications for market design. Flexibility, which underpins the system's ability to respond dynamically to changing conditions, should not be treated in isolation but integrated with energy efficiency strategies to enable cost-effective system optimisation. Importantly, utility-scale storage — such as that promoted under Italy's **MACSE** framework (*Misure per l'Acquisto della Capacità di Stoccaggio di Elettricità*) — is pivotal to enabling flexibility and securing supply in a decarbonised system (ARERA, 2024).

Finally, Table 1 summarises how adequacy, flexibility, and resilience each support power-system reliability. Flexibility is the system's ability to adjust quickly to routine fluctuations in renewable output and demand.

This differs from adequacy, which checks if total capacity is sufficient, and from resilience, which focuses on coping with major shocks, although the three concepts can overlap.

Table 1: Understanding Flexibility: Key Concepts and Definitions.

Concepts	Core question	Focus	Key levers
Adequacy	Is there enough capacity?	Meet peak demand (ENTSOE, 2024)	Installed capacity; capacity markets
Flexibility	Can we react swifty to demand and supply shifts?	Handle variability & uncertainty (ENTSOE, 2024; Covatariu and von der Fehr, 2024)	Flexible gen.; storage; demand; interconnectors
Resilience	Can the system withstand, adapt, and recover from disruptions?	Absorb & recover from shocks (Baldursson et al., 2023)	Grid strengthening; redundancy; black start

1.2. Measurement

1.2.1. Flexibility Needs

The rapid expansion of weather-dependent variable renewable energy (VRE), such as wind and solar, combined with growing electrification across the economy, is significantly increasing both the variability and uncertainty of electricity generation, while also driving up overall electricity demand. This trend makes system flexibility more critical than ever.

Traditionally, variability in power systems was primarily driven by demand, following predictable intraday and seasonal consumption patterns. However, in increasingly decarbonised energy systems, the key challenge is managing both the variability of renewable generation and the rapidly growing electricity demand.

According to ACER and EEA (2023), flexibility needs in European energy systems are expected to double by 2030 across all three timeframes: daily (2.4×), weekly (1.8×), and seasonal (1.3×). The sharpest rise in short-term flexibility needs is driven by the intermittent nature of solar PV generation, which can fluctuate significantly within short intervals. Over longer periods, seasonal complementarities between solar and wind may help balance variability.

From 2030 to 2050, flexibility needs are projected to triple, with the main driver shifting from changes in the generation mix to increased electrification of seasonal space heating end-uses (EEA & ACER, 2023). Similarly, ENTSO-E (2024) forecasts a doubling of flexibility needs across all timeframes between 2025 and 2033. Insufficient flexibility can lead to several adverse outcomes, including curtailment of renewable energy, increased system stress, volatile electricity prices, underuse or early retirement of valuable assets, and inefficient use of resources that could otherwise reduce greenhouse gas (GHG) emissions (Cochran et al., 2014; IRENA, 2018; ENTSO-E, 2024).

While the projected flexibility volumes provide an important indication of the system's energy balancing needs, it is equally critical to consider the flexibility dimension of the whole energy system. First, ensuring system stability will require sufficient flexible capacity (measured in GW) capable of rapid response across different timescales. Complementary conventional generation and strategic flexibility are vital for a resilient transition (Brunner et al., 2020).

Future planning must address both energy volumes and capacity availability to enable a reliable and resilient integration of high shares of variable renewables.

1.2.2. Duration Indicator

According to Cochran et al. (2014, p. 7), an adequate metric to measure system flexibility is the *'maximum upward or downward change in the supply/demand balance that a power system is capable of meeting over a given time horizon and a given initial operating state'*.

ENTSO-E uses three indicators to measure flexibility needs: two long-duration indicators and one short-duration indicator.

The first long-duration indicator refers to multiple days of low VRE generation and assesses the system needs, stress, and the role of interconnectors in mitigating this stress.

The second long-duration indicator is based on annual, weekly, or daily residual load variability and looks at sharp changes in VRE supply and demand.

The short duration indicator refers to errors in forecasting VRE supply and demand on an intraday basis and assesses the operational flexibility to match such variations in a timely manner (but without the ability to alleviate longer duration adverse events).

Indicators of limited system flexibility include difficulties in balancing supply and demand, often evidenced by frequency deviations or load shedding. Other signs include the curtailment of renewable energy due to excess generation or grid constraints; balance violations that reflect challenges in meeting system balancing requirements; negative market prices, which may indicate inflexible generation or insufficient demand-side response; limited storage or transmission capacity; and significant price volatility, characterised by large swings between low and high prices (Cochran et al., 2014).

1.2.3. Flexible Components of the Energy System

Different elements of the energy system can contribute to enhancing flexibility (Cochran et al., 2014). These include generation, transmission and distribution grids, demand-side resources, and system operations.

Flexible generation refers to the ability of power plants to ramp output up or down quickly and to operate efficiently at low output levels.

Flexible grids have sufficient capacity to support balancing resources without congestion, can tap into the flexibility resources of neighbouring systems, and are increasingly supported by digital technologies that optimise network use.

Flexible demand-side resources are the sum of interventions in matching demand to supply. This includes consumption adjustments, distributed generation, grid flexibility, and storage, all of which are supported by digital technologies and responsive to market signals.

Finally, *flexible system operations* make effective use of the existing flexibility in the system. They rely on improved forecasting, communication, and coordination — such as integration with neighbouring systems or more granular market designs — to enable and incentivise flexibility-enhancing behaviour.

Additionally, *sector coupling* is identified as a source of flexibility (IRENA, 2018).

Note that the decarbonisation of sectors such as heating, transport, and gas — through electrification, hydrogen, or biogases — can support the flexibility of energy system components through mechanisms like energy storage (e.g., EVs, home batteries, gas storage) and demand adjustment, especially when combined with digital tools.

1.3. Scope of Flexibility in this Report

In this report, flexibility is defined not just within the power sector but across the entire energy system. This broader view acknowledges that both the sources of variability and uncertainty — such as those revealed by the recent energy crisis — and the potential flexibility solutions, like power-to-gas and energy storage, span multiple sectors. These include not only the electricity sector but also the current and future gas industries, as well as bioenergy.

Therefore, flexibility is defined as the energy system's overall ability to effectively manage the variability and uncertainty of demand, supply, and grid availability across all relevant timeframes within the context of decarbonisation.

While this report recognises the importance of all aspects related to flexibility, it focuses on selected dimensions that are most relevant for current policy and market discussions. It examines the technological solutions enabling flexibility, the regulatory frameworks shaping their deployment, the spatial and institutional experiences across countries, and the temporal aspects of flexibility across different operational timeframes. The emphasis is placed on short- to medium-term flexibility needs, ranging from hours to months.

This report does not attempt to provide an exhaustive overview of all aspects of flexibility in energy systems. Rather, it focuses on several critical areas that are particularly relevant to the evolving needs of the European energy landscape. It examines operational flexibility and assesses how well current and anticipated flexibility needs align with existing market rules and regulatory frameworks in Europe.

The analysis includes insights from selected EU Member States as well as non-EU countries, offering a comparative perspective on practical approaches to flexibility. Particular attention is given to both current and emerging flexibility resources. These include demand-response mechanisms, distributed energy resource (DER) management, and the role of low-carbon gases such as hydrogen and biogases. Additionally, the report highlights the potential contributions of data centres and energy-intensive industries like steel and cement. Emerging business models that support flexibility solutions are also explored, along with the growing role of digitalisation in enhancing system flexibility. Finally, in terms of temporal focus, the report concentrates on flexibility needs over short- to medium-term horizons — ranging from hours to weeks and months — rather than long-term, multi-year scenarios.

Three analytical strengths set this report apart. First, it adopts a **case study approach** that anchors theoretical concepts in real-world examples, enhancing practical applicability. This addresses gaps identified in ACER's 2025 'Public consultation on prioritising the removal of barriers to electricity demand response,' which specifically called for illustrative cases. Second, it employs **textual analysis with embedding techniques** to characterise flexibility concepts within regulatory and policy documents, providing deeper insights than traditional definitional approaches. Third, the framework applies a **whole-energy system perspective** that encompasses all energy vectors — including heating, transport, and industry — offering a more holistic view of energy challenges and solutions. Together, these distinctive methodological elements provide an integrated understanding of flexibility in complex energy systems.

Figure 1 summarises the different dimensions of flexibility discussed in this report.

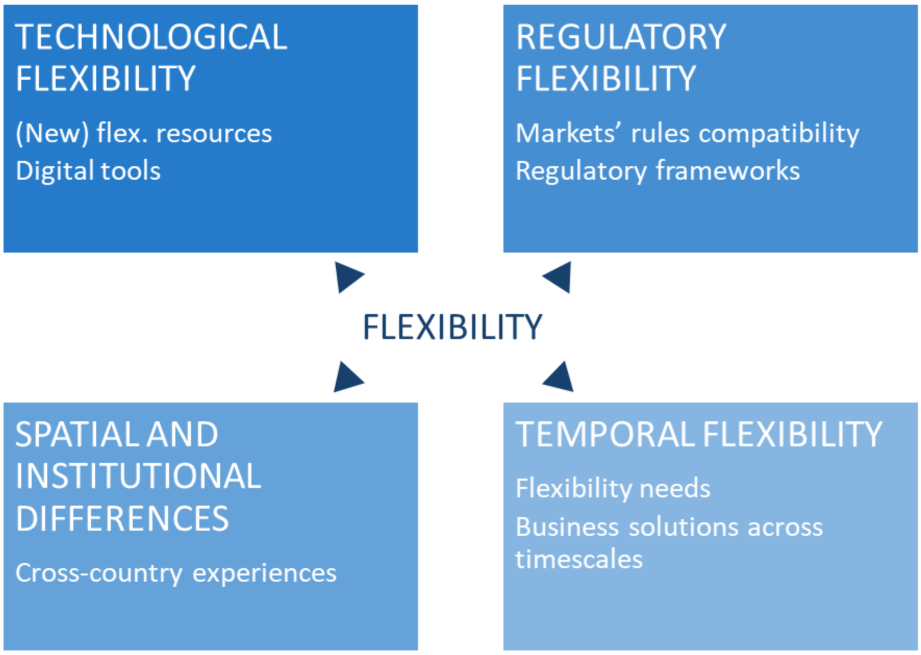

Figure 1: Dimensions of Flexibility
Source: Authors.

Chapter 2. Different Technologies, Different Contributions to Flexibility

Electricity systems must be balanced at all times to prevent brownouts and blackouts, making flexibility a critical requirement. Traditionally, large industrial consumers who were able to shut down parts of production and primarily large conventional power plants — usually coal, gas, and capabilities of conventional electricity producers helped stabilise the grid in response to sudden changes and outages. However, the energy landscape is shifting. The rise of electrification, the retirement of conventional generators, the growth of intermittent renewable sources, and nuclear phase-outs in some countries have weakened traditional forms of flexibility. As a result, new technological solutions are essential to maintaining grid stability and ensuring a reliable power supply.

2.1. Supply-Side Flexibility

Currently, natural gas is a significant provider of flexibility across all relevant timeframes and use cases. It can be stored relatively easily for later use to heat residential and commercial buildings, in industrial processes, and for electricity and/or heat generation. Natural gas provides both inter-seasonal and intraday flexibility. In addition to being technically feasible to store, gas can also fuel power plants that can ramp up and down in a relatively short time to meet the needs of the power system. However, with decarbonisation, it is widely believed that the use of unabated natural gas will need to be reduced by 2030 and phased out by 2050.

The respondents to ACER's 'Public consultation on prioritising the removal of barriers to electricity demand response' (ACER, 2025) rated the technical potential of conventional thermal generation as the fourth highest, with better technical potential assigned to pumped storage (3rd place), batteries (2nd place), and nuclear generation (1st place). Although traditionally, nuclear capacity has been considered a form of baseload generation that operates at stable production levels with low marginal pricing, the French example shows that it can be used in a more flexible way to complement intermittent renewables in load following mode (Cany et al., 2018).

Hydropower as a Benchmark Flexible Technology

Hydropower has been used for decades to enhance energy system flexibility by storing energy in the form of water in upper reservoirs. However, not all hydropower plants offer this capability, as many are run-of-river systems with little or no storage capacity and therefore limited flexibility. During periods of high electricity demand, water is released to generate power, providing a reliable and cost-effective backup.[1] When demand is low, excess electricity may be used to pump water back to the reservoir when not full, allowing the system to function like a large-scale, rechargeable battery. This

[1] Hydropower's role in electricity markets is significant, as its ability to store and release energy strategically influences equilibrium prices. With zero operating costs and being a storable resource, producers can optimise generation timing to maximise returns. By withholding supply during periods of low prices and increasing it during peak demand, they impact both price dynamics and thermal power producers' decisions (Crampes & Moreaux, 2001; Bushnell, 2003).

mature technology offers fast ramping capabilities, grid stability services, and cost-effective, large-scale energy balancing.[2]

2.1.1. Flexible Gas Options in Decarbonisation

If natural gas-operated turbines are gradually phased out of electricity systems due to higher costs, reduced availability of natural gas in Europe following the 2021-2022 energy crisis, and environmental concerns, a significant source of flexibility would be missing from energy systems. One option for maintaining or even enhancing the role of gas in flexibility is the use of biomethane and hydrogen.

The former has near-identical applications to natural gas, including heating (injected to the current gas grid), mobility or power generation, using various feedstocks, such as agricultural waste (Budzianowski and Brodacka, 2017). Applications are already significant in Germany and France, for example, where the potential is considered high for injection to the existing grid but also for flexible power generation (GRDF, 2021; Schröer and Latacz-Lohmann, 2024).

Biogas and Biomethane as Flexible Renewable Energy Sources

Biogas and biomethane, both derived from organic matter, represent key dispatchable renewable energy sources that offer a degree of flexibility similar to the one available from variable renewables like wind and solar. Biomethane could have near-identical applications as natural gas. Unlike intermittent sources, they can be stored and deployed on demand, making them valuable assets for maintaining grid stability and system reliability. Biogas is valuable for stabilising the grid when needed, especially during peak times or periods of system stress. However, it may be less efficient for heating applications through electricity generation and is therefore better suited for critical electricity or industrial uses.

In particular, biomethane functions as a drop-in replacement for fossil natural gas, supporting decarbonisation while enhancing operational flexibility. Hence, it can serve as a potentially sustainable alternative to fossil-based natural gas. Its success depends on market conditions, regulations, and technological advancements. A stable biomass supply, often secured through contracts with local agricultural and zootechnical firms, is essential for continuous production (Corato & Moretto, 2011).

Biomethane is the most flexible form of renewable energy source in terms of storability and compatibility with existing infrastructure, enhancing system resilience and efficiency (Table 1). As a renewable gas, it can be stored and used on demand, integrating seamlessly into current pipelines, storage, and distribution networks. This compatibility enables biomethane to offer dispatchable energy, supporting grid stability and complementing intermittent sources like wind and solar (IEA, 2020) by balancing electric supply for specific electric needs or providing end-user demand flexibility via hybrid equipment (e.g. hybrid heat pumps or flexible co-generation). However, biogas-based electricity generation at the plant level is less flexible than natural gas-based generation, as anaerobic digestion (AD) facilities typically have a very limited on-site storage capacity, often of only to a few hours. This curbs their ability to ramp up or down in real time, underscoring the importance of integrating biomethane into broader gas networks for effective system-level flexibility.

[2] https://www.energy.gov/eere/water/how-pumped-storage-hydropower-works?utm_source

Meanwhile, biogas plants contribute to grid stability by providing balancing and ancillary services, such as frequency and voltage regulation (IEA, 2020). Biogas plants can be dispatched quickly during peak electricity demand. Many biogas plants produce both electricity and heat together (Combined Heat and Power), which affects efficiency and how much flexibility they can offer to the grid.

2.1.2. Hydrogen as a Source of System Flexibility

Hydrogen is increasingly recognised as a promising contributor to energy system flexibility, particularly when produced through electrolysis powered by variable renewable energy (VRE). In periods of excess VRE generation, hydrogen production offers an additional and scalable storage option, complementing electricity storage and demand-side load shifting, both of which are often constrained in capacity or duration (Hanley, Deane & Gallachóir, 2018; Wang et al., 2018). This approach helps reduce curtailment and convert surplus electricity into a versatile energy carrier.

Once produced, hydrogen can be deployed in multiple end-uses, including power generation via fuel cells and turbines, heating (e.g., through grid blending), industrial processes, and mobility heating. However, this versatility comes with efficiency losses due to energy conversions across different applications. Importantly, the production process itself is flexible, allowing electrolysis units to ramp up or down in response to VRE availability (Lange et al., 2023).

As a hydrogen market emerges — especially for decarbonising hard-to-abate sectors — its economic viability as a flexibility resource improves (Ahang, Granado & Tomasgard, 2025). Modelling work confirms the critical role of low-carbon gases in supporting a net-zero energy system dominated by renewables (Chyong et al., 2024). Combinations of hydrogen, biomethane, and other bioenergy sources (including e-fuels and bioenergy with carbon capture and storage [BECCS]) are expected to provide both inter-seasonal flexibility (e.g., methane and hydrogen storage balancing seasonal PV generation) and intraday flexibility (e.g., hydrogen storage in pressurised tanks or liquid form).

Green hydrogen — produced from renewable electricity — offers a long-duration storage option with minimal energy loss, in contrast to conventional batteries (Schlapbach & Züttel, 2001). However, its widespread deployment still faces economic and geopolitical challenges. Green hydrogen remains two to three times more expensive than blue hydrogen, but has nonetheless seen cost reductions in 2024, which were attributed to the increased renewable electricity production and advancements in electrolysis technology (Montel, 2025). Green hydrogen uptake is necessary not just for decarbonisation efforts, but also to protect the economic value of renewable energy investments, by absorbing excess renewable electricity and preventing curtailment and negative market prices.

In Europe, pipeline transport is the most cost-effective method for distances under 1,500 km (Lebrouhi et al., 2022; Carlson et al., 2023; Yang et al., 2025). Continued technological innovation and the expansion of international hydrogen trade are expected to drive adoption (Antweiler & Schlund, 2024). Notably, co-locating electrolysis with offshore wind farms can improve system efficiency and influence electricity prices, potentially lowering them during periods of excess supply or increasing them in low-price regions, though the overall impact depends on regional market dynamics (Durakovic et al., 2023).

2.1.3. Energy Storage

To effectively integrate increasing amounts of solar and wind energy, various energy storage solutions have been developed to enhance grid flexibility and reliability. These technologies can be broadly categorised into four main types: mechanical (e.g., pumped hydropower, flywheels), chemical (e.g., batteries, hydrogen, gas), thermal (e.g., hot water tanks, molten salts, seasonal thermal storage), and electrical (e.g., superconducting magnetic storage). Additionally, vehicle-to-grid systems and various conversion technologies — such as heat pumps (converting electricity to heat, with flexibility provided through associated heat storage like hot water tanks or building inertia) and electrolysis (converting electricity to hydrogen) — further contribute to system flexibility (Després et al., 2017; Carabelo et al., 2021). Power-to-X (P2X) technologies offer another layer of flexibility by converting surplus renewable electricity into hydrogen and other energy carriers through electrochemical processes (Rego de Vasconcelos & Lavoie, 2019). This enables excess renewable energy to be stored and reconverted back into electricity or repurposed for other uses, such as heating, cooling, and transportation, helping to balance supply and demand across the energy system more effectively. However, it is important to note that this added flexibility comes at the cost of efficiency losses, as each conversion step, from electricity to hydrogen or other carriers, incurs energy penalties that reduce overall system efficiency.

Battery Energy Storage Systems (BESS) are crucial in maintaining grid stability by providing ancillary services such as frequency regulation, voltage control, and real-time demand matching (Rangarajan et al., 2023). The sharp decline in lithium-ion battery costs (see Figure 5), driven by the electrification of light-duty vehicles and widespread use in consumer electronics, has significantly expanded BESS applications across electricity grids, ancillary services, and the transportation sector. While cost reductions have made energy storage more accessible (MIT, 2022), battery costs are mainly capacity

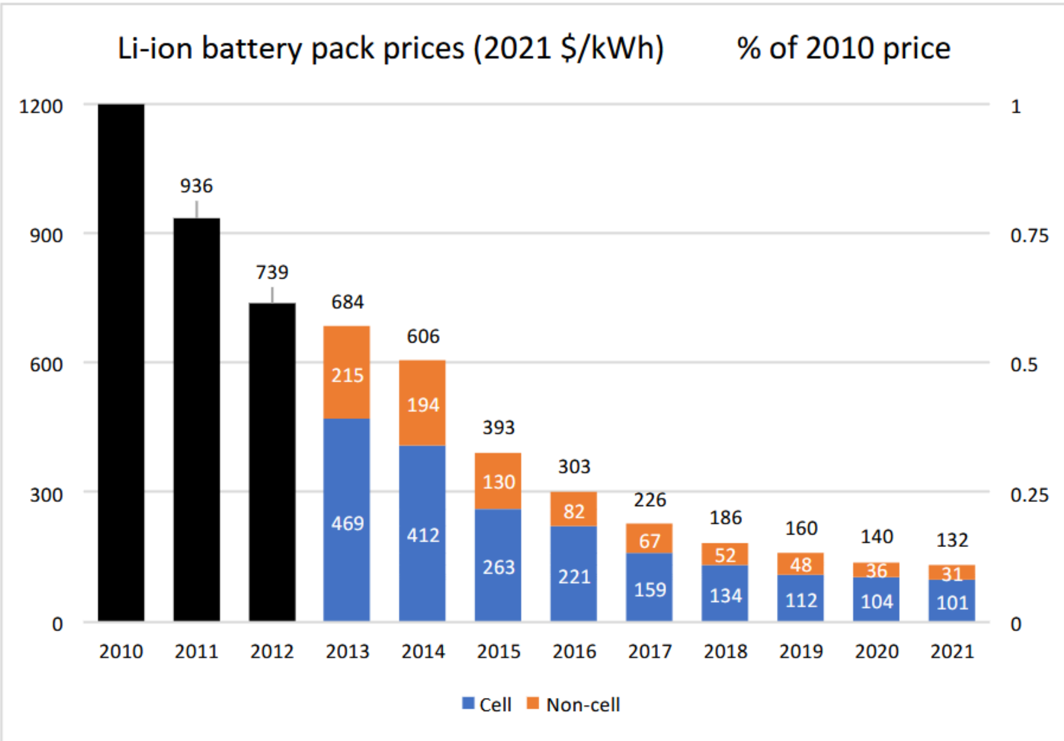

Figure 2: Global Li-ion Battery Prices for 2010–2021
Source: Bloomberg New Energy Finance (2021).

costs, and service cost depends on usage frequency. Lithium-ion batteries typically last 500–5000 cycles (5–10 years with daily use), but infrequent use, such as once per month, can make storage prohibitively expensive — up to 1150 €/MWh — making batteries unsuitable for seasonal storage.

2.2. Demand-Side Flexibility

Demand flexibility can be divided into two types: implicit and explicit. The former is based on consumers´ reactions to price signals, while the latter refers to dispatchable flexibility, such as balancing services (Hussain et al, 2023). Respondents to ACER's 2025 public consultation rated the industrial, commercial, and residential demand responses as flexibility options with high technical potential (ACER, 2025).

2.2.1. Demand Response and Electrification

Demand-side flexibility encompasses four main sectors: residential, commercial, industrial, and agricultural. Although this section primarily focuses on the residential and commercial areas, it is essential to recognise that industrial applications also play a vital role in broader flexibility strategies, which are discussed in the next subsection.

In the residential sector, demand flexibility is increasingly enabled by two major trends: **electrification** and the growing potential for **demand response**. Heat pumps, for instance, are steadily replacing other fossil fuel-based heating systems. This shift not only reduces household energy costs, but also aligns energy consumption with renewable generation, thereby supporting the decarbonisation of heating systems (Rosenow et al., 2022). Smart household appliances contribute further, with global adoption reaching 9.2% in 2024. In the European Union, 63% of individuals aged 16–74 now use internet-connected devices at home — ranging from smart thermostats to lighting and appliances — which can be programmed to operate during off-peak hours, unlocking new demand-side response opportunities (Eurostat, 2024).[3]

The electrification of heat, through both resistive heating and heat pumps, adds another layer of flexibility. These systems can act as **distributed thermal energy storage**, especially when combined with intelligent control systems that respond to external signals such as grid congestion or fluctuating electricity prices (IRENA, 2018; Thomaßen et al., 2021). Heat pumps, in particular, can help to alleviate grid stress when their demand response capabilities are actively leveraged (Felten et al., 2018). Despite this potential, they currently meet only around 10% of the global heating demand in buildings. Sales also declined in 2023 — by 3% globally and 5% in Europe — mainly due to steep drops in countries like Poland and Finland, likely a result of high upfront investment costs (Barnes and Bhagavathy, 2020).

At the same time, the widespread adoption of electric vehicles (EVs) is rapidly enhancing demand-side flexibility in both residential and commercial contexts (IEA, 2024). According to the European Commission's impact assessment of the CO2 emission performance standards of cars and vans, with

[3] More details at https://www.statistiques.developpement-durable.gouv.fr/tableau-de-bord-solaire-photovoltaique-troisieme-trimestre-2024

a high penetration of EVs, their electricity consumption could reach around 11% of total electricity consumption in 2040, compared to a share much below 1% in 2020. Smart charging infrastructure enables EVs to become responsive loads, capable of adjusting their charging schedules based on grid conditions, electricity prices, and mobility needs. These systems optimise charging behaviour by integrating real-time data on renewable availability and grid congestion, effectively turning EVs into active participants in the power system. When combined with algorithms, artificial intelligence, and automation, this flexibility can be monetised, offering a new value stream for end users and contributing to overall system stability.[4]

Together, these developments highlight how **electrification —** particularly of heat and transport — combined with **digital demand response mechanisms (see Section** 2.2.3. AI and Data Centres**)**, is reshaping the role of consumers in the energy system. Households are no longer passive users of electricity; instead, they are emerging as active, responsive nodes that enhance grid flexibility across all time frames: from seconds and minutes to hours and days, and even across seasonal or annual cycles.

2.2.2. Industrial Decarbonisation

Industrial facilities — particularly energy-intensive ones such as aluminium smelters, cement plants, or pulp and paper mills — are already contributing to the energy system's flexibility by adjusting their electricity consumption in response to system needs. While some industrial processes require continuous operation to remain viable (Depree et al., 2016; Zhang and Grossmann, 2016; Ranaboldo et al., 2024), others have built-in capabilities to ramp consumption up or down within production constraints. Their large and concentrated electricity loads make them particularly valuable in systems with a growing share of VRE, and their potential contribution to demand-side flexibility is being actively assessed across several sectors (Pierri et al., 2020; Ranaboldo et al., 2024; Mossie et al., 2025).

Demand response in industry is evolving through the integration of advanced technologies and operational changes. Combined Heat and Power (CHP) units, widely used in many industrial operations, exemplify this flexibility. By synchronising heat and electricity production, CHP systems can be scheduled to balance grid needs. Biogas-powered CHP units can respond dynamically to daily electricity demand fluctuations, enhancing both industrial energy efficiency and grid reliability (Wang et al., 2019). Hybrid boilers are also being developed to benefit from low or even negative electric prices when there is an over-production of VREs. In parallel, small-scale renewable energy installations and energy storage systems are becoming increasingly important, offering flexibility in both heavy industries, such as cement, and lighter sectors, like food processing (Tang et al., 2019).

A major source of emerging industrial flexibility lies in the electrification of processes, particularly within hard-to-abate sectors. While electrification will drive up overall electricity consumption — putting additional pressure on grids — it also introduces new possibilities for responsive, controllable demand. One key example is the transformation of the steel industry. The shift from coal-based blast furnace/basic oxygen furnace (BF-BOF) processes to hydrogen-based direct reduced iron–electric arc furnace (DRI–EAF) systems is projected to increase electricity demand by a factor of four compared to

[4] https://energycommunityplatform.eu/communities/hyperion-energy-community/

conventional EAF operations (Boldrini et al., 2024). Yet, this transition also opens the door for significant demand-side flexibility.

Electrolysers, which produce hydrogen for DRI processes, can be designed to ramp production up or down based on grid signals, allowing steel plants to modulate their electricity demand without disrupting output. Depending on system configuration — such as electrolyser capacity, hydrogen storage, grid connection, and market conditions — between 5% and 40% of total electricity consumption could be shifted to different times of the day (Boldrini et al., 2024; Fuhrlaender, Vermeulen and Schnuelle, 2025). These capabilities offer promising opportunities not only for load shifting but also for providing frequency regulation and other ancillary services to the power system.

Electrolysers have the capability of quickly reacting and absorbing excessive renewable generation (Ruhnau, 2022); thus, if placed in the proximity of renewable energy parks, they can absorb electricity, replacing the inefficient curtailing of the renewables production. Green hydrogen can then be either stored, injected into the natural gas grid and used for heating, mobility, or grid stability purposes (via fuel cells) (Stamatakis et al., 2022; Cozzolino and Bella, 2024).

Furthermore, even partial electrification of industrial process heat presents flexibility potential. Hybrid heating systems that can switch between electric boilers and fossil-fuel-based systems allow facilities to adjust their electricity use in response to grid conditions, particularly during times of VRE surplus or scarcity, as reflected in electricity prices (DG Energy et al., 2022). Electric boilers are already being deployed for medium-temperature applications, and if high-temperature heat pumps continue to advance and become more cost-competitive, they could significantly expand the role of electrified heat in supporting industrial flexibility over the medium term.

In summary, the industrial sector is becoming a key player in demand-side flexibility through a combination of demand response capabilities and electrification. While increased electricity use presents challenges, it also enables flexible, controllable loads that can respond dynamically to the evolving needs of a decarbonised, VRE-dominated energy system.

2.2.3. AI and Data Centres

The infrastructure that underpins digital technology, and especially data centres (DCs), is becoming a significant consumer of electricity, especially in the US, China and Europe (IEA, 2024). Currently at 1% of global electricity consumption and 2-4% of electricity consumption in US, China and Europe, the increased demand for computing power associated with the adoption of AI, is expected to lead to significant growth in consumption (IEA, 2024). Some countries (e.g., Ireland)[5] and jurisdictions (e.g. the state of Virginia in the US)[6] are beginning to experience the impact of the growth and concentration in data centres' electricity on their electricity grids. The exact impact is difficult to forecast, as it depends on the adoption of AI and other digital technologies, the process of increasing efficiency in data centres, as well as the pace of grid reinforcements and capacity additions. However, it is safe to assume that growth will continue and will be significant through 2030 and beyond.

[5] https://datacentremagazine.com/critical-environments/power-hungry-data-centres-put-pressure-on-irelands-grid

[6] https://www.datacenterdynamics.com/en/news/unconstrained-data-center-growth-in-virginia-could-outstrip-power-supply-report/

At the same time, data centres can become an important source of flexibility for the energy system.[7] Their power use can be modulated, allowing their participation in demand response programs via two types of mechanisms: 1) shifting the computing work of the server spatially (from one DC to another) or temporally contributing to peak shaving and 2) using the equipment (batteries, on-site or off-site generation, or air conditioning systems) to manage their generation and consumption in a flexible way (Cao *et al.*, 2024; Riepin, Brown and Zavala, 2025). Because of the continuous nature of their operations, data centres are equipped with uninterruptable power supplies with battery storage. These systems tend to be oversized for redundancy purposes and can be used for ancillary services (Alaperä, Honkapuro and Paananen, 2018). There are commercial energy services companies[8] who offer solutions[9] on behalf of data centres to enable the generation of new revenue streams while providing flexibility to the system. Data centres can also use their flexible cooling profile as well as the potential to recover the waste heat and integrate it in district heating systems for additional flexibility benefits, as already experienced in Sweden and Denmark (Jerez Monsalves, Bergaentzlé and Keles, 2023). A more eye-catching example came from the Paris Olympics in 2024, when waste heat from a nearby data centre was used[10] to heat the water in the Olympic Aquatic Centre. While the prospects seem significant, it is hard to evaluate how much flexibility is currently provided by data centres, as information tends to be scarce.

To conclude, flexibility requirements must be met through a combination of supply-side solutions, such as flexible generation and energy storage, and demand-side strategies that adjust consumption patterns. A comparison of renewable energy technologies and their potential to participate in flexibility services is presented in Table 2. Hydropower has been used for decades to enhance energy system flexibility; in places where there are not adequate water resources, the flexibility was traditionally provided by natural gas, which now, in the scope of decarbonisation, it is believed to be phased out by 2050. Biomethane is the most flexible renewable energy source in terms of storability and compatibility with existing infrastructure, enhancing system resilience and efficiency.

[7] https://www.datacenterflexibility.com/
[8] https://www.enelx.com/uk/en/demand-response/flexibility-for-data-centres
[9] https://cpowerenergy.com/decarbonizing-data-centers-gives-grid-flexibility/
[10] https://www.wired.com/story/ai-is-heating-the-olympic-pool/

Table 2: Low-Carbon Renewable Energy Carriers: Comparison and Potential

Technology	Storability	Integration with Existing Infrastructure	Dispatchability	Primary Advantage	Challenges
Hydropower	High	Existing infrastructure required	Yes/no	Reliable backup power, cost-effective storage when physically feasible, immediate power generation.	It can influence market prices, requires significant infrastructure. Production capacity limitations – potential sites already equipped at over 90%.
Biomethane	High	Seamless	Yes	Flexible, integrates into existing gas grid infrastructure, supports grid stability. Long term energy storage with minimal decay.	Production capacity may have some limitations.
Green Hydrogen	Very High	Limited	No	Long-term energy storage with minimal decay, beneficial effects on VRES affordability.	High production cost, technology still evolving.

Table 3 presents the matrix of different flexibility options (supply and demand side) described in the report and maps their contribution to the flexibility duration, from the intraday time dimension to long-term (months), it also indicates if the flexibility solution in question contributes to the green transition. Supply-side flexibility traditionally refers to conventional thermal power plants operating with gas or coal, as well as hydropower and nuclear energy. However, we also highlight the emergence of new supply-side flexibility sources, such as biogases (including biomethane and renewable hydrogen) and renewable energy source (RES) curtailment. The solutions differ in their efficiency, which is especially visible in the case of RES curtailment. Although it is used as a short-term solution, it is not optimal as it both increases the payback timeframe of the RES investment and reduces its contribution to the grid; it is therefore marked in orange in the table, indicating its shortcomings as a green transition solution.

Energy storage encompasses both conventional technologies — like gas storage, thermal storage, and pumped hydro — and newer solutions, including battery energy storage systems (BESS), vehicle-to-grid (V2G) technologies, and power-to-X (P2X) applications.

Demand-side flexibility centres on the capacity of individual consumers and industries to adjust their energy use, with particular emphasis on flexible operations from electrolysers and data centres. The trade-off between the operations of industry and the amount of flexibility it can provide is visible in Table 3. On one hand, industry, including data centres, can adjust its demand in the span of hours, but its contribution to the longer-term flexibility provision is limited. Industry can shift its load but with limits. Electrolysers on the other hand can easily absorb the surplus of electricity in the short term, which is then stored as green hydrogen and can be used for flexibility needs in the longer term, for e.g. via fuel cells providing electricity back to the grid.

Finally, interconnectors represent a critical category, as they provide flexibility across all timeframes by enabling cross-border energy exchanges. Colour coding reflects how well the flexibility solution contributes to the relevant time dimension; green is used when the flexibility option can be used in the particular time frame: orange when the usage of the flexibility solution is subject to limitations; red is used when the flexibility solution cannot be used in the relevant time dimension or is heavily limited.

Table 3: Time Dimension of Different Types of Flexibility

	Intraday (hours)	Medium-Term (weeks)	Long-Term (months)	Green Transition Solution
Supply Side Flexibility				
Thermal units gas				
Thermal units coal	*ramp up rates and long start-up times*			
Hydro				
Nuclear	*mostly stable baseload, but also load following*	*mostly stable baseload, but also load following*	*mostly stable baseload, but also load following*	
Biogas/Biomethane				
Renewable hydrogen				
RES curtailment				
Energy Storage				
Battery Energy Storage System (BESS)				
Pumped Hydro				
V2G	*possible but not matured technology*			
Power-2-X				
Thermal storage		*district heating*	*possible (e.g. Aquifer Thermal Energy Storage)*	
Gas storage				
Demand-Side Flexibility				
Consumers				
Industry				
Electrolysers (green hydrogen)				
Data centres				
Interconnectors				

Note: Green – yes; Orange – with limitations; Red – no/very limited.
Source: Authors.

Chapter 3. Regulatory Framework and Enablers

A low-carbon energy system can only function effectively if energy can be moved, stored, and controlled rapidly and reliably. Without such flexibility, system stability and safety cannot be maintained. Since every act of flexibility is influenced, either enabled or constrained, by formal rules, this section begins with a systematic review of the relevant regulatory and policy framework. It then provides a concise overview of the key enablers of flexibility: transmission and distribution system operators (TSOs and DSOs, respectively), aggregators, local flexibility markets, collective self-consumption schemes, and the digital tools that connect and optimise their interactions.

3.1. Regulatory Framework

In the EU, flexibility-related policy initiatives are covered in various legislative acts, many of which require implementation at the Member State's level, making a comprehensive overview complex.

The regulatory framework is outlined below to define the playing field for flexibility. The next subsection employs embedding techniques to analyse the content of those texts, inquiring not only how often flexibility is invoked but also how it is framed across demand- and supply-side, market, assessment, and system dimensions.

3.1.1. Brief Regulatory Overview

Renewable energy has been a central EU priority since 2001, with significant efforts to decarbonise the energy sector. The REPowerEU Plan, introduced in response to the 2021–2023 energy crisis, further accelerated the shift toward renewables, amplifying the need for flexibility in the energy system.

Energy system flexibility has become a priority at the EU level in recent years. It features prominently in the *Electricity Market Design Reform*, the *Gas and Hydrogen Market Package*, the *Energy System Integration Strategy*, and a range of technical regulations and planning frameworks.

The *Clean Energy for All Europeans Package* (2019) introduced two core legislative texts for electricity markets: the *Electricity Regulation (EU) 2019/943* and the *Electricity Directive (EU) 2019/944.* These documents set foundational provisions for system flexibility. Article 6 of the Electricity Regulation mandated that balancing markets be fully opened to all resources, including demand response and storage. Articles 20 and 21 required TSOs and DSOs to procure balancing and non-frequency ancillary services via market-based mechanisms. The Electricity Directive reinforced consumer-related flexibility measures, including support for dynamic electricity pricing and aggregator access.

In December 2023, as part of the *Electricity Market Design Reform*, the Electricity Regulation was updated and is now reflected in *Regulation (EU) 2024/1747.* These amendments introduced national flexibility objectives and new instruments to support non-fossil flexibility sources.

The *Gas and Hydrogen Market Package* (adopted in May 2024) recognises the contribution of gaseous fuels to system flexibility. It updates the legal framework for gaseous fuels, outlines the role of gas and hydrogen TSOs in planning optimal electrolyser locations and sizes, and facilitates the integration of hydrogen. Provisions also support third-party access to hydrogen infrastructure and the injection of low-carbon gases such as biomethane.

The *REPowerEU Plan* (2022) adds flexibility considerations in the context of energy security and accelerated clean energy deployment, including measures for demand response and storage. It sets specific targets for renewable gases, including hydrogen and biomethane.

Several public consultations launched by the European Commission that started in 2024 are expected to influence the regulatory treatment of flexibility, including the Energy Security Consultation (Fitness check evaluating EU energy security architecture) and the Consultation on Infrastructure Criteria for Renewable Integration[11]. These consultations are expected to address demand-side flexibility, infrastructure prioritisation, and resilience metrics. Consultations on the on the draft network code on demand response and the one regarding the methodology for flexibility assessments have also been completed, with draft texts ready for analysis.

The *European Resource Adequacy Assessment (ERAA),* conducted by ENTSO-E, focuses solely on electricity. Discussions are ongoing to expand the scope to consider flexibility contributions from other sectors, including gas and hydrogen, as well as demand-side measures and storage.

The increasing focus on flexibility in the EU has prompted the development of cross-sectoral analytical tools and metrics to support integrated planning and investments. One such tool is the joint cross-sector Cost-Benefit Analysis (CBA) methodology developed by ENTSO-E[12]and ENTSO-G, which provides a harmonised approach to evaluating infrastructure projects that span both electricity and gas systems. This framework enables the assessment of the combined value of investments — such as electrolysers, power-to-gas facilities, or shared storage assets — that contribute to system adequacy, decarbonisation, and operational flexibility.

In parallel, there have been advances in work on economic valuation metrics relevant to security of supply and system planning.[13] These include Value of Lost Load (VoLL) and Cost of Disrupted Gas (CoDG) and Hydrogen (CoDH), which aim to quantify the societal and economic impact of supply interruptions across different vectors. While electricity is expected to become the predominant energy carrier in the decarbonised system, the inclusion CoDG, and CoDH provides an analytical basis to assess the contribution of decentralised gas infrastructure — such as biomethane and hydrogen-ready distribution networks — as sources of long-duration or locational flexibility. For gas distribution system operators, these developments offer a potential avenue for formal recognition of the role that gas assets may continue to play in enhancing resilience and balancing, particularly during seasonal demand peaks or periods of electricity system stress.

[11] https://errin.eu/news/european-commission-launches-consultation-2025-research-and-technology-infrastructure-strategy

[12] https://www.entsoe.eu/news/2024/05/07/entsog-and-entso-e-publish-their-joint-electricity-and-hydrogen-interlinked-model-2024-progress-report-for-public-consultation/

[13] https://www.entsog.eu/sites/default/files/2023-02/ENTSOG%20Preliminary%20Draft%20CBA%20Methodology_for%20Consultation.pdf

In conclusion, the EU’s policy framework for flexibility includes multiple layers of binding and non-binding instruments, touching on electricity, gas, and hydrogen. These frameworks reflect a growing emphasis on the role of flexibility in delivering a decarbonised energy system.

3.1.2. Embedding-Based Textual Analysis

This subsection reports the results of a corpus-based study that maps how recent EU documents frame **energy-system flexibility**. Eleven texts, among directives, regulations, strategy papers and methodological reports were selected on two criteria: **(i) publication date** (all date from 2019-2024) and **(ii) recognised influence on energy system operation or planning** (see Appendix A- Documents used in the textual analysis for the full list). Although the corpus is not exhaustive, its breadth is sufficient to reveal robust trends in the evolving discourse on flexibility. Because these texts differ markedly in length and purpose, most term frequencies have been **normalised per 1 000 words** to ensure comparability.

Figure 3 displays the normalised count of the word ‘*flexibility’* across the corpus. As expected, legally binding instruments mention the term more frequently than high-level policy communications; nonetheless, the *Action Plan for Affordable Energy* stands out for its unusually frequent use, exceeding that of all other Commission communications.

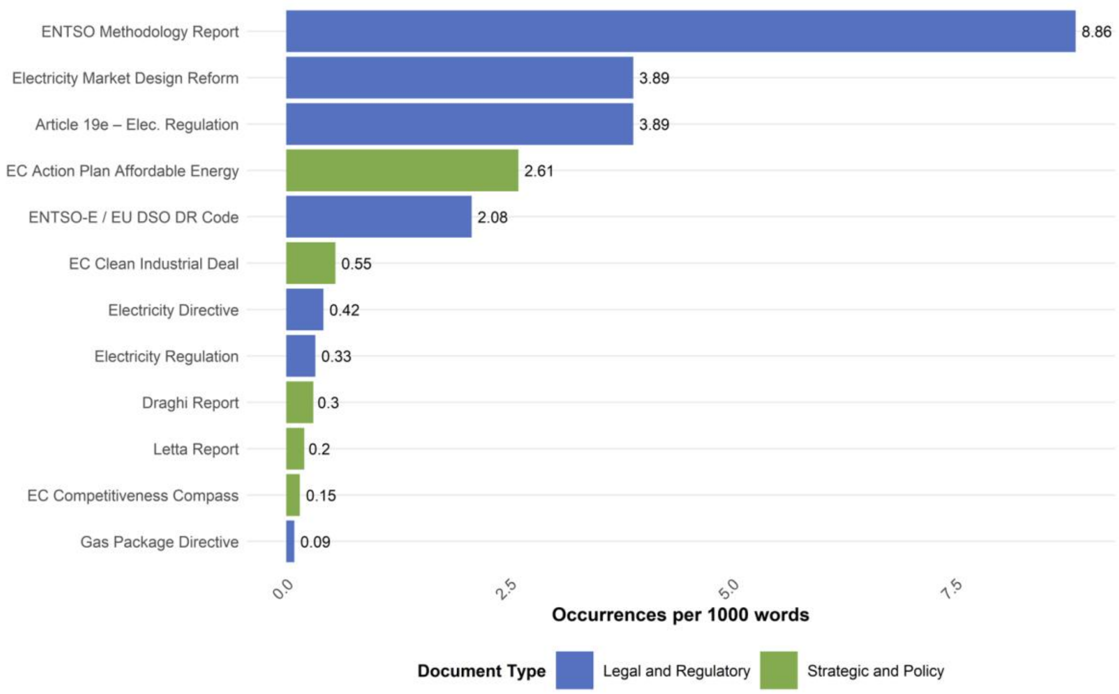

Figure 3: Frequency of "Flexibility" by Document

Simply counting how often ‘*flexibility*’ appears is informative but incomplete. Hence, to grasp what the term actually means in each context, we examined the words that surround it and adopt an embedding-based analytical procedure.

The Embedding-Based Textual Analysis Approach

To probe how flexibility is conceptualised, we applied an embedding-based textual analysis. Word embeddings capture the semantic neighbourhood of each token, allowing us to group linguistically similar usages that may appear in different syntactic forms. For every occurrence of *'flexibility',* we extracted a ±5-word window, then manually verified and coded each snippet into a precise keyword.

For ease of interpretation, the extracted keywords were consolidated into five analytical categories, each capturing a distinct aspect of flexibility:

1. **Demand-side** keywords concern the *actors* who modify their consumption, covering consumer participation, demand-response programs, and other delegation mechanisms.
2. **Supply-side** terms refer to the *resources* that deliver flexibility, including clean or low-carbon generation, storage technologies, and other physical assets.
3. **Market-mechanism** keywords describe the *economic signals*—price incentives, investment cues, and regulatory barriers—that govern the deployment of flexible options.
4. **Assessment** terms relate to *analytical processes*: identifying flexibility needs, maintaining registers, and developing planning methodologies.
5. **System** keywords characterise the *spatial or temporal context* in which flexibility operates, such as grid-level coordination or system-wide balancing over various timeframes.

These five lenses — (1) *who flexes demand*, (2) *which resources supply it*, (3) *what market signals trigger action*, (4) *how much flexibility is deemed necessary*, and (5) *at what grid scale or time horizon it must be delivered* — form the conceptual framework for the subsequent analysis, summarised in Figure 4.

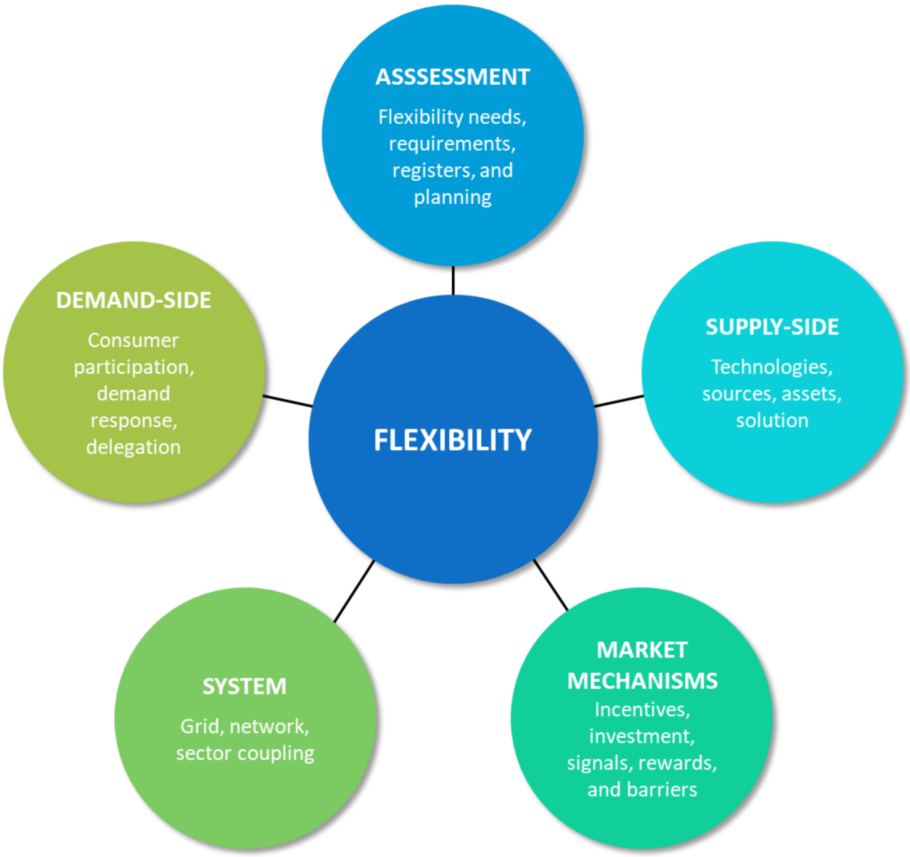

Figure 4: Conceptual Categories of Flexibility
Source: Authors.

Dominant Concepts

Figure 5 presents the 25 keywords most frequently linked to *'flexibility'* and groups them by colour. There is a clear dominance of *assessment*-related terms (yellow), such as *'flexibility means*' and '*flexibility register,'* underscoring the focus on diagnosing flexibility requirements. The two next-largest clusters are *supply-side* (light blue), which encompasses expressions such as *'non-fossil flexibility*' or *'flexibility resource,'* and '*system'* (pink). By comparison, keywords tied to the '*demand-side'* (blue) and '*market mechanisms'* (brown) occur far less often.

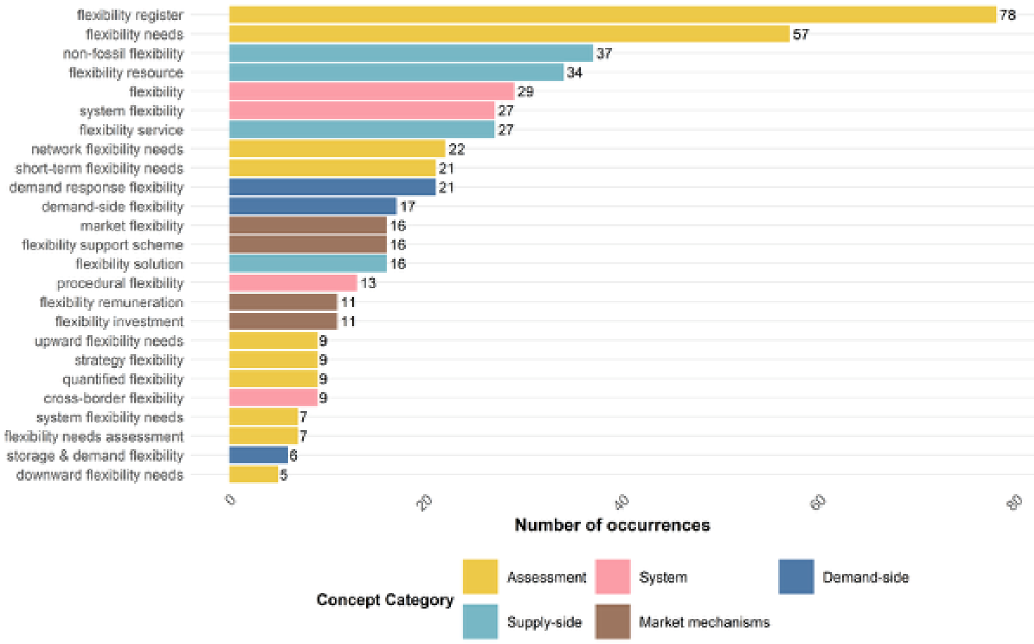

Figure 5: Top 25 Keywords Associated with 'Flexibility'

To gain a better understanding of how flexibility is characterised across the different documents, we conducted textual analysis with embeddings by document.

Flexibility concept groups by documents

We distinguished between legal documents (Figure 6) and policy documents (Figure 7). The bubble charts illustrate the frequency of occurrences across various documents (vertical axis) and different regulatory concepts (horizontal axis).

The *ENTSO Methodology Report* stands out for containing the most references, particularly to flexibility-needs assessment and system flexibility (each exceeding 100 mentions). The *ENTSO-E / EU DSO DR Code* also places substantial emphasis on assessment topics.

In contrast, the *Electricity Market Design Reform* and *Electricity Directive* offer a more balanced coverage across all five flexibility categories, whereas *Article 15e of the Electricity Regulation* records fewer references in every category.

Notably, the *Gas Package Directive* makes only a few references to flexibility, so few that no single concept group stands out, highlighting its limited engagement with the topic.

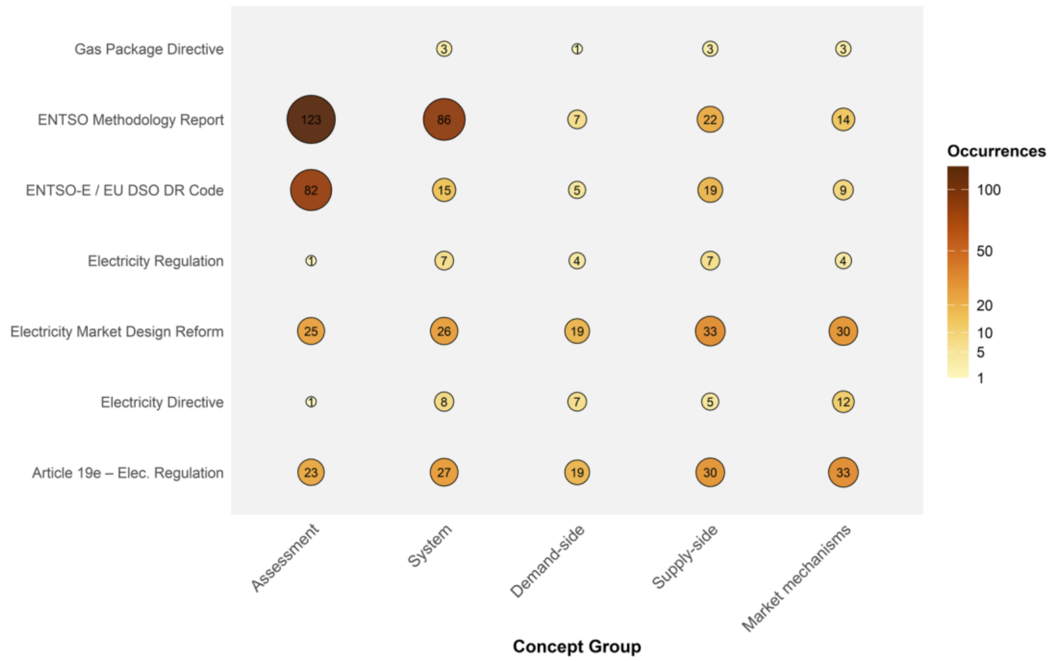

Figure 6: Flexibility Concept Groups across Legal Documents
Note: Circle size and colour intensity indicate number of occurrences.
Source: Authors.

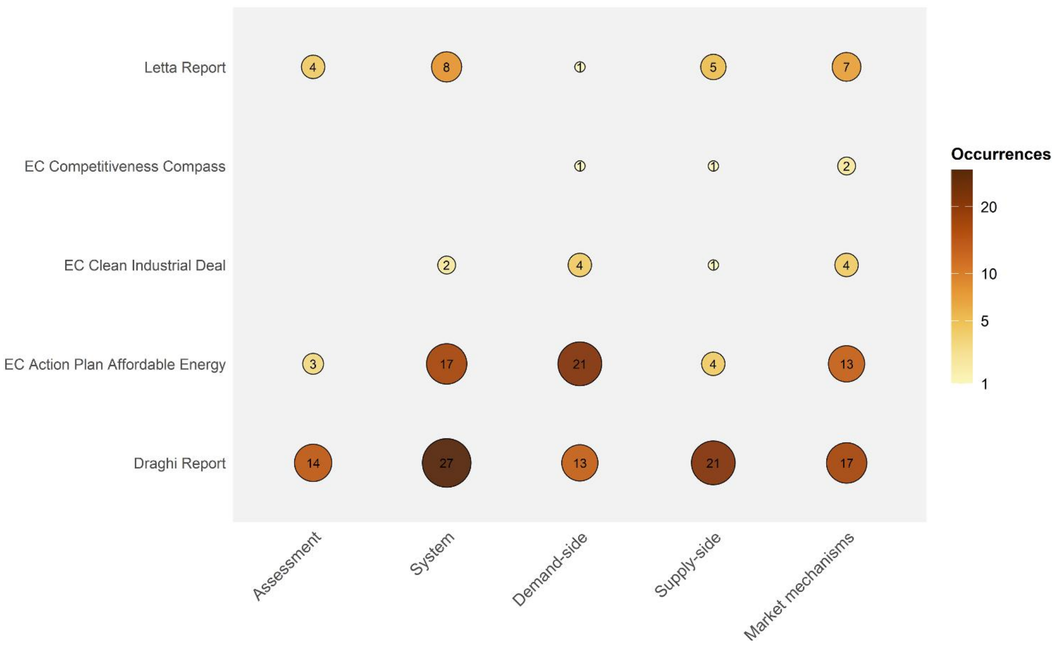

Figure 7: Flexibility Concept Groups across Policy Documents
Circle size and colour intensity indicates number of occurrences.
Source: Authors

Overall, methodology-oriented documents concentrate heavily on assessing flexibility requirements, whereas market-focused texts provide a broader, but less intense, coverage of the flexibility landscape.

Among the policy documents that were analysed (Figure 7), the *Draghi Report* features the most frequent references to flexibility concepts, displaying consistently high engagement across all categories, including a strong emphasis on *'system flexibility'* (dark red bubble) and significant mentions of other concepts (orange-red bubbles). The *Action Plan for Affordable Energy* follows closely, particularly in terms of demand-side management. The *Letta Report* reflects a moderate level of engagement (yellow-orange bubbles), with slightly more focus on 'market mechanisms' and '*Flexibility needs assessment*.' In contrast, the *Competitiveness Compass* and the *Clean Industrial Deal* show minimal attention to flexibility, as indicated by smaller, pale-yellow bubbles.

Taken together, the findings depict a regulatory discourse that diagnoses flexibility requirements and system flexibility in considerable detail but allocates less textual space to the actors, market mechanisms, and technologies responsible for delivering it. The next section, therefore, turns to those enablers — TSOs, DSOs, aggregators, local market operators, collective self-consumption schemes, and digital platforms — by exploring how they understand and implement the regulatory expectations surrounding flexibility outlined in this subsection.

3.2. Enablers

Technologies can deliver the required flexibility only when supported by specific enablers.

Network and system operators play a critical role in creating incentives for using and providing flexibility, while new actors such as aggregators, along with advances in digitalisation, increasingly contribute to enabling flexibility across the system.

3.2.1. Energy Grids DSO and TSO

Energy grids allow for spatial flexibility, which is especially important given the high penetration of intermittent renewables. Through trade, electricity can be transported from areas with excess supply to those with high demand, facilitating geographical smoothing of intermittent power. Europe is already well connected with coupled wholesale electricity markets; however, issues and costs related to connecting new renewable investments, particularly offshore wind, persist. According to 2050 net-zero scenarios, the share of trade in final consumption is expected to at least double compared to the situation in 2018 (Chyong et al., 2024).

The inherent unpredictability of renewable generation increases forecast errors, thereby demanding more resources to smooth out the imbalances. This explains the growing role of DSOs responsible for managing flexibility in the modern medium and low-voltage grid. However, the efficient management of DER requires access not only to consumption data but also to the small-scale production data of prosumers who are often connected to the distribution grid behind the meter. The information on their net consumption (consumption minus own generation) is only available to the DSOs.

The literature highlights a potential conflict of interest when TSOs and DSOs procure flexibility services in the same market, such as who should have priority over available resources (Burger et al. 2019;

Gerard et al. 2018) and how to balance the overall grid when solving local congestion issues (Hadush and Meeus, 2018).

3.2.2. Aggregators

Due to technological, economic, behavioural, or knowledge constraints, small consumers cannot participate in the energy markets. Therefore, aggregators have become an increasingly important group of flexibility providers.

In the EU, the Energy Directive 2019/944 and the Clean Energy Package promote resource aggregation; yet many Member States have still not embedded these principles in national law (Moura & Brito 2019). Early research distinguished between 'load aggregators,' which shift residential consumption, and 'production aggregators' or virtual power plants that coordinate distributed generators (Lu et al. 2020; Burger et al. 2017). The concept has since broadened: modern aggregators may combine both functions, integrate storage and any other distributed energy resource, and operate assets linked only by communication networks. Typical operational tasks include real-time optimisation of HVAC schedules in smart buildings, coordinated charging of city-wide EV fleets, and dispatch of aggregated rooftop PV to ease local congestion (Rodriguez et al. 2024).

Lu et al. (2024) divide the resources managed by aggregators into three categories. (1) Consuming resources—shiftable or curtailable loads such as heat pumps, washing machines or industrial processes—can provide ancillary services from peak shaving to frequency regulation. (2) Producing resources comprise small-scale wind, solar, hydro and CHP units that inject power. (3) Bi-directional resources include stationary batteries and EVs capable of vehicle-to-grid exchange. Assets need only a data link, not physical proximity, to be pooled, giving aggregators access to households, SMEs and prosumers using behind-the-meter technologies.

Balancing economic incentives, operational simplicity, and consumers' tolerance for risk and loss of control is central to designing an effective contract. Five contract archetypes shape aggregator–customer relations: time-of-use tariffs, dynamic pricing, fixed load capping, dynamic load capping, and direct load control. Drawing on the framework of He et al. (2013), they can be compared across seven attributes — signal form and volatility, price and volume risk, financial upside, complexity, and loss of autonomy. Price-based contracts use tariff signals to elicit responses; volume-based contracts restrict demand within agreed bounds; control-based contracts assign appliance operation to the aggregator. Static contracts, such as time-of-use tariffs or fixed caps, announce signals well in advance and remain stable for long periods. Dynamic contracts track wholesale prices in near-real-time, improving system efficiency but exposing consumers to higher price or volume risk and greater decision-making complexity. Direct load control is simpler for the user because the aggregator manages devices; however, it reduces autonomy.

3.2.3. Local Flexibility Markets

Local flexibility markets are regulated in the electricity market design, which states that Member States' regulation should be adjusted to incentivise DSOs to use flexibility services provided by Distributed Energy Sources, i.e. distributed generation, demand-side flexibility, and energy storage.

The aim of creating flexibility markets is to enable the participation of DES in providing flexibility as a service/product. Flexibility can be used for various purposes, e.g., for congestion management and redispatch, system balancing, and for the Balancing Responsible Parties to balance their portfolios. Schittekatte and Meeus (2020) review the literature and identify six controversies focusing on the design of such markets. One of the issues is the design of the trading platform. It could be a separate platform dedicated to congestion management where DSOs, and optionally also the TSO, act as buyers for flexibility services, or another option is to introduce an integrated market model which allows DSOs to purchase flexibility for congestion management via access to existing short-term wholesale markets. The second controversy is who should operate the market i.e., be responsible for setting the platform, clearing the market, and settling the transactions. Potential solutions include a neutral market facilitator who assures equal market access for participants but is not necessarily involved in operating the market (ENTSO-E: 2019); a market operator independent from market operations (Burger et al. 2019; Stanley et al.; 2019). Some authors argue that the choice about the operator depends on the type of market i.e., separated, or integrated (Gerard et al; 2018). The third issue is the question of whether flexibility should be traded in long or short-term contracts (ENTSO-E, 2019; Schittekatte and Meeus, 2020). The fourth design issue focuses on the standardisation of flexibility products at both the Member State and EU levels (ENTSO-E, 2019; CEER, 2018).

3.2.4. Collective Self-Consumption

The emergence of smart grids is reshaping consumer behaviour in the electricity market. Unlike traditional consumers, who passively purchase and receive energy from the grid, prosumers actively manage both their consumption and production. Prosumers, who are both consumers and producers of electricity, can generate power for self-consumption, reducing their electricity bills; store excess energy for future household use, or exchange it with the broader community. These exchanges occur through P2P electricity trading platforms or within emerging energy communities (Sousa et al., 2019). The interactions between prosumers and the grid depend on several factors, including the tariff cost structure and the price offered by the grid for purchasing surplus electricity, as prosumers respond to these prices to obtain monetary gains (Ottesen et al., 2016; Gautier et al., 2018, 2021).

By sharing surplus energy within a community, prosumers contribute to collective self-consumption, enhancing overall efficiency and sustainability. The concept of collective self-consumption expands on the idea of prosumers generating electricity for their own use while selling excess energy to the local collective. This exchange can take place through peer-to-peer (P2P) trading, within the same building, or within an energy community (Alam et al., 2017; Zafar et al., 2018; Zhang et al., 2018; Sousa et al., 2019).

The continuous integration of Distributed Energy Resources, alongside advancements in Information and Communication Technology, such as smart meters and P2P electricity trading platforms, is fostering greater participation of new actors in electricity production. P2P electricity trading platforms introduce a transformative shift in the electricity market, making it more dynamic and decentralised. These platforms exhibit strong network effects, where the value of participation increases as more users engage with the platform or with compatible products (Cortade and Poudou, 2022). Direct network effects occur as a growing number of participants enhance liquidity, reduce transaction costs, and improve price efficiency. Indirect network effects emerge as complementary services—such as smart meters, energy management systems, and demand response programs—expand in response to a growing user base. P2P electricity trading enables direct energy exchange among participants, allowing locally generated energy from small-scale DERs in homes, offices, and industrial facilities to be traded between prosumers and energy consumers. This collaborative approach enhances investment flexibility, whose value is influenced by factors such as technology adoption costs and the shape of electricity demand curves (Castellini et al., 2021). The effectiveness of these platforms depends on the heterogeneity of households in terms of consumption and load (Cortade and Poudou, 2022).

Energy communities, composed of citizens, social enterprises, public institutions, and community organisations, play a crucial role in the energy transition by collectively investing in, producing, selling, and distributing renewable energy, but also by enabling decentralised energy flexibility through controllable local resources and by enhancing grid efficiency via high collective self-consumption. As legal entities, energy communities invest in decentralised production units, generating electricity that can be sold to their members or to the grid when production exceeds local consumption. While energy communities introduce additional complexity to the electrical system—originally not designed to accommodate their role—this complexity is offset when their collective self-consumption rate is sufficiently high, strengthening direct network effects (Gautier et al., 2025). Their role is reinforced in the Renewable Energy Directive (EU) 2018/2001 and Electricity Market Directive (EU) 2024/1711.

3.2.5. Digitalisation

There are hardly any aspects of flexibility that are not impacted by digitalisation. As part of the energy system's digitalisation, smart meters have played a critical role in enabling flexibility. By the end of 2021, 54% of European households had a smart electricity meter, rising to around 80% by 2023 (ACER, 2024).[14]

Smart meters record energy usage at 30-minute intervals, allowing suppliers to offer dynamic tariffs that lower costs during off-peak hours or periods of high renewable generation (Bardow et al., 2023). Besides this "energy flexibility" value stream, it is also possible to consider a "grid flexibility" value for customers.

Smart meters also empower consumers to adjust their consumption based on real-time price signals, supporting demand-side response initiatives and improving grid stability. Figure 8 illustrates the growth in smart meter adoption in Europe.

More generally, flexibility requires the cost-effective adjustment of the system to predicted or unpredicted changes in supply and/or demand. Digital technology can (and already does) help significantly to enhance this process in three main ways: data acquisition and processing (through sensors and communication networks).

For the very short run, sensors can help generate quasi-real-time data from the network, and remote control and automation technologies can enable rapid action based on that data. For example, IoT enabled equipment can provide information on supply, demand, and the state of the network on a continuous basis. This can help to optimise grid operations in response to rapid changes.

[14] See at https://energy.ec.europa.eu/topics/markets-and-consumers/smart-grids-and-meters_en#:~:text=According%20to%20the%20EU%20Agency,at%20the%20end%20of%202022.

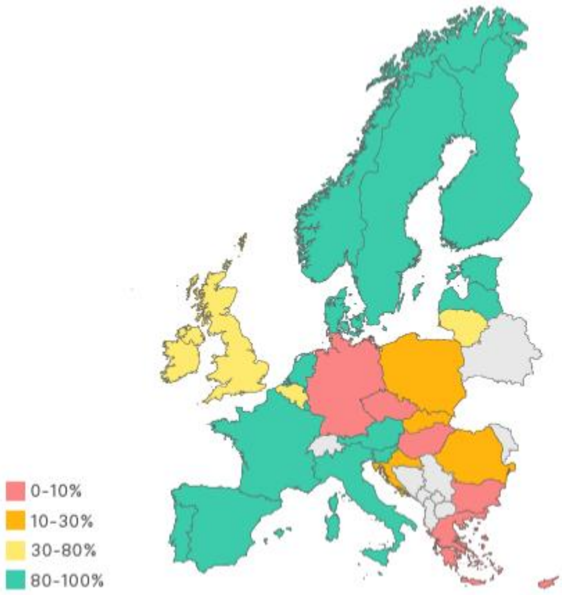

Figure 8: Roll-Out of Smart Meters among Households across Member States, EEA Member Norway, and Great Britain – 2023 (%)
Source: ACER.

For the short run, digitalisation can enable optimised DER management, helping to match demand with the VRE supply and to control DERs by ramping up or down EV charging, hybrid heat pumps, or battery storage. At the system level, digitalisation can enable dynamic pricing (linked to DER management) with the help of smart meters. In addition, AI/ML can improve forecasting accuracy both for VRE supply and load (IEA, 2023b).

For the longer run, AI and digital simulations can improve the planning processes and investment decisions in flexibility-enhancing infrastructures like interconnectors, storage, and flexible industrial and residential demand.

To navigate through all these potential applications of digital technology to enhance flexibility, DG Energy (2022) uses a framework to categorise and select the use cases and business models that show the greatest potential. The criteria include the type of flexibility provided (ancillary, wholesale, or grid/congestion), the amount of flexibility potential (in terms of adjustable power and adjustable energy), the degree of maturity of the solutions, and the requirements for structural change for them to be possible. This results in a list of 8 use cases and 14 business models of digitally enabled flexibility solutions.

These include DER management, VPPs with various applications (including hydrogen and biomethane), energy communities, industrial load control, home automation, EV smart charging, and V2G. All are seen as made possible by TSO and DSO grid automation and optimisation as well as system pricing that reflects the time, pattern and location of generation and consumption, which is also enabled by digitalisation.

Some of the relatively mature and high-potential digitally enabled flexibility use cases are EV smart charging, VPPs for ancillary services and for internal balancing, and on-site building optimisation for commercial HVAC. Home automation and V2G are also seen as high-potential solutions, but they are still in the pilot/demonstration phase and/or require significant structural changes.

However, digital solutions are not without their challenges. They have significant data sharing and privacy implications and generate important costs in terms of computing and communication networks (see Section 2.2.3. AI and Data Centres).

Chapter 4. Remaining Flexibility Issues

As mentioned in the previous chapter, the EU regulatory framework provides a solid foundation for flexibility, though some gaps remain. Existing and forthcoming regulatory initiatives, along with recently issued strategic and policy documents, address the key gaps in enhancing energy sector flexibility. They aim to facilitate all forms of flexibility, both temporal and technological, and promote an integrated approach between electricity and gaseous fuels.

However, regulation alone is insufficient. Simply enforcing or transposing legislation does not guarantee implementation when structural or economic barriers persist. For example, despite the requirements of Electricity Directive 2019/944, some countries have yet to deploy smart meters or fully use them for dynamic pricing (ACER & CEER, 2024).

This section highlights outstanding flexibility challenges that require more than EU-level regulatory intervention. These challenges are grouped into five categories: generation (upstream), storage, demand-side, transmission, and distribution (T&D), and system-level solutions.

In connection with these remaining flexibility challenges, we propose nine flexibility solutions and illustrate them through case studies from various countries, highlighting different business models and regulatory approaches that demonstrate how these challenges can be addressed in practice. This list is not exhaustive; we excluded topics like interconnection and industrial demand-side flexibility, as they are already major priorities with well-identified barriers and are addressed in the regulatory framework discussed in the previous chapter. Although some categories may overlap (e.g., price signals and smart meters), we treat them separately for the sake of clarity. Table 4 summarises the context, solution, key features, outcomes, as well as the case studies related to each category .

4.1. Flexibility Solutions in Practice

4.1.1. Generation/Upstream

Incentivising Generation Units to Reduce Flexibility Needs

Denmark, a world leader in wind energy (producing almost 60% of electricity generation in 2023), offers a strong example of supply-side flexibility interventions. This has been made possible by policy and market interventions, including reforms targeting combined heat and power (CHP) plants. Through regulation and incentives, CHP plants were required to decouple heat and electricity production and encouraged to adopt thermal storage where feasible. This encouraged the flexible operation of these plants, ramping electricity generation up and down depending on the amount of wind generation.

Additionally, Denmark promoted system-friendly behaviour from wind generation itself. Advanced wind forecasting systems reduced uncertainty, allowing wind farms to participate in balancing markets (as a pilot). Market designs exposing wind producers to spot and balancing prices further incentivise better forecasting, portfolio management, and price-responsive dispatch. Together with strong interconnections and demand-side flexibility, these measures have made Denmark a living laboratory for high VRE (variable renewable energy) integration.

Table 4: Flexibility Solutions in Practice

Category	Flexibility Type	Focus Area	Impact	Actors & Country
Generation/ Upstream	Supply-side (Generation)	Flexible CHP Operation	Enhanced VRE integration and grid balancing	CHP Plants, Wind Sector Policies (Denmark)
	Supply-side (Bioenergy)	Biogas Plant Flexibility	Enabling biogas plants in reserve markets	Next Kraftwerke, Biogas Sector (Germany)
Storage	Mobile Storage (EVs)	Vehicle-to-Grid (V2X) Storage	Distributed peak shaving and emergency grid support	PG&E, CPUC (USA - California)
	Stationary Storage	Community Battery Storage	Improved local grid stability and solar integration	Ausgrid, ARENA (Australia)
	Hydrogen Storage & Grid Services	Hydrogen Electrolysis Flexibility	Dual-revenue model; participation in PCR market	Shell Rhineland, REFHYNE Project (Germany)
Demand	Demand-side Response	Dynamic Pricing & Demand Response	Consumer load shifting; energy bill savings	National Utilities and Consumers (Sweden)
	Demand-side Enabling Technology	Smart Meter Rollout & DR	Consumer engagement in dynamic tariffs and DR programs	ARERA, Italian DSOs (Italy)
Transmission & Distribution	Distributed Energy Resources (DER)	Dynamic Operating Envelopes	Increased DER integration and deferred investments	Australian DSOs, National Guidelines (Australia)
	Local & National Flexibility Market	DSO-TSO Coordination	Coordinated flexibility procurement across grids	Svenska Kraftnät, Vattenfall, Ellevio (Sweden)
System	Integrated Gas-Electricity Demand Shifting	Dual-Energy Heating Program	Peak demand reduction and deferred investments	Hydro-Québec, Energir (Canada - Québec)
	System-wide Market Coordination	Aggregator Participation Platform	Simplified registration of distributed flexibility assets	Ofgem, Elexon (United Kingdom)

Use Bioenergy Opportunities

Bioenergy in various forms can contribute to flexibility based on regional and country-specific conditions (Schipfer *et al.*, 2022; Chyong *et al.*, 2024). The potential for flexibility contributions is widely believed to be underused. For example, in Germany, biomass (mainly through biogas) represents 8.8% of electricity generation, and significant efforts have been made to incentivise these plants to feed into the grid at times of high prices (IEA Bioenergy, 2024). A flexibility bonus has been in place since 2012 for biomass-based electricity (and heat) plants, but success has been limited.[15]

A case study from Next Kraftwerke highlights how a 2.2 MW biogas CHP plant in Lower Saxony transitioned from a fixed feed-in model to flexible operation, providing secondary reserves to the system (aFRR).[16] Using the flexibility bonus introduced in 2012, the plant adopted the market premium model and began participating in spot markets and control reserve markets. The plant was integrated into Next Kraftwerke's Virtual Power Plant (VPP) by installing a remote-control unit that enabled real-time communication and control. Consequently, the biogas plant's combined heat and power (CHP) units were operated remotely, adjusting output in response to grid demands, with operators receiving both capacity payments and activation remuneration for their services.

The model demonstrates the potential for biogas plants to enhance energy system flexibility.

4.1.2. Storage

Mobile storage - PG&E's Vehicle-to-Everything (V2X) Program

Pacific Gas & Electric (PG&E), together with the California Public Utilities Commission (CPUC), launched V2X pilots in 2022 to explore the use of electric vehicle (EV) batteries for grid services. The pilots target residential, commercial, and community microgrid use cases. Participants install bidirectional chargers and enrol in an emergency load reduction program which offers $2/kWh for energy injected during peak emergencies (typically 4–9 PM on high-demand days). The V2X pilots aim to demonstrate backup power capabilities (vehicle-to-home/building), shifting of EV charging to off-peak times, and dispatch of EV energy to the grid to improve reliability. PG&E has set a goal of 2 million EVs participating in grid integration by 2030.

A significant application is the Oakland School District's 100% electric school bus fleet (74 buses, each with 140 kWh batteries).[17] Managed by an AI-driven VPP, the fleet offers 2.7 MW of bidirectional charging capacity, feeding an estimated 2.1 GWh annually into the grid. Buses can charge during midday and discharge during evening peaks, effectively operating as distributed batteries to offset gas peaked plants. Though still in the pilot stage, this program demonstrates the scalability of EV batteries for demand response, peak shaving, and backup power services.

[15] https://biogas.fnr.de/biogas-nutzung/stromerzeugung/stand-der-flexibilisierung-von-biogasanlagen
[16] https://www.next-kraftwerke.com/vpp/case-studies/biogas-secondary-reserve
[17] https://www.pge.com/en/newsroom/currents/future-of-energy/articles-4040-pge-helps-zum-deploy-nations-100-electric-school-bus-fleet-oakland-new-school-year.html

Stationary storage - Australia's experience with utility-scale batteries

Ausgrid has implemented several grid-connected battery storage projects to explore the role of storage in improving local network reliability and enabling greater flexibility. The Newcastle Community Battery - a 250 kWh/500 kW lithium-ion battery commissioned in 2020 - was designed to manage peak load, absorb excess rooftop solar output during the day, and release it during the evening peak. The battery was one of the first in Australia to be placed 'behind the transformer,' i.e., within the distribution network, rather than at customer or transmission level.

One of the key lessons is the value of network-side storage: Ausgrid reported smoother voltage fluctuations and reduced reverse power flows on sunny days. The project also highlighted important regulatory questions that may be relevant in an EU context. DSOs in Australia cannot provide frequency control ancillary services or monetise the full value of the battery. Nevertheless, the pilot is seen as successful, and Australia is planning to fund 400 community batteries in the network, with an aggregated storage capacity of up to 281 MWh,[18] according to the Department of Climate Change, Energy, the Environment and Water.[19]

Hydrogen-Related Pilots

The REFHYNE 1 project, located at Shell's Rhineland refinery, demonstrates the integration of large-scale hydrogen electrolysis with grid management strategies. The project uses a 10 MW Proton Exchange Membrane (PEM) electrolyser, producing approximately 1,300 tons of hydrogen per year (about 1% of the current hydrogen use at the refinery).

A key feature of the project is its operational flexibility. The electrolyser is designed to operate in a responsive mode, adjusting its hydrogen production based on the refinery's internal electricity demands. This flexibility not only helps balance the refinery's internal grid but also enables the facility to participate in Germany's Primary Control Reserve (PCR) market. By providing ancillary services to the national grid, the electrolyser contributes to the overall stability and reliability of the grid.

The project's business model combines hydrogen sales for refinery processes with revenues from grid balancing services, demonstrating a dual-revenue approach to ensure the viability of large-scale electrolyser. Building on the success of REFHYNE 1, an investment decision has been made to move forward with REFHYNE II, which will scale operations up to a 100 MW electrolyser. This expansion underscores the growing interest in hydrogen's role in decarbonisation, storage, and grid management.

4.1.3. Demand Side

Price Signals and Demand Elasticity

Sweden is a notable case of a significant share of consumers having retail contracts with dynamic pricing (Hindman Persson, 2020; ACER & CEER, 2024). Price signals in Sweden primarily take the form of dynamic tariffs, but so far there is limited integration with local flexibility markets, which remain in a pilot phase. The country is also implementing changes to network tariffs to allow for variable

[18] https://arena.gov.au/news/arena-funds-national-community-battery-roll-out/
[19] https://www.dcceew.gov.au/energy/renewable/community-batteries

components and incentivise shifts in consumption that reflect network constraints. By 1 January 2027, all Swedish grid companies must implement time-of-use tariffs under regulation EIFS 2022:1, aiming to reflect grid conditions and promote demand-side flexibility through cost-based price signals.[20]

The results are starting to emerge. During the energy prices crisis caused by the post-pandemic recovery and the Ukraine war, there has been a notable shift in consumer behaviour. During this period, households on dynamic hourly electricity price contracts - those whose electricity costs were directly linked to wholesale market prices - achieved significant savings (ACER & CEER, 2024).

As wholesale electricity prices spiked (especially in 2022), fixed-price contracts became more expensive and many of the consumers whose fixed-price contracts expired opted to switch to variable price contracts, hourly (soon quarterly) and monthly average price. By 2024, in one of the Swedish bidding zones (the South zone SE4 that includes Malmo), only around 5% of households remained on fixed-price contracts, while over 64% moved to monthly spot-based pricing and 13% to dynamic contracts on an hourly basis. This shifting potential is significant, due to the reliance on electricity for heating. Over 1 million homes use heat pumps in the country, hence the potential to reduce bills, reduce wholesale prices and grid congestion is relevant.

In parallel, Sweden has begun implementing time-differentiated and demand-based distribution network tariffs that incorporate forward-looking components. These tariffs aim to encourage consumers to reduce demand during constrained periods on the distribution grid. However, currently there is not enough information to evaluate their progress.

Sweden’s experience illustrates the economic value and systemic benefits of enabling household-level demand flexibility when supported by dynamic pricing structures and suitable enabling technologies.

Smart-Meter and Data Sharing

Sweden was an early mover in smart metering, completing its first nationwide rollout by 2009 and currently finalising a second-generation upgrade (AMI2) by 2025. These advanced meters enable hourly readings, real-time data access, and two-way communication — laying the groundwork for time-of-use tariffs, demand-side flexibility, and integration into local flexibility markets. Similarly, Italy began its national smart meter rollout in 2001 and made installation mandatory from 2011, becoming one of the first European countries to reach 80% coverage — second only to Sweden. The first-generation (1G) smart meters enabled basic functionalities, including remote readings, connection and disconnection, and modulation of power levels. In 2016, the Italian energy regulator ARERA established the technical requirements for second-generation (2G) smart meters, which offer significantly enhanced capabilities. These include flexible switching (no longer limited to the first day of the month), and direct access for consumers to detailed consumption data at 15-minute intervals via connected devices such as smartphones. This real-time visibility supports greater consumer awareness and facilitates engagement with dynamic pricing offers. Moreover, 2G smart meters are designed to support demand-side response by enabling remote load control and, in the future, the provision of ancillary services to the electricity system. As of January 2022, all new installations must use 2G meters, with regulatory targets aiming for 90% deployment by 2025 and 96% by 2026. By the end of 2021, approximately 50% of existing 1G meters had been replaced. Thanks, in part, to the

[20] https://ei.se/bransch/tariffer-nattariffer/vagledning-for-utformning-av-nattariffer-enligt-eifs-20221

availability of smart meters, the Italian regulatory framework has evolved to support DR initiatives (Del Greco, Losi and Mauro, 2022). Mechanisms such as the “Unità Virtuali Abilitate Miste” (UVAM), Mixed Virtual Enabled Units, and “Unità di Consumo per il Mercato della Capacità” (UCMC), Consumption Unit for the Capacity Market, have been introduced to encourage flexible consumption, small-scale generation, and storage to participate in the ancillary services market (MSD). These structures allow for the aggregation of distributed energy resources, enabling a more flexible energy system. While there is not enough data to evaluate the impact of these two mechanisms, the fact that they were launched is an example of the enabling effect of large-scale smart meter penetration.

4.1.4. Transmission and Distribution

DSO Flexibility

The Dynamic Operating Envelopes (DOE) initiative is intended to evolve static injection limits into dynamic, time- and location-sensitive constraints that better reflect real-time network capacity and allow for more flexible injection of customer-generated energy (ARENA, 2022). DOEs offer an adaptive mechanism that permits greater injections when capacity allows, while curbing them during periods of local or system-wide congestion. This enhances system-wide flexibility and defers the need for costly infrastructure upgrades. DOEs are calculated by DSOs based on local network conditions and can be communicated in real-time to DER-enabled devices using a dedicated communication protocol. Devices receiving the signal then adjust injection levels accordingly. This shift enables DER integration and customer participation in flexibility services, potentially enabling new applications such as smart EV charging or load orchestration at the household level. Some of the Australian DSOs have received regulatory approval to integrate DOEs into their offering for solar customers. The government and the regulator are working on guiding the expansion and standardisation of DOEs and the Common Smart Inverter Profile is being adopted as the national communications standard. In some Swedish regions like Uppland and Skåne, the DSO used market-based flexibility services during the winter season (November–March) to manage local grid congestion, reducing peak demand by activating resources such as heat pumps, electric boilers, and batteries through coordinated day-ahead and intraday markets.[21]

DSO-TSO Coordination

The sthlmflex project in Sweden illustrates collaboration between TSOs and DSOs. Started in 2020, the project involves Svenska Kraftnät (TSO), Vattenfall Eldistribution (DSO), and Ellevio (DSO), with NODES serving as the market operator. The primary objective is to address capacity constraints in the Stockholm region by procuring flexibility services from various providers.

Flexibility services are provided by aggregators, building operators and industrial users. Aggregators pool smaller distributed energy resources - heat pumps and batteries (including EVs) - to meet the market’s minimum bid size of 1 MW. For example, the Stockholm School Properties Company integrated around 50 school buildings into the sthlmflex market. The schools adjust their electricity consumption during peak demand periods, contributing to grid stability without loss of comfort.

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[21] https://www.svk.se/siteassets/2.utveckling-av-kraftsystemet/forskning-och-utveckling/coordinet/coordinet_wp4_d4.7.2_final-report.pdf

In terms of results, during the winter of 2020 - 2021, sthlmflex activated 2,276.4 MWh of flexibility services, with average activation prices around 485 SEK/MWh, ranging between 200 and 2,500 SEK/MWh. In the 2022-2023 winter season, Stockholm Exergi contributed 15 MW of demand reduction from 17 industrial-scale heat pumps, part of the district heating system of the city.

As part of the project, the two DSOs can procure flexibility across each other's networks. This is achieved through mechanisms like temporary subscription exchanges and enabling dynamic adjustments to transmission capacity allocations. Such coordination is meant to demonstrate the potential for optimal use of flexibility resources, enhancing grid reliability and deferring the need for traditional infrastructure investments. Moreover, flexibility bids not used at the local level can be transferred to the national manual Frequency Restoration Reserve (mFRR) market, ensuring that available flexibility resources are used across different grid levels.

4.1.5. System

Integrated Gas-Electricity Framework

Hydro Quebec's dual-energy program in collaboration with gas DSO Energir promotes the installation of heating systems that primarily use electricity and automatically switch to natural gas during peak winter periods when electricity demand is highest (Séguin and Bigouret, 2023). The aim is to ensure that 70% of heating needs are met with renewable electricity, with natural gas providing a backup during periods of extreme cold. HC aims for a reduction in peak electricity demand by nearly 2,000 MW by 2030, thanks to this program. The is also meant to defer significant infrastructure investments and maintain grid reliability during peak periods.

HC also offers financial assistance to residential customers transitioning to dual-energy systems and a dedicated tariff when the outdoor temperature is below a certain threshold (-12°C to -15°C, depending on the region). This structure encourages the use of electricity for heating during milder temperatures and shifts consumption to natural gas during colder periods.

The dual-energy program is an example of coordination between utilities and the government to enable demand-side solutions for grid flexibility, integration of renewable energy sources while maintaining system reliability and reducing costs.

Aggregator Participation

In March 2025, Ofgem announced the appointment of Elexon as the operator for the UK's new Flexibility Market Asset Registration (FMAR) system. This digital platform is designed to centralise the registration of flexible energy assets such as batteries, EVs, heat pumps, and smart appliances across multiple markets. From 2027, asset owners and aggregators will be able to register via the FMAR system, significantly reducing administrative burdens and costs.

The FMAR forms part of Ofgem's broader Flexibility Digital Infrastructure strategy to create the digital backbone needed for greater flexibility in the energy system. Elexon is already managing the UK's Balancing and Settlement Code (BSC). It was selected to also develop and operate the FMAR system to support real-time visibility of distributed assets and facilitate their participation in grid services. The system is expected to enhance market transparency, improve TSO-DSO coordination and facilitate demand-side management through aggregators.

4.2. Lessons from the Case Studies

Increasing flexibility is a result of a combination of factors, each with its own varying potential in time and across regions. All case studies are leveraging specific country characteristics and are meant to work in conjunction with other complementary measures. For example, flexible generation and wind integration in Denmark are coupled with demand-side management and grid-level flexibility enhancements. In Germany, the REFHYNE project is just one among many demonstration projects investigating the role of hydrogen, including regulatory sandboxes such as the Nord German Regulatory Sandbox. Overall, credible progress in flexibility will depend on integrating multiple solutions simultaneously: incentivizing flexible generation, enhancing storage and smart grids, coupling electricity with gaseous fuels, and adapting demand-side behaviours.

Local Conditions Enable Local Solutions

The case studies show that local energy system characteristics significantly shape flexibility opportunities.

The Nordics have specific features of the energy system that make it possible for them to implement solutions that would be challenging in other systems. The dynamic tariffs success can be partly attributed to the adoption of heat pumps and their potential for shifting significant consumption. The potential of the gas-electricity integration in Quebec is related to the large hydro deployment and the weather conditions in that part of the world. The same goes for EVs in California, with a high penetration of solar PV and EV adoption, the specific context was favourable for the V2X trials. These examples are highly valuable applications but must be understood in their specific contexts. Identifying which elements are transferable to other regions and which depend on unique local conditions is critical for effective replication.

Hydrogen Demonstration Projects are Scaling Pp

Hydrogen is emerging as a credible source of flexibility. Despite some setbacks, several projects, particularly in the EU, are now operational. Their experiences are useful not only for assessing hydrogen’s role in energy storage and flexible operation of electrolyser, but also for learning from practical challenges, including operational and regulatory hurdles. The positive investment decision for REFHYNE II, with a ten time-larger electrolyser, proves that initial challenges are being progressively overcome, reinforcing hydrogen’s potential contribution to system flexibility.

Demand-Side Flexibility: Growing Initiatives but Data Gaps Remain

The potential of demand-side participation, through aggregators, Virtual Power Plants (VPPs), and DSO-level flexibility markets, is widely recognised.

However, systematic data collection on how much flexibility these initiatives deliver remains scarce. It remains difficult to distinguish between pilot programs that are still at the experimental stage and initiatives that have achieved business-as-usual status. This lack of clarity complicates the task for policymakers, regulators, and the public.

Developing better metrics to monitor real-world demand adaptation will be crucial for scaling up effective models.

Optimizing Gas Resources and Integrated Systems

The EU recognises the potential of optimising existing gas infrastructure and integrating new gaseous fuels (such as biomethane and hydrogen) to increase flexibility.

While strategies promoting a more integrated approach to electricity and gas are well established, concrete case studies of successful electricity-gas flexibility integration remain relatively rare.

Understanding the barriers, whether technical, economic, or regulatory, behind this scarcity deserves further investigation.

Addressing these challenges will require greater information sharing among stakeholders, the development of supportive business ecosystems, cross-border learning, and exchange of best practices, and, most importantly, solutions tailored to local flexibility needs.

Chapter 5. Flexibility in Europe - Regional Differences

This chapter provides a snapshot of the current state of flexibility in Europe, as defined in Chapter 1: Defining Flexibility in the Energy System. It highlights the varying degrees of market openness across different countries and cases. Several EU countries have emerged as leaders in renewable energy integration, while others are lagging behind. This variation reflects underlying system differences: countries with historically stable baseload systems (such as those dominated by nuclear power) have had less immediate need for flexibility, while those with higher shares of variable renewables experience stronger flexibility pressures. The effective scaling of demand-side flexibility also depends critically on the deployment of adapted tariff structures and economic incentives.

5.1. Multidimensional Flexibility in the United Kingdom

The United Kingdom is transforming its energy system to meet the 2050 net-zero target, with major efforts across electricity, heat, transport, and gas. Renewable energy and electrification form the backbone of this transition, with offshore wind capacity set to expand from 14 GW (2022) to 50 GW by 2030, and solar PV projected to reach 70 GW by 2035. This rapid growth in variable renewable generation necessitates more dynamic grid management. Simultaneously, the transportation sector is evolving with electric vehicles projected to represent 25% of new car sales by 2025 and to reach 11 million vehicles by 2030. Prosumers are gaining increasing importance in the UK energy landscape, building on earlier support mechanisms, such as the Feed-in Tariff scheme. Over 350,000 households and businesses are now registered as flexible prosumers and energy sellers, contributing to grid flexibility through assets like rooftop solar, home batteries, and electric vehicles.

We outline five key developments that shape the UK´s flexibility approach.

Institutional Reform

The Electricity System Operator (ESO) has been replaced by the independent National Energy System Operator (NESO), which is mandated to deliver a zero-carbon electricity system by 2025. This transformation is supported by the *Smart Systems and Flexibility Plan*, the *Open Networks Project* (launched in 2017) [22], and significant updates to the Balancing Mechanism.[23] The UK National Energy System Operator has played a critical role in advancing energy flexibility through its Demand Flexibility

[22] Launched in 2017, and still ongoing – more details at https://www.energynetworks.org/work/open-networks/

[23] The Balancing Mechanism (BM) operates from gate closure (one hour before real time) until the end of the 30-minute settlement period. During this window, the Electricity System Operator (ESO) can instruct parties to adjust their generation or consumption. These actions are carried out via their Balancing Mechanism Unit (BMU) – more details at https://www.nationalgrid.com/sites/default/files/documents/Wider%20BM%20Access%20Roadmap_FINAL.pdf#:~:text=This%20means%20ensuring%20electricity%20generation%20and%20demand,firm%20requirement.%20What%20is%20the%20Balancing%20Mechanism?

Service (DFS). In November 2024, it expanded DFS to a year-round program with real-time alerts, flexible participation, and broader business access.[24]

Gas System Development

With approximately 80% of UK homes relying on gas for heating, gas decarbonisation is critical to meeting climate goals. The *Heat and Buildings Strategy* aims to install 600,000 heat pumps annually by 2028.[25] Concurrently, the Green Gas Support Scheme promotes biomethane injection into the gas grid, while demonstration projects like HyDeploy and H100 Fife test hydrogen integration into local networks. New regulatory initiatives introduced in 2022 are preparing for hydrogen deployment, with power-to-gas technologies emerging as flexible demand assets that can help balance the electricity grid while producing clean gases.

Digital Platforms

Specialised platforms have emerged to coordinate flexibility services, including Flexible Power (a collaborative initiative by four UK DSOs launched in 2020) and Piclo Flex (a major marketplace for flexibility services operating internationally since 2019). Peer-to-peer trading platforms like Piclo Mission Innovation and CommUNITY are connecting prosumers with local consumers, supporting decentralised energy exchange.

Table 5 presents a summary illustrating how these platforms fulfil different yet complementary roles in the UK's flexibility ecosystem. Together, these platforms are helping to operationalise flexibility in the UK energy system, contributing to the projected £30-70 billion in system cost savings between 2020-2050.

Electric Vehicle Integration

Electric vehicles now contribute significantly to grid flexibility in the UK, not only by reducing transport emissions, but also by enhancing grid stability. EVs support grid stability through smart charging, which adjusts charging patterns based on grid conditions, and vehicle-to-grid (V2G) technology, which enables bi-directional energy flows turning EVs into mobile storage assets. The government's Electric Vehicle Smart Charging Action Plan outlines strategies to maximise the benefits of smart charging. It emphasises the role of smart charging in reducing peak electricity demand and integrating renewable energy sources into the grid.[26]

Key initiatives include Nissan and the University of Nottingham's 2024 plans for bi-directional charging, and Project INFLEXION, which evolved from a 2018 V2X pilot by Kaluza, OVO Energy, Indra, and Nissan, recently joined by Volkswagen Group UK. Kaluza's platform uses AI to optimise V2G charging based on real-time market signals, charging when prices and carbon levels are low and exporting when the

[24] https://www.neso.energy/publications/markets-roadmap/demand-side-flexibility-routes-market-review
[25] Full details at https://www.ofgem.gov.uk/sites/default/files/2023-08/Smoothing%20the%20Journey%20engaging%20domestic%20consumers%20in%20energy%20flexibility%20CFI%20final%20version.pdf
[26] https://assets.publishing.service.gov.uk/media/655dfabf046ed400148b9e0a/electric-vehicle-ev-smart-charging-action-plan.pdf

Table 5: UK's Major Flexibility Platforms

Feature	Flexible Power	Piclo Flex	Piclo Mission Innovation
Type	DSO-operated collaborative initiative	Private marketplace	P2P electricity trading platform
Launch Year	2020	2019	2015
Operators /Developers	Four UK DSOs (NGED, Northern Powergrid, SSEN, SP Energy Networks)	Piclo (independent software company)	Piclo, supported by UK government
Initial Funding	DSO-funded	UK Department for Energy Security and Net Zero (formerly BEIS)	Energy Entrepreneurs Fund, UK Department of Energy and Climate Change
Primary Function	Publishes DSO flexibility needs with standardised data on requirements	Enables DSOs to competitively procure flexibility from broad participant pool	Facilitates P2P electricity trading between prosumers and local consumers
Key Features	• Issues dispatch signals • Shares settlement information • Longer-term contracting (multi-month delivery periods)	• Competitive procurement • Attracts speculative users/investors • End-to-end flexibility services	• Direct electricity exchange • Local energy communities • Connects rooftop PV owners with nearby consumers
Geographic Coverage	UK	14 geographic areas in UK operated by 6 DSOs	UK, Italy, Netherlands
International Presence	No	Ireland, Italy, Portugal, Australia, select U.S. states	Part of Piclo's international operations
Relationship	DSO-operated portal for tender-based procurement	Digital marketplace connecting flexibility providers with DSOs	Alternative mechanism for flexibility through direct P2P exchange
Economic Impact	Contributing to projected £30–70B system cost savings (2020–2050)	Unlocking decarbonisation through flexibility	Supporting grid stability and renewable uptake
Website	https://www.flexiblepower.co.uk/	https://www.piclo.energy/	https://www.piclo.energy/

*Note: **User Base**: Over 350,000 households and businesses are registered as flexible prosumers and energy sellers across these platforms.*

grid needs support. Meanwhile, Dreev (an EDF-Nuvve joint venture) conducts V2G trials in the UK alongside deployments in France and Denmark.

These developments integrate EVs as dynamic assets within the UK's increasingly flexible energy system.

A Flexibility Market

Ofgem has fast-tracked the Flexibility Market Asset Registration (FMAR) system for launch in 2027, a year ahead of schedule. Developed by Elexon,[27] this national registry will track all flexible assets (such as EV chargers, smart appliances, and battery storage) in the UK electricity system. The system supports the Virtual Lead Party model, allowing independent aggregators to access wholesale markets without supplier licenses. This enables consumers to adjust electricity use based on grid conditions, helping to balance supply and demand with cleaner energy. Unlike commercial platforms with limited visibility, FMAR is a granular, locationally aware system which operates by tracking, identifying, and verifying the characteristics and locations of distributed energy resources across all flexibility markets, regardless of provider or technology type. It gives network operators real-time visibility of flexible assets for efficient procurement and dispatch.

5.3. Dynamic and Localised Flexibility in Spain

Spain is becoming a leader in flexibility through regulatory reforms, innovation, and prosumer engagement. The Plan Nacional Integrado de Energía y Clima targets 81% renewable electricity and 48% renewables in final energy consumption by 2030, supported by planned expansions of 76 GW solar PV, 62 GW wind, and 22.5 GW energy storage. A blackout affecting the entire Iberian Peninsula in May 2025 raised concerns about the Spanish system’s ability to handle generation imbalances and led to a temporary suspension of the power exchange between Spain and Portugal. Although the exact cause of the incident remains unclear, it raised concerns about the Spanish system's ability to handle generation imbalances. Spain's electrification targets include 1.8 million EVs and 5 million heat pumps by 2030, with a 7.8% increase in electric cars in 2024. The country aims for 12 GW of green hydrogen electrolysers by 2030, positioning itself as a hydrogen hub within Europe.

Renewables already generate over 50% of Spain's electricity, led by wind (24%) and solar (16%). Prosumer connections have grown to 258,000 with 27 GW capacity, with Andalusia and Catalonia leading adoption. However, the country recorded its first negative electricity prices in 2024, signalling the growing influence of renewables and increasing need for flexibility services to manage periods of oversupply.

We outline four key developments that define Spain´s approach to flexibility.

Regulatory Reform

Spain has implemented significant regulatory changes to support energy system flexibility. Royal Decree 1183/2020 established clear procedures for accessing and connecting to the grid, with specific provisions for energy storage and hybrid renewable-storage facilities. The country has introduced

[27] Elexon is a non-for-profit organisation originally established in 2000 to manage the balancing and settlement code (https://www.elexon.co.uk/)

capacity tenders for energy storage and is piloting local flexibility markets through regional and DSO-led initiatives. Grid codes have been updated to require renewable generators to contribute to frequency and voltage control. A noteworthy achievement was the completion of a full smart meter rollout in 2018, covering approximately 99% of electricity consumers and creating a foundation for more advanced flexibility services, including dynamic real-time electricity prices for residential consumers.

Gas-Related Policy

While Spain's gas system currently centres on LNG imports and pipeline connections with France and North Africa, steps are being taken toward decarbonisation and cross-vector innovation. The PNIEC outlines goals to expand green gas production, targeting 4 GW of renewable hydrogen electrolysers by 2030. Although flexibility in the gas sector remains limited mainly to short-term balancing, interest in power-to-gas technologies is growing. Spain is also participating in EU-level initiatives to establish a hydrogen backbone, positioning its surplus renewable power potential as a driver for cross-border hydrogen trade.

Distributed Flexibility

Spain is advancing distributed flexibility through various initiatives. Since 2019, OMIE (the Spanish electricity market operator) and IDAE (Institute for Energy Diversification and Saving) have been developing the IREMEL project, which explores both short and long-term local flexibility markets through five pilot projects across different regions. The objective is to identify effective market designs for integrating local flexibility resources. Additionally, the Smartgrid Flextools project (2020-2023), coordinated by Fundación CIRCE, has developed digital tools to forecast, model, and optimise flexibility services at the distribution level, exploring how real-time data and digital twins can support demand-side flexibility in urban grids.

Energy Community

Energy communities are becoming an important component of Spain's energy transition. The Strategic Project for Renewable Energies, Hydrogen, and Storage (PERTE ERHA) includes funding lines for energy communities, potentially involving flexibility pilots. Since 2021, supported by national and EU funding, numerous community initiatives have emerged focusing on collective self-consumption, local renewable generation, and early forms of flexibility management. Key examples include Som Energia, a citizen-led cooperative operating community-scale solar PV projects; La Corriente in Madrid, enabling shared PV installations with real-time consumption tracking; Barrio Solar in Zaragoza, which uses public buildings for shared generation; and San Francisco de Asís in Crevillent, a local cooperative combining solar PV with smart meters and collective governance. While most projects currently focus on self-consumption, they demonstrate the growing potential for energy communities to become flexibility providers in local energy systems.

5.3. Consumer-Driven Flexibility with Sector Coupling in Italy

Italy has implemented a comprehensive approach to energy flexibility with three major changes.

Regulatory Framework for Flexibility

Italy has established a robust regulatory framework centred around UVAMs, which allow aggregators to combine various flexible resources into dispatchable units for market participation. The FAST Reserve Pilot Project was launched to secure ultra-fast frequency response from storage technologies. ARERA Resolution 555/2020 introduced dynamic pricing and real-time metering, while Decreet MITE 16/09/2020 established feed-in tariffs for renewable energy communities. Regulations also now require energy-intensive industries to conduct audits and implement efficiency measures.

Market Platforms and Flexibility Services

Several digital platforms have emerged to enable flexibility trading. E-Distribuzione partnered with Piclo Flex to launch Italy's first local flexibility procurement platform (see above for a description of the platform). By mid-2023, over 300 UVAMs were qualified, representing more than 1 GW of flexible capacity. The Equigy crowd balancing platform uses blockchain technology to enable small-scale consumer participation in grid balancing. Project EDGE focuses on procuring flexibility services from distributed resources to address local grid constraints, while commercial aggregators like Enel X, Edison Next, and Flexcity are now offering real-world flexibility services.

Sector Coupling and Electrification

Italy is increasingly focusing on sector coupling to enhance system flexibility. The PNIEC targets 5 GW of electrolyser capacity by 2030 for green hydrogen production, with Hydrogen Valleys being developed in several regions. Electric heat pumps and district heating upgrades are being promoted through tax incentives. In the mobility sector, Italy aims to install 8.8 million EV charging points by 2030, with V2G pilot projects already underway in Turin and Rome. Support schemes have also been created to modernise district heating and cooling systems, enabling integration of renewable sources into urban infrastructure.

5.4. Flexibility-First Integrated Approach in the Nordic Region

The Nordic region leads the clean energy transition with 61.6% renewable energy consumption in 2023. Norway relies heavily on hydropower, Denmark excels in wind generation, and all countries benefit from Nord Pool market integration. These nations effectively tackle energy system challenges through cross-border electricity trading, optimised hydro reservoir management, market-based demand response, and sector coupling. Denmark has become a testing ground for high renewable integration by decoupling heat and power generation, implementing advanced wind forecasting, and designing markets that expose producers to price signals. The region features widespread district heating systems, high EV adoption (80% of new car sales in Norway), nearly complete smart meter coverage, and strong prosumer enablement. This approach positions Nordic countries to achieve full decarbonisation while maintaining reliability and cost efficiency.

The Nordic region has pioneered a comprehensive flexibility-first strategy. Norway and Sweden use hydropower reservoirs as seasonal storage and fast-ramping capacity to balance variable renewables. It is essential to note that in countries such as Sweden and Finland, a substantial portion of renewable energy originates from dispatchable hydropower, which offers inherent system flexibility and facilitates the integration of renewables more effectively compared to systems primarily reliant on variable sources, such as solar and wind.

While the Nordic region's flexibility-first approach encompasses numerous policies and initiatives that cannot be comprehensively covered in this report, we focus on key integrated strategies. Throughout these efforts, advanced digitalisation serves as the critical foundation, enabling sophisticated coordination across systems and establishing the Nordic region as a global benchmark for flexibility integration.

Flexibility Market Platforms

Local flexibility markets throughout the Nordic countries are primarily coordinated via the innovative NODES platform. In Norway, the Euroflex initiative unites eight major DSOs to develop specialised flexibility products such as ShortFlex™, LongFlex™, and MaxUsage™. Sweden has established local flexibility markets around Gothenburg (Effekthandel Väst) and Mölndal, building on the CoordiNet initiative to enable market-based procurement of flexibility services—such as congestion relief and deferred grid investments, using platforms like NODES and SWITCH,[28] while Finland's TSO Fingrid is piloting congestion management markets in collaboration with Helsinki's DSO, focusing on integrating distributed flexibility resources. Denmark takes a distinctive approach outside the NODES platform, where the transmission system operator Energinet has developed comprehensive strategies enabling smart integration of combined heat and power plants, heat pumps, and energy storage systems to enhance overall system flexibility. In Sweden, pilot projects such as CoordiNet, sthlmflex, and Effekthandel Väst have helped refine product types and workflows, although many challenges remain regarding interoperability, baseline validation, and liquidity.[29]

TSO-DSO Coordination

The sthlmflex initiative in Stockholm demonstrates effective TSO-DSO coordination, where Svenska Kraftnät collaborates with Vattenfall Eldistribution and Ellevio to address capacity constraints. Flexibility services are provided by aggregators, building operators, and industrial users. During the winter of 2020-2021, it activated 2,276.4 MWh of flexibility services. The Stockholm School Properties Company integrated around 50 school buildings into this market, while Stockholm Exergi contributed 15 MW of demand reduction from 17 industrial-scale heat pumps in 2022-2023. Importantly, flexibility bids not used at the local level can be transferred to the national manual Frequency Restoration Reserve (mFRR) market, ensuring efficient use of flexibility resources across multiple grid levels.

Sector Coupling

Sector coupling is advancing rapidly across the region, with Denmark leading the way by integrating renewable energy across electricity, heating, transport, and industrial sectors. Innovative projects such as *GreenLab Skive* demonstrate this approach through a green industrial cluster with shared energy infrastructure (SymbiosisNet™). Large-scale thermal energy storage facilities in Høje Taastrup

[28] https://ei.se/download/18.42d391b41872c3dd1d564e0/1680785760065/Flexibilitet-i-distributionsnäten-deluppdrag-3-Ei-R2023-05.pdf

[29] https://ei.se/download/18.6be87cd11961dff00ba48e1/1744696274662/Konsultrapport-Kartläggning-av-lokala-flexibilitetsmarknader-Sweco.pdf

further showcase the commitment to cross-sector integration. The planned Danish hydrogen backbone represents the next frontier, designed to enable transport and storage of green hydrogen across sectors and borders. Nevertheless, Sweden observes that the current tax structures and lack of coordinated planning between energy sectors (e.g., heating, transport, electricity) hinder integrated flexibility.[30]

Dynamic Pricing

Sweden has successfully implemented dynamic pricing models with remarkable results. The use of dynamic pricing (e.g., hourly tariffs) have been considered in conjunction with more traditional mechanism.[31] During the recent energy price crisis, the southern SE4 bidding zone (including Malmö) experienced a significant shift toward variable pricing contracts, with only 5% of households remaining on fixed-price contracts by 2024. This transition demonstrates the potential for price signals to drive consumer behaviour and enhance system flexibility (Tangerås et al. 2025, SNS report).

5.5 Cross-European Cooperation for Enhanced Flexibility

Regulators and system operators across Europe play a pivotal role in enabling flexibility markets and establishing conditions for broader participation. Through defining access rules and piloting digital coordination platforms, these institutional actors are instrumental in unlocking the full potential of both demand and supply-side flexibility resources. The following examples illustrate how flexibility is structured and governed across different European jurisdictions.

Cross-Border TSO-Led Platform

Equigy is a blockchain-based crowd-balancing platform developed by five European transmission system operators: Austrian Power Grid (APG), TenneT (Netherlands and Germany), Swissgrid (Switzerland), Terna (Italy), and TransnetBW (Germany). This innovative platform enables distributed energy resources (DERs) to participate in balancing and congestion management services. The platform supports a range of short-term products, including Frequency Containment Reserve (FCR), automatic and manual Frequency Restoration Reserve (aFRR and mFRR), and redispatch services. By standardising digital infrastructure and interfaces across national borders, Equigy effectively reduces entry barriers and transaction costs, particularly for smaller, decentralised actors. The European balancing platforms MARI (for manually activated reserves) and PICASSO (for automated frequency restoration) marks a major milestone in completing the EU's target market design for electricity balancing. The aim of these platforms is to increase market liquidity, reduce distortions, and support a fair, transparent, and efficient balancing process, ensuring real-time stability of the power system and enhancing social welfare across Europe.[32]

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[30] https://ei.se/download/18.42d391b41872c3dd1d564e0/1680785760065/Flexibilitet-i-distributionsnäten-deluppdrag-3-Ei-R2023-05.pdf

[31] https://ei.se/download/18.6be87cd11961dff00ba48e1/1744696274662/Konsultrapport-Kartläggning-av-lokala-flexibilitetsmarknader-Sweco.pdf

[32] This transition follows the Electricity Balancing Regulation (2017).

Coordinated Congestion Management between TSO and DSO

GOPACS (Grid Operators Platform for Congestion Solutions) is a flexibility coordination platform developed by Dutch grid operators, including TenneT (TSO) and regional DSOs in the Netherlands. It facilitates congestion management by enabling the strategic deployment of flexible generation and demand resources through well-designed redispatch mechanisms. Rather than functioning as a trading platform itself, GOPACS ingeniously matches flexibility offers submitted by market participants, either directly or through Congestion Service Providers (CSPs), with real-time grid requirements. This system integrates seamlessly with established intraday markets such as EPEX Spot and ETPA.

Participation requires registration as electricity suppliers, aggregators, or large consumers, with smaller consumers able to participate exclusively through aggregator services. The platform supports two complementary redispatch mechanisms: mandatory redispatch using pre-contracted flexibility with fixed and per-request fee structures, and voluntary market-based redispatch where participants submit bids through established trading platforms. All bids must include precise locational data, though they may originate outside congested areas provided they contribute positively to overall system balancing.

Additionally, GOPACS enhances grid management through day-ahead congestion management via Capacity Restriction Contracts. These contracts can include either time-blocked or on-demand commitments, tailored to specific network requirements. All participation necessitates prior contractual arrangements with the relevant network operator, ensuring accountability and service quality.

Enabling Aggregator Access by regulation

Across Europe, multiple Member States are progressively adapting their electricity market frameworks to formally recognise aggregators and facilitate their participation in flexibility services. Croatia has taken a significant step by legally recognising both traditional aggregators and independent aggregators, allowing their participation in ancillary services and capacity markets. Similarly, Spain is advancing toward regulating independent aggregation since 2024 through an updated General Regulation on electricity supply.

These regulatory reforms reflect a growing European consensus on the importance of decoupling flexibility provision from traditional supplier roles. By creating clear pathways for aggregator participation, these countries are facilitating more granular, decentralised market engagement, ultimately enhancing system flexibility while creating new business opportunities within the evolving energy landscape.

To summarise, European countries exhibit significant variation in the development of their flexible market.[33]The UK leads with well-developed local flexibility markets and broad prosumer participation opportunities, though collective self-consumption remains limited. Spain and Italy occupy a middle ground with partially open markets, hindered by restrictions on small prosumers and limited aggregator presence. Croatia lags behind, lacking both local flexibility and capacity markets. Prosumer

[33] Rodriguez et al. (2024) assessed prosumer access to energy markets (day-ahead, intraday, ancillary services, adequacy, constraint management, and local flexibility) across several countries.

engagement has increased throughout Europe, with households participating individually, through businesses with rooftop solar, or via energy communities like Spain's Som Energía. The proliferation of renewable technologies has fostered innovative business models, including aggregation services, peer-to-peer trading platforms, and integrated energy districts where electricity, heating, and mobility are managed locally.

Chapter 6. Options and Recommendations

6.1. Uncertain Trade-Offs in System Flexibility Planning and Policy

Energy system flexibility faces various uncertainties and complex trade-offs that policymakers must navigate while planning for future needs. These challenges encompass technological, economic, regulatory, and geopolitical domains, resulting in a decision-making environment characterised by significant complexity.

Technological Uncertainty

The optimal mix of technologies that provide flexibility has not been identified yet. Natural gas power plants offer significant flexibility and can facilitate higher penetration of variable renewable energy (VRE); however, their long-term role in a net-zero future is contested. While they are generally viewed as transitional solutions that should be phased out by mid-century, studies indicate that gas plants equipped with carbon capture and storage (CCS) could serve a cost-effective function in net-zero scenarios despite existing uncertainties.[34] Additionally, high levels of uncertainty make low CAPEX gas backup more attractive.

Battery energy storage systems (BESS) have seen favourable cost evolution and increasing deployment; however, questions persist regarding future costs, resource availability for manufacturing, optimal deployment models, and competition from alternative technologies. Similarly, hydrogen is an energy vector that has undergone a “hype cycle” and faces a wide range of projections.[35] For example, German demand estimates vary from 29 to 101 TWh annually by 2030 and from 200 to 700 TWh by 2045/2050 (Merten and Scholz, 2023) with comparable uncertainty in the UK (AFRY, 2023).

The potential for biomethane to replace fossil natural gas while maintaining its flexibility functions, including storage, remains debated, particularly regarding its complementary role to electrification (IEA, 2020; Marconi and Rosa, 2023).

Adequacy vs. Flexibility

It is important to note that there is an inherent trade-off between system adequacy and flexibility, as relying heavily on flexible resources, such as industrial demand response, can affect the quality or continuity of service; for example, while data centres can offer load shifting or temporary curtailment, excessive flexibility demands risk compromising uptime and service reliability (von der Fehr & Covatariu, 2024).

[34] https://publications.parliament.uk/pa/cm5901/cmselect/cmpubacc/351/report.html

[35] https://www.spglobal.com/commodity-insights/en/news-research/blog/energy-transition/102124-beyond-the-hype-hydrogen-gets-serious

Price Signal Dilemma

A fundamental tension exists between the short-term price signals needed to drive flexible behaviour and the long-term certainty required for capital-intensive investments. While price signals theoretically incentivise actors to adjust production and consumption according to system needs, the reality of exposing consumers and producers to wide price fluctuations has proven politically challenging, as demonstrated by government interventions during recent price spikes across Europe.[36] Creating effective long-term investment signals while preserving short-term price responsiveness presents a persistent challenge. Designing markets that simultaneously support operational flexibility and capital-intensive infrastructure development requires careful balancing to avoid technology lock-in effects (Blyth *et al.*, 2023).

Centralisation vs. Decentralisation

Another significant trade-off exists between supporting large-scale, centralised solutions (pumped storage, large hydrogen facilities, long-distance interconnectors) and small-scale, decentralised approaches (demand response, active distribution system operators, virtual power plants). While both pathways may need to evolve concurrently, they require different enabling environments that could create contradictory policy signals and regulatory frameworks.

Digitalisation Promises and Challenges

Despite its widely discussed potential, digitalisation has yet to fully deliver transformative value in the energy sector. Smart meters and other digital technologies have not consistently achieved expected outcomes, with some experts describing the digital transformation in energy as ‘tragically overhyped’ (McKinsey & Co, 2020).The pace and impact of digitalisation remain uncertain, complicated by concerns over data sharing, privacy, and security.

Geopolitical Complications

Geopolitical factors add another layer of uncertainty affecting most technological solutions. These include questions about future availability of affordable natural gas in Europe (from U.S. LNG or even Russian sources), trade tensions with China and its dominance in critical value chains, and the competitive position of European players in key technologies, as illustrated by battery manufacturer Northvolt's challenges despite substantial government support.

These multidimensional uncertainties necessitate adaptive, robust policy frameworks that can accommodate evolving technology landscapes, market dynamics, and geopolitical conditions while sustaining the progress of decarbonisation. Instead of pursuing seemingly optimal pathways based on current incomplete information, policymakers should prioritise developing flexible regulatory environments that enable diverse technological solutions while avoiding irreversible commitments to potentially suboptimal technological trajectories.

[36] https://www.bruegel.org/dataset/national-policies-shield-consumers-rising-energy-prices

6.2. Summary of Policy Recommendations from Recent Reports

Flexibility is becoming a prominent issue in Europe as the share of VRE in the electricity mix continues to grow. Several high-quality reports have been published recently, addressing various aspects of flexibility. In this sub-section, we provide a summary and an aggregation of their main policy recommendations. From this exercise, we can identify a near-consensus on the most relevant policy options for the EU.

Table 6: Summary of Policy Recommendations from Recent Reports

Category	Key Recommendations	Sources
Market Access	• Define responsibilities for new actors (aggregators, energy communities) • Ensure non-discriminatory market access for DERs • Simplify licensing and permitting processes	ACER (2025) ACER-CEER (2024)
Consumer Engagement	• Accelerate smart meter deployment • Enable dynamic pricing • Implement demand response incentives	ACER (2025) ACER-CEER (2024) EP-Trinomics (2025)
Flexibility Market Design	• Enhance short-term and balancing markets • Align cross-border market structures • Standardise balancing products • Strengthen long-term investment signals	ACER (2025) Eurelectric (2025) EP-Trinomics (2025)
Infrastructure	• Prioritise flexible alternatives to grid expansion • Use integrated network planning • Develop interoperable data platforms • Strengthen cybersecurity for smart grids	ACER (2025) EP-Trinomics (2025) McKinsey et al. (2021)
Planning & Innovation	• Implement National Flexibility Needs Assessments • Coordinate at the EU level • Support energy communities and V2G services • Remove legal barriers to innovative models	EP-Trinomics (2025) Magnus (2024) ACER-CEER (2024)

From these aggregated policy recommendations, several commonalities emerge. They primarily advocate for implementing existing regulations rather than introducing new legislative acts. Many aspects of implementation are still in the consultation or design phase and will take several more months to years to be put into effect. In the meantime, particularly at the Member State level, there is uneven progress on key aspects of flexibility. Many countries have not achieved their targets for smart meter deployment; most consumers remain on fixed-price contracts, and the participation of demand-side resources in various markets and schemes is minimal.

Many recommendations refer to removing barriers to flexibility-enhancing solutions, including aggregators, price signals at retail and network levels, digitalisation, active DSOs and NWAs, a level playing field between technologies, such as DR, and market principles in ancillary services. Most of them require specific interventions at the MS level, adapted to the regulatory realities of each country. Often, the barriers are also linked to some of the trade-offs discussed above, including affordability or intricate data protection issues.

The need for more information is also reflected in calls for thorough assessments of flexibility needs. While flexibility is universally acknowledged as a crucial goal on the path to net zero, outside policy circles, interest in it is still relatively new, and knowledge about the current state and needs remains insufficient.

Cross-border issues are prominent, including the interconnection, standardisation, and integration of balancing markets, to leverage potential temporal or weather-related synergies across regions.

Many of these policy recommendations are not specific to flexibility but overlap with other goals of the energy sector, including increased investments and issues related to long-term contracts, signals, or permitting processes. While flexibility has a distinct definition, enhancing it contributes to other overall goals of the energy sector, such as adequacy and decarbonisation, provided that affordability and data privacy can also be ensured.

6.3. Policy Recommendations

Building on the analysis presented in this report, our policy recommendations are structured across two key dimensions, reflecting the dual need to accelerate implementation and address system-wide coordination challenges.

The first dimension refers to the uncertainty and trade-off previously discussed. On one end of the spectrum, there are 'low uncertainty policy measures. These are policies likely to be needed in most decarbonisation scenarios. On the other end of the spectrum, there are 'adaptive approaches' (Pollitt, Covatariu and Duma, 2024), where policies need to be prepared for scenarios and trigger points as certain trends emerge and materialise (e.g. thresholds for EV penetration, hydrogen scaling in iron and steel, etc).

The other dimension follows the approach in DG Energy (2022) and refers to the degree of structural change required for the policy to be implemented. The 'low' structural changes end of the spectrum describes policy measures that are either 'soft, 'incremental or attainable without major opportunity costs, while the 'high' end of the spectrum describes policies with major implications, costs, or expected to generate resistance due to impact on certain stakeholders.

Most recommendations refer to ensuring or facilitating implementation of existing EU legal acts at the MS level. EU already has comprehensive and adequate legislation in place, including the Fit for 55 Package, the REPowerEU Plan, the Hydrogen and Decarbonised Gas Package,[37] the Digitalisation Action Plan,[38] the Action Plan for Grids, Heat Pumps, and others. However, the main challenges are in the implementation.

Table 7: Summary of Policy Recommendations

	Low structural change	**High structural change**
Low uncertainty	**LULS1**. Ensure an integrated whole-system approach to flexibility planning across energy carriers	**LUHS1**. Enable effective market signals at different levels **LUHS2**. Accelerate demand response, aggregation, DER participation **LUHS3**. Boost digitalisation at key nodes for flexibility
Adaptive approach	**AALS1**. Keep options open and adopt selectively	**AAHS1**. Take an adaptive approach to green hydrogen (and other power to x)

Source: Authors.

LULS1. Ensure an integrated, whole-system approach to flexibility planning across energy carriers (electricity, gas, heat)

Ensuring that the planning and operation of the energy system is coordinated between the various sub-sectors becomes key for improving system flexibility. The existing EU strategy for energy system integration and the coordination processes through the NECP represent an adequate starting point.[39] As recognised by a recent study by the European Commission on integration (DG Energy, 2024), a greater focus on flexibility in these processes is required.

As stipulated by the Electricity Market Design Reform Directive,[40] and Regulation of 2024,[41] the DSO entity and ENTSO-E are performing a public consultation on the methodology of a future flexibility needs assessment that Member States will need to conduct through all their energy DSOs and TSOs.[42] ACER will then need to perform a pan-European flexibility needs assessment based on submissions from Member States. These would come in addition to other processes like NECP, the NRAA and ERAA that focus more on adequacy than flexibility.[43]

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[37] https://energy.ec.europa.eu/topics/markets-and-consumers/hydrogen-and-decarbonised-gas-market_en
[38] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52022DC0552&qid=1666369684560
[39] https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=COM:2020:299:FIN
[40] https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=OJ:L_202401711
[41] https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=OJ:L_202401747
[42] https://consultations.entsoe.eu/system-development/public-consultation-on-flexibility-needs-assessmen/
[43] https://www.entsoe.eu/outlooks/eraa/

These efforts tend to be electricity-centric and would benefit from a greater integration of current or short-term natural gas, but also future decarbonised gaseous gas sources, and with heating, which can also be an important local flexibility resource. While electricity grids and storage remain key constraints, integrating gas and heat networks can add flexibility and ease system pressures.

LUHS1. Enable effective price signals at different levels (generation, retail, and network)

Greater flexibility requires more active and adaptive behaviours from various actors in the markets, at different levels. Prices can induce these behaviours and can enable the identification and remuneration of the value of flexibility services.

Ensuring that the needed technologies (storage and other providers of flexibility) are adequately remunerated so that they invest and continue to operate is crucial and requires a balanced interplay between efficient energy markets and longer-term flexible capacity mechanisms.

Moreover, prices need to reflect the dynamics between supply and demand for every relevant time horizon, including in the short term. This is valid both for price-based and incentive-based supply and demand response approaches, as the price signals must be sufficient to determine consumers or third parties on their behalf to make the needed behavioural adjustments (Cabot and Villavicencio, 2024). This includes dynamic pricing at the supply level for both electricity and to a much lesser extent, gas, which expose consumers to close to real time prices and incentivise adjustments in consumption. While such retail contracts exist as an option throughout Europe, with a high take up in the Nordics, for example, most consumers in other countries are still relying on fixed contracts. For example, in the Netherlands, only 6% of contracts were based on dynamic pricing in early 2025.[44]

In addition, distribution tariffs would also benefit from having a dynamic component to reflect time- or location-based congestion and incentivise the shifting of consumption. The 2021 ACER assessment of electricity distribution tariffs found that few countries implement even basic night-day differentiated tariffs and no country has dynamic components in the tariff.[45]

The retail and grid dynamic components can also interact and can, under certain circumstances, reinforce each other (Stute and Klobasa, 2024).

While legal provisions for sharper market signals have been included in legislation even before the Clean Energy Package, the fact that they are still not fully implemented demonstrates the technical, legal, and social challenges that surround this issue.

LUHS2. Accelerate demand response, aggregation, DER participation

Bring demand response closer to its potential through aggregation and DER participation in flexibility markets.

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[44] https://www.acm.nl/en/publications/acms-energy-monitor-new-fixed-contracts-are-three-percent-more-expensive

[45] https://www.acer.europa.eu/sites/default/files/documents/Publications/ACER%20Report%20on%20D-Tariff%20Methodologies.pdf

There are still significant barriers to entry for smaller scale flexibility resource and competition with large scale sources of flexibility is not on a level playing field.

This matter has also been included in legislation as far back as CEP, but implementation is lagging behind. For example, the CEP already stipulates the right of consumers to participate in all markets and be compensated for the flexibility they provide, but this has not materialised at scale in many Member States (Arthur D. Little, 2023). Also, in many countries, the provisions on incentivizing demand response participation in congestion management at transmission or distribution levels are not yet operationalised.[46]

The network code for demand response is currently under development and can be an opportunity to operationalise and move some of the legislative provisions to the implementation phase.[47]

LUHS3. Boost digitalisation at key nodes for flexibility

Related to the previous two recommendations, neither price signals nor favourable legislation will be enough for the future large need for flexibility to be met. Many of the processes required for proportional and timely adjustments in supply and demand depend on digital technology, both in networks (including meters) and at the level of consumers. Even with improved information and awareness, and improved price signals, significant responsiveness of individual consumers/prosumers will not be possible without digital technology. Digitalisation is a prerequisite for the processes to be scaled up.

Smart meters are a first step, but even after their (delayed) rollout, ensuring that their functionalities are used for greater system flexibility is critical. There is still not enough information about the impact of their rollout, their different applications in Member States, from the most basic (remote reading) to the more advanced (smart charging of EVs). While likely to remain a significant barrier, the complexities around data sharing, privacy and cybersecurity must be addressed.

AALS1. Keep options open for new technologies

There are numerous pilots and regulatory sandboxes around Europe involving promising yet unproven technologies that may become important sources of flexibility, either directly (new digital tools) or indirectly (CCS for fossil or bio-based gas). In parallel with the 'low uncertainty' measures, a structured process of collecting (and disseminating) results from pilots and sandboxes, as well as continued funding from EU mechanisms for conducting them, would allow Europe to keep its options open and avoid making decisions that lock-in or lock-out certain technological solutions. In addition, regular stock taking exercises that evaluate the progress activities involving DERs in different markets, as well as the status of different business models, would be warranted. In the crowded space of new technological solutions, pilots, and ventures, keeping track of what solutions survive the hype cycle can be critical.

[46] https://www.tugraz.at/fileadmin/user_upload/tugrazExternal/f560810f-089d-42d8-ae6d-8e82a8454ca9/files/lf/Session_B1/214_LF_Kalt.pdf

[47] https://montel.energy/assets/08---sven-kaiser---boosting-flexibility-(i)--electricity-market-reform-1727355278.pdf

AAHS1: Adaptive regulation for hydrogen integration

It is crucial to adopt an adaptive approach to green hydrogen (and other power-to-x options) as a source of flexibility while keeping up with developments in the overall hydrogen market for other uses, such as decarbonising the iron and steel industry and/or heavy transport and hard-to-abate sectors more generally (Ahang, Granado and Tomasgard, 2025). While hydrogen will be the subject of wider policy efforts, its applications as a flexibility source should continue to be studied, demonstrated and piloted, in preparation for a gradual expansion of its role in improving system flexibility. As the results of the Hydrogen Bank and the German CfD scheme become known, the role of hydrogen flexibility can be more precisely evaluated. In the meantime, R&D on relevant aspects for flexibility, including operations and optimal location of electrolysers and hydrogen storage, should continue.

Chapter 7. Conclusion

Achieving a flexible, integrated energy system is essential for delivering a decarbonised, secure, and cost-effective European energy transition. Higher shares of variable renewable energy (VRE) demand increased flexibility through measures such as demand response, energy storage, and improved grid interconnections (Heptonstall & Gross, 2020). Integration also requires balancing supply and demand, reducing curtailment, and optimising system operations (Perez-Arriaga & Battle, 2012). The effectiveness of these efforts depends on regional geography, infrastructure, and levels of interconnection. Emerging technologies—such as batteries, hydrogen, and smart meters—enabled by digitalisation, show strong potential to enhance flexibility.

However, unlocking this potential depends critically on supportive regulatory frameworks and well-designed market incentives. Regulation must evolve to create investment signals and operational frameworks that allow new flexibility solutions to scale effectively.[48]

The growing penetration of VRE and the anticipated electrification of heating, transport, and industry have pushed flexibility to the centre of EU energy policy. Although many flexibility measures currently focus on the electricity sector, the EU has embraced a 'whole-system' approach, integrating electricity, gas, and other energy vectors.

Textual analysis of EU legislation and regulation shows that flexibility is well-recognised and increasingly well-defined at the policy level. Existing frameworks are largely adequate in their aims to support flexibility-enhancing behaviours, technologies, and market functions. However, legislation alone is insufficient because the implementation gap remains significant.

Case studies across Member States reveal that while traditional flexibility sources like hydropower and industrial demand response are well established, newer solutions—such as residential demand response, aggregator-led services, smart EV charging, and the flexible use of hydrogen—are often still in pilot or early-stage implementation. These solutions show promise but are not yet widely scaled or fully understood in terms of their deviation from Business as Usual and the quantifiable flexibility they provide.

Implementation varies significantly across Member States due to different energy mixes, policy priorities, and infrastructure readiness. The EU's adaptable regulatory framework allows for national tailoring, which is appropriate. For instance, the Nordics—with strong hydro and digitalised demand—require different solutions than countries still dependent on fossil fuels or phasing out nuclear power. Others lag behind due to delays in smart meter deployment, fixed retail pricing, and restricted demand-side participation. Bridging these gaps is essential for a cohesive European flexibility strategy.

Finally, this report emphasises the need to manage uncertainty and make strategic trade-offs. Promising technologies and market designs must be tested under real-world conditions to assess their cost, impact, and stakeholder responses. A prudent strategy involves accelerating the deployment of

[48] For instance, UKERC has recently published a report which examines the key role of flexibility in transforming the Great Britain power system for Clean Power 2030 and the broader net zero goal, highlighting the policy and regulatory landscape required to support these transitions, see https://ukerc.ac.uk/publications/flexibility-in-the-gb-power-system-future-needs-alternative-sources-and-procurement/.

proven solutions—such as digitalisation, battery storage, interconnections, and efficient market design—while remaining adaptive to more uncertain options like green hydrogen, power-to-X, and transformative demand-side shifts.

In summary, the foundation for a flexible European energy system is in place. The challenge ahead lies in translating policy ambition into coordinated action across all Member States—tailored to local contexts but aligned with shared goals for a resilient, decarbonised, and integrated energy future.

References

Abrell, J., Rausch, S. and Streitberger, C. (2019) 'The economics of renewable energy support', *Journal of Public Economics*, 176, pp. 94–117. Available at: https://doi.org/10.1016/j.jpubeco.2019.06.002.

ACER (2024) *Security of EU electricity supply*. Agency for the Cooperation of Energy Regulators. Available at: https://www.acer.europa.eu/sites/default/files/documents/Publications/Security_of_EU_electricity_supply_2024.pdf.

ACER & CEER (2024) *Energy retail - Active consumer participation is key to driving the energy transition: how can it happen?* European Union Agency for the Cooperation of Energy Regulators. Available at: https://www.acer.europa.eu/news/active-consumer-participation-key-driving-energy-transition-how-can-it-happen.

AFRY (2023) *Net Zero Power and Hydrogen: Capacity Requirements for Flexibility*. The Climate Change Commission. Available at: https://www.theccc.org.uk/wp-content/uploads/2023/03/Net-Zero-Power-and-Hydrogen-Capacity-Requirements-for-Flexibility-AFRY.pdf.

Ahang, M., Granado, P.C. del and Tomasgard, A. (2025) 'Investments in green hydrogen as a flexibility source for the European power system by 2050: Does it pay off?', *Applied Energy*, 378, p. 124656. Available at: https://doi.org/10.1016/j.apenergy.2024.124656.

Alam, M.R., St-Hilaire, M. and Kunz, T. (2017) 'An optimal P2P energy trading model for smart homes in the smart grid', *Energy Efficiency*, 10(6), pp. 1475–1493. Available at: https://doi.org/10.1007/s12053-017-9532-5.

Alaperä, I., Honkapuro, S. and Paananen, J. (2018) 'Data centers as a source of dynamic flexibility in smart girds', *Applied Energy*, 229, pp. 69–79. Available at: https://doi.org/10.1016/j.apenergy.2018.07.056.

Antweiler, W. and Schlund, D. (2024) 'The emerging international trade in hydrogen: Environmental policies, innovation, and trade dynamics', *Journal of Environmental Economics and Management*, 127, p. 103035. Available at: https://doi.org/10.1016/j.jeem.2024.103035.

ARENA (2022) *DEIP Dynamic Operating Envelopes Workstream: Outcomes Report*. Australian Renewable Energy Agency. Available at: https://arena.gov.au/knowledge-bank/deip-dynamic-operating-envelopes-workstream-outcomes-report/.

Arthur D. Little (2023) *Taking demand-side response to the household level*. Available at: https://www.adlittle.com/en/insights/viewpoints/taking-demand-side-response-household-level (Accessed: 20 February 2025).

Banerji, A. *et al.* (2013) 'Microgrid: A review', in *2013 IEEE Global Humanitarian Technology Conference: South Asia Satellite (GHTC-SAS)*. *2013 IEEE Global Humanitarian Technology Conference: South Asia Satellite (GHTC-SAS)*, pp. 27–35. Available at: https://doi.org/10.1109/GHTC-SAS.2013.6629883.

Blyth, W. *et al.* (2023) 'Transition risk: Investment signals in a decarbonising electricity system', *Applied Energy*, 352, p. 121938. Available at: https://doi.org/10.1016/j.apenergy.2023.121938.

Boldrini, A. *et al.* (2024) 'Flexibility options in a decarbonising iron and steel industry', *Renewable and Sustainable Energy Reviews*, 189, p. 113988. Available at: https://doi.org/10.1016/j.rser.2023.113988.

Brown, C. *et al.* (2024) *Generating surplus: the challenges and opportunities of large-scale renewables deployment*. Available at: https://www.ucl.ac.uk/bartlett/sustainable/sites/bartlett_sustainable/files/working_paper6_generating_surplus.pdf.

Brunner, C. *et al.* (2020) 'The future need for flexibility and the impact of fluctuating renewable power generation', *Renewable Energy*, 149, pp. 1314–1324. Available at: https://doi.org/10.1016/j.renene.2019.10.128.

Budzianowski, W.M. and Brodacka, M. (2017) 'Biomethane storage: Evaluation of technologies, end uses, business models, and sustainability', *Energy Conversion and Management*, 141, pp. 254–273. Available at: https://doi.org/10.1016/j.enconman.2016.08.071.

Bushnell, J. (2003) 'A Mixed Complementarity Model of Hydrothermal Electricity Competition in the Western United States', *Operations Research*, 51(1), pp. 80–93. Available at: https://doi.org/10.1287/opre.51.1.80.12800.

Cabot, C. and Villavicencio, M. (2024) 'The demand-side flexibility in liberalised power market: A review of current market design and objectives', *Renewable and Sustainable Energy Reviews*, 201, p. 114643. Available at: https://doi.org/10.1016/j.rser.2024.114643.

Cao, Y. *et al.* (2024) 'Managing data center cluster as non-wire alternative: A case in balancing market', *Applied Energy*, 360, p. 122769. Available at: https://doi.org/10.1016/j.apenergy.2024.122769.

Caraballo, A. *et al.* (2021) 'Molten Salts for Sensible Thermal Energy Storage: A Review and an Energy Performance Analysis', *Energies*, 14(4), p. 1197. Available at: https://doi.org/10.3390/en14041197.

Carlson, E.L., Pickford, K. and Nyga-Łukaszewska, H. (2023) 'Green hydrogen and an evolving concept of energy security: Challenges and comparisons', *Renewable Energy*, 219, p. 119410. Available at: https://doi.org/10.1016/j.renene.2023.119410.

Castellini, M. *et al.* (2021) 'Photovoltaic Smart Grids in the prosumers investment decisions: a real option model', *Journal of Economic Dynamics and Control*, 126, p. 103988. Available at: https://doi.org/10.1016/j.jedc.2020.103988.

Chyong, C.K. *et al.* (2024) 'Modelling flexibility requirements in deep decarbonisation scenarios: The role of conventional flexibility and sector coupling options in the European 2050 energy system', *Energy Strategy Reviews*, 52, p. 101322. Available at: https://doi.org/10.1016/j.esr.2024.101322.

Cochran, J. *et al.* (2014) *Flexibility in 21st century power systems*. National Renewable Energy Lab.(NREL), Golden, CO (United States). Available at: https://www.osti.gov/biblio/1130630 (Accessed: 31 January 2025).

Commission, E. *et al.* (2024) *Study on promoting energy system integration through the increased role of renewable electricity, decentralised assets and hydrogen – Final report*. Publications Office of the European Union. Available at: https://doi.org/doi/10.2833/560304.

Cortade, T. and Poudou, J.-C. (2022) 'Peer-to-peer energy platforms: Incentives for prosuming', *Energy Economics*, 109, p. 105924. Available at: https://doi.org/10.1016/j.eneco.2022.105924.

Cozzolino, R., & Bella, G. (2024). A review of electrolyzer-based systems providing grid ancillary services: current status, market, challenges and future directions. *Frontiers in energy research*, *12*, 1358333

Crampes, C. and Moreaux, M. (2001) 'Water resource and power generation', *International Journal of Industrial Organization*, 19(6), pp. 975–997. Available at: https://doi.org/10.1016/S0167-7187(99)00052-1.

CREA (2023) *Opportunities and challenges of flexibility technologies for achieving a net-zero electricity future in China*. Centre for Research on Energy and Clean Air. Available at: https://energyandcleanair.org/wp/wp-content/uploads/2023/04/CREA_ISETS_Opportunities-and-challenges-of-flexibility-technologies-for-achieving-a-net-zero-electricity-future-in-China_Final_April-2023.pdf.

Del Greco, L., Losi, A. and Mauro, M. (2022) 'Demand Response in the Italian regulation and first results', *Energia Elettrica Supplement Journal*, 99. Available at: https://doi.org/DOI:10.36156/ENERGIA07.

Denholm, P., Cole, W. and Blair, N. (2023) *Moving Beyond 4-Hour Li-Ion Batteries: Challenges and Opportunities for Long(er)-Duration Energy Storage*. NREL, p. NREL/TP--6A40-85878, 2000002, MainId:86651. Available at: https://doi.org/10.2172/2000002.

Depree, N. *et al.* (2016) 'The "Virtual Battery" — Operating an Aluminium Smelter with Flexible Energy Input', in E. Williams (ed.) *Light Metals 2016*. Cham: Springer International Publishing, pp. 571–576. Available at: https://doi.org/10.1007/978-3-319-48251-4_96.

Després, J. *et al.* (2017) 'Storage as a flexibility option in power systems with high shares of variable renewable energy sources: a POLES-based analysis', *Energy Economics*, 64, pp. 638–650. Available at: https://doi.org/10.1016/j.eneco.2016.03.006.

DG Energy *et al.* (2022) *Digitalisation of energy flexibility*. Brussels: European Commission. Available at: https://data.europa.eu/doi/10.2833/113770 (Accessed: 1 February 2025).

DG Energy (2024) *Study on promoting energy system integration through the increased role of renewable electricity, decentralised assets and hydrogen*. European Commission: Directorate-General for Energy. Available at: https://data.europa.eu/doi/10.2833/560304.

D'haeseleer, W. *et al.* (2017) 'Flexibility Challenges for Energy Markets: Fragmented Policies and Regulations Lead to Significant Concerns', *IEEE Power and Energy Magazine*, 15(1), pp. 61–71. Available at: https://doi.org/10.1109/MPE.2016.2629742.

Di Corato, L. and Moretto, M. (2011) 'Investing in biogas: Timing, technological choice and the value of flexibility from input mix', *Energy Economics*, 33(6), pp. 1186–1193. Available at: https://doi.org/10.1016/j.eneco.2011.05.012.

EEA & ACER (2023) *Flexibility solutions to support a decarbonised and secure EU electricity system*. European Environment Agency & Agency for the Cooperation of Energy Regulators. Available at: https://www.eea.europa.eu/en/analysis/publications/flexibility-solutions-to-support.

ENTSO-E (2022) *ENTSO-E Vision - A Power System for a Carbon Neutral Europe*. European Network of Transmission System Operators for Electricity. Available at: https://eepublicdownloads.entsoe.eu/clean-documents/tyndp-documents/entso-e_Vision_2050_report_221006.pdf.

ENTSO-E (2024) *System Flexibility Needs for the Energy Transition*. Available at: https://eepublicdownloads.blob.core.windows.net/public-cdn-container/clean-documents/Publications/System_Needs/entso-e_System_Needs_Energy_Transition_v10.pdf.

Eurelectric (2025) *Redefining Energy Security in the age of electricity*. Brussels: Eurelectric. Available at: https://energy-security.eurelectric.org/wp-content/uploads/Eurelectric-report-energy-security-in-the-age-of-electricity-1.pdf.

Eurelectric (2025)'What is flexibility in the power sector?'. Available at: https://www.eurelectric.org/in-detail/what-is-flexibility-in-the-power-sector/ (Accessed: 19 May 2025).

European Commission *et al.* (2023) *Flexibility requirements and the role of storage in future European power systems*. Publications Office of the European Union. Available at: https://doi.org/doi/10.2760/384443.

Florence School of Regulation (2025) 'Flexibility in power systems'. Available at: https://fsr.eui.eu/flexibility-in-power-systems/ (Accessed: 19 May 2025).

Fogelberg, S. and Lazarczyk, E. (2017) 'Wind power volatility and its impact on production failures in the Nordic electricity market', *Renewable Energy*, 105, pp. 96–105. Available at: https://doi.org/10.1016/j.renene.2016.12.024.

Fuhrlaender, D., Vermeulen, B. and Schnuelle, C. (2025) 'Green hydrogen transformation of the iron and steel production system: An integrated operating concept for system-internal balance, lower emissions, and support for power system stability', *Applied Energy*, 381, p. 125104. Available at: https://doi.org/10.1016/j.apenergy.2024.125104.

Gautier, A., Jacqmin, J. and Poudou, J.-C. (2018) 'The prosumers and the grid', *Journal of Regulatory Economics*, 53(1), pp. 100–126. Available at: https://doi.org/10.1007/s11149-018-9350-5.

Gautier, A., Jacqmin, J. and Poudou, J.-C. (2021) 'Optimal grid tariffs with heterogeneous prosumers', *Utilities Policy*, 68, p. 101140. Available at: https://doi.org/10.1016/j.jup.2020.101140.

Gautier, A., Jacqmin, J. and Poudou, J.-C. (2025) 'The energy community and the grid', *Resource and Energy Economics*, 82, p. 101480. Available at: https://doi.org/10.1016/j.reseneeco.2025.101480.

Gorman, W. *et al.* (2024) 'Grid connection barriers to renewable energy deployment in the United States', *Joule*, p. 101791. Available at: https://doi.org/10.1016/j.joule.2024.11.008.

GRDF (2021) *Biomethane as renewable gas: benefits and perspectives*. Available at: https://www.grdf.fr/english/biomethane-main-projects (Accessed: 9 February 2025).

Hanley, E.S., Deane, J. and Gallachóir, B.Ó. (2018) 'The role of hydrogen in low carbon energy futures–A review of existing perspectives', *Renewable and Sustainable Energy Reviews*, 82, pp. 3027–3045. Available at: https://doi.org/10.1016/j.rser.2017.10.034.

Heffron, R. *et al.* (2020) 'Industrial demand-side flexibility: A key element of a just energy transition and industrial development', *Applied Energy*, 269, p. 115026. Available at: https://doi.org/10.1016/j.apenergy.2020.115026.

Heptonstall, P.J. and Gross, R.J.K. (2021) 'A systematic review of the costs and impacts of integrating variable renewables into power grids', *Nature Energy*, 6(1), pp. 72–83. Available at: https://doi.org/10.1038/s41560-020-00695-4.

Hindman Persson, T. (2020) 'The Swedish Experience with Dynamic Retail Tariffs'. Available at: https://fsr.eui.eu/the-swedish-experience-with-dynamic-retail-tariffs/.

Horstink, L. *et al.* (2020) 'Collective Renewable Energy Prosumers and the Promises of the Energy Union: Taking Stock', *Energies*, 13(2), p. 421. Available at: https://doi.org/10.3390/en13020421.

IEA (2019) *The Role of Gas in Today's Energy Transitions – Analysis*. Paris: Interational Energy Agency. Available at: https://www.iea.org/reports/the-role-of-gas-in-todays-energy-transitions (Accessed: 1 February 2025).

IEA (2020) *Outlook for biogas and biomethane: Prospects for organic growth*. Available at: https://www.iea.org/reports/outlook-for-biogas-and-biomethane-prospects-for-organic-growth/an-introduction-to-biogas-and-biomethane (Accessed: 18 February 2025).

IEA (2023a) *Italy 2023 Energy Policy Review*. International Energy Agency. Available at: https://iea.blob.core.windows.net/assets/71b328b3-3e5b-4c04-8a22-3ead575b3a9a/Italy_2023_EnergyPolicyReview.pdf.

IEA (2023b) *Why AI and energy are the new power couple – Analysis, IEA*. Available at: https://www.iea.org/commentaries/why-ai-and-energy-are-the-new-power-couple (Accessed: 9 February 2025).

IEA (2024) *What the data centre and AI boom could mean for the energy sector – Analysis*. Available at: https://www.iea.org/commentaries/what-the-data-centre-and-ai-boom-could-mean-for-the-energy-sector (Accessed: 9 February 2025).

IEA Bioenergy (2024) *Implementation of bioenergy in Germany – 2024 update*. Interational Energy Agency. Available at: https://www.ieabioenergy.com/wp-content/uploads/2024/12/CountryReport2024_Germany_final.pdf.

IRENA (2018) *Power system flexibility for the energy transition*. Abu Dhabi: International Renewable Energy Agency. Available at: https://www.irena.org/publications/2018/Nov/Power-system-flexibility-for-the-energy-transition (Accessed: 1 February 2025).

Jerez Monsalves, J., Bergaentzlé, C. and Keles, D. (2023) 'Impacts of flexible-cooling and waste-heat recovery from data centres on energy systems: A Danish case study', *Energy*, 281. Available at: https://doi.org/10.1016/j.energy.2023.128112.

Kondziella, H. and Bruckner, T. (2016) 'Flexibility requirements of renewable energy based electricity systems – a review of research results and methodologies', *Renewable and Sustainable Energy Reviews*, 53, pp. 10–22. Available at: https://doi.org/10.1016/j.rser.2015.07.199.

Lange, H. *et al.* (2023) 'Technical evaluation of the flexibility of water electrolysis systems to increase energy flexibility: A review', *International Journal of Hydrogen Energy*, 48(42), pp. 15771–15783. Available at: https://doi.org/10.1016/j.ijhydene.2023.01.044.

Li, X. and Mulder, M. (2021) 'Value of power-to-gas as a flexibility option in integrated electricity and hydrogen markets', *Applied Energy*, 304, p. 117863. Available at: https://doi.org/10.1016/j.apenergy.2021.117863.

Lu, X., Wang, Y., Li, Y. and Zhang, Z. (2020) 'Fundamentals and business model for resource aggregator of demand response in electricity markets', *Energy*, 204, p. 117885. Available at: https://doi.org/10.1016/j.energy.2020.117885.

Lund, P.D. *et al.* (2015) 'Review of energy system flexibility measures to enable high levels of variable renewable electricity', *Renewable and Sustainable Energy Reviews*, 45, pp. 785–807. Available at: https://doi.org/10.1016/j.rser.2015.01.057.

Magnus Energy (2024) *Disentangling flexibility and its needs assessment methodology*. Available at: https://magnusenergy.com/wp-content/uploads/2025/03/magnus-energy-disentangling-flexibility-and-its-needs-sssessment-methodology.pdf.

Marconi, P. and Rosa, L. (2023) 'Role of biomethane to offset natural gas', *Renewable and Sustainable Energy Reviews*, 187, p. 113697. Available at: https://doi.org/10.1016/j.rser.2023.113697.

Margolis, R., Feldman, D. and Boff, D. (2017) *Q4 2016/Q1 2017 Solar Industry Update*. NREL/PR-6A20-68425. National Renewable Energy Lab. (NREL), Golden, CO (United States). Available at: https://www.osti.gov/biblio/1358147 (Accessed: 13 February 2025).

McKinsey & Co (2020) 'Digital transformation in energy: Achieving escape velocity'. Available at: https://www.mckinsey.com/industries/oil-and-gas/our-insights/digital-transformation-in-energy-achieving-escape-velocity.

Merten, F. and Scholz, A. (2023) *Meta-Analysis of the Costs of and Demand for Hydrogen in the Transformation to a Carbon-Neutral Economy*. Wuppertal Institute. Available at: https://epub.wupperinst.org/frontdoor/deliver/index/docId/8417/file/8417_Hydrogen.pdf.

Mills, R. (2024) *How Data Centers Can Set the Stage for Larger Loads to Come*, *RMI*. Available at: https://rmi.org/how-data-centers-can-set-the-stage-for-larger-loads-to-come/ (Accessed: 2 February 2025).

Mlecnik, E. *et al.* (2020) 'Policy challenges for the development of energy flexibility services', *Energy Policy*, 137, p. 111147. Available at: https://doi.org/10.1016/j.enpol.2019.111147.

Möbius, T. *et al.* (2023) 'Risk aversion and flexibility options in electricity markets', *Energy Economics*, 126, p. 106767. Available at: https://doi.org/10.1016/j.eneco.2023.106767.

Mossie, A.T. *et al.* (2025) 'Energy demand flexibility potential in cement industries: How does it contribute to energy supply security and environmental sustainability?', *Applied Energy*, 377, p. 124608. Available at: https://doi.org/10.1016/j.apenergy.2024.124608.

NESO (2020) *Introduction to energy system flexibility*. Available at: https://www.neso.energy/document/173721/download.

Nikolakakis, T. (2015) *Integrating Variable Renewable Energy into Power System Operations*. Washington, DC: World Bank. Available at: https://openknowledge.worldbank.org/entities/publication/d3a195d1-6acf-51af-8295-3bf2c6f164f4.

Ottesen, S.Ø., Tomasgard, A. and Fleten, S.-E. (2016) 'Prosumer bidding and scheduling in electricity markets', *Energy*, 94, pp. 828–843. Available at: https://doi.org/10.1016/j.energy.2015.11.047.

Papaefthymiou, G., Haesen, E. and Sach, T. (2018) 'Power System Flexibility Tracker: Indicators to track flexibility progress towards high-RES systems', *Renewable Energy*, 127, pp. 1026–1035. Available at: https://doi.org/10.1016/j.renene.2018.04.094.

Pierri, E. *et al.* (2020) 'Integrated methodology to assess the energy flexibility potential in the process industry', *Procedia CIRP*, 90, pp. 677–682. Available at: https://doi.org/10.1016/j.procir.2020.01.124.

Pilpola, S. and Lund, P.D. (2019) 'Different flexibility options for better system integration of wind power', *Energy Strategy Reviews*, 26, p. 100368. Available at: https://doi.org/10.1016/j.esr.2019.100368.

Pollitt, M., Covatariu, A. and Duma, D. (2024) *Towards a More Dynamic Regulation for Energy Networks*. Centre on Regulation in Europe. Available at: https://cerre.eu/wp-content/uploads/2024/03/CERRE_Dynamic_Regulation_Report_FINAL-1.pdf.

Ranaboldo, M. *et al.* (2024) 'A comprehensive overview of industrial demand response status in Europe', *Renewable and Sustainable Energy Reviews*, 203, p. 114797. Available at: https://doi.org/10.1016/j.rser.2024.114797.

Rangarajan, A., Foley, S. and Trück, S. (2023) 'Assessing the impact of battery storage on Australian electricity markets', *Energy Economics*, 120, p. 106601. Available at: https://doi.org/10.1016/j.eneco.2023.106601.

Rego De Vasconcelos, B. and Lavoie, J.-M. (2019) 'Recent Advances in Power-to-X Technology for the Production of Fuels and Chemicals', *Frontiers in Chemistry*, 7, p. 392. Available at: https://doi.org/10.3389/fchem.2019.00392.

Riepin, I., Brown, T. and Zavala, V.M. (2025) 'Spatio-temporal load shifting for truly clean computing', *Advances in Applied Energy*, 17, p. 100202. Available at: https://doi.org/10.1016/j.adapen.2024.100202.

RMI (2024) *Powering the Data-Center Boom with Low-Carbon Solutions*. Rocky Mountains Institute. Available at: https://rmi.org/wp-content/uploads/dlm_uploads/2024/11/Powering_the_Data_Center_Boom_with_Low_Carbon_Solutions_report.pdf.

Rodríguez-Vilches, R., Martín-Martínez, F., Sánchez-Miralles, Á., de la Cámara, J.R.G. and Delgado, S.M., 2024. Methodology to assess prosumer participation in European electricity markets. *Renewable and Sustainable Energy Reviews*, *191*, p.114179. Available at: https://doi.org/10.1016/j.rser.2023.114179.

Rosenow, J. *et al.* (2022) 'Heating up the global heat pump market', *Nature Energy*, 7(10), pp. 901–904. Available at: https://doi.org/10.1038/s41560-022-01104-8.

Ruhnau, O. (2022). How flexible electricity demand stabilizes wind and solar market values: The case of hydrogen electrolyzers. *Applied Energy*, *307*, 118194.

Schipfer, F. *et al.* (2022a) 'Status of and expectations for flexible bioenergy to support resource efficiency and to accelerate the energy transition', *Renewable and Sustainable Energy Reviews*, 158, p. 112094. Available at: https://doi.org/10.1016/j.rser.2022.112094.

Schlapbach, L. and Züttel, A. (2001) 'Hydrogen-storage materials for mobile applications', *Nature*, 414(6861), pp. 353–358. Available at: https://doi.org/10.1038/35104634.

Schröer, D. and Latacz-Lohmann, U. (2024) 'Flexibilization or biomethane upgrading? Investment preference of German biogas plant operators for the follow-up of guaranteed feed-in tariffs', *GCB Bioenergy*, 16(2), p. e13111. Available at: https://doi.org/10.1111/gcbb.13111.

Séguin, H. and Bigouret, A. (2023) 'Hybrid heat in Quebec: Energir and Hydro-Quebec's collaboration on building heat decarbonization', *Canadian Climate Institute*. Available at: https://climateinstitute.ca/publications/hybrid-heat-in-quebec/.

Shu, D.Y. *et al.* (2023) 'The role of carbon capture and storage to achieve net-zero energy systems: Trade-offs between economics and the environment', *Renewable and Sustainable Energy Reviews*, 178, p. 113246. Available at: https://doi.org/10.1016/j.rser.2023.113246.

Sinsel, S.R., Riemke, R.L. and Hoffmann, V.H. (2020) 'Challenges and solution technologies for the integration of variable renewable energy sources—a review', *Renewable Energy*, 145, pp. 2271–2285. Available at: https://doi.org/10.1016/j.renene.2019.06.147.

Sousa, T. *et al.* (2019) 'Peer-to-peer and community-based markets: A comprehensive review', *Renewable and Sustainable Energy Reviews*, 104, pp. 367–378. Available at: https://doi.org/10.1016/j.rser.2019.01.036.

Stamatakis, E., Perwög, E., Garyfallos, E., Millán, M. S., Zoulias, E., & Chalkiadakis, N. (2022). Hydrogen in grid balancing: the European market potential for pressurized alkaline electrolyzers. *Energies*, *15*(2), 637.

Steadman, S., Bennato, A.R. and Giulietti, M. (2023) 'From energy consumers to prosumers: the role of peer effects in the diffusion of residential microgeneration technology', *Journal of Industrial and Business Economics*, 50(2), pp. 321–346. Available at: https://doi.org/10.1007/s40812-023-00264-2.

Stute, J. and Klobasa, M. (2024) 'How do dynamic electricity tariffs and different grid charge designs interact? - Implications for residential consumers and grid reinforcement requirements', *Energy Policy*, 189, p. 114062. Available at: https://doi.org/10.1016/j.enpol.2024.114062.

Trinomics & Artelys (2022) *Study on flexibility options to support decarbonization in the Energy Community*. Energy Community. Available at: https://www.energy-community.org/documents/studies.html.

Villar, J., Bessa, R. and Matos, M. (2018) 'Flexibility products and markets: Literature review', *Electric Power Systems Research*, 154, pp. 329–340. Available at: https://doi.org/10.1016/j.epsr.2017.09.005.

Wang, D. *et al.* (2018) 'Quantifying the flexibility of hydrogen production systems to support large-scale renewable energy integration', *Journal of Power Sources*, 399, pp. 383–391. Available at: https://doi.org/10.1016/j.jpowsour.2018.07.101.

Wang, K. *et al.* (2023) 'Dynamic network tariffs: Current practices, key issues and challenges', *Energy Conversion and Economics*, 4(1), pp. 23–35. Available at: https://doi.org/10.1049/enc2.12079.

Wang, W. *et al.* (2019) 'Combined heat and power control considering thermal inertia of district heating network for flexible electric power regulation', *Energy*, 169, pp. 988–999. Available at: https://doi.org/10.1016/j.energy.2018.12.085.

Zafar, R. *et al.* (2018) 'Prosumer based energy management and sharing in smart grid', *Renewable and Sustainable Energy Reviews*, 82, pp. 1675–1684. Available at: https://doi.org/10.1016/j.rser.2017.07.018.

Zhang, C. *et al.* (2018) ‘Peer-to-Peer energy trading in a Microgrid’, *Applied Energy*, 220, pp. 1–12. Available at: https://doi.org/10.1016/j.apenergy.2018.03.010.

Zhang, Q. and Grossmann, I.E. (2016) ‘Planning and Scheduling for Industrial Demand Side Management: Advances and Challenges’, in M. Martín (ed.) *Alternative Energy Sources and Technologies: Process Design and Operation*. Cham: Springer International Publishing, pp. 383–414. Available at: https://doi.org/10.1007/978-3-319-28752-2_14.

Appendix A- Documents used in the textual analysis

	Demand Side	Supply Side	Storage	Short-term (Hourly/Daily)	Long-term (Seasonal/Annual)	Binding	Compensation	Mandatory
Reg. 2024/1747 (EMDR)	Yes – demand response & smart meters (art. 18, 23)	Yes – renewable energy sources + peak shaving (rec. 17, 46)	Yes – energy storage (rec. 46–47)	Yes – intraday market (rec. 13–15), peak shaving before/day-ahead (art. 7a)	Yes – 5–10y flexibility needs assessment (art. 19e)	Mixed – binding for TSOs/DSOs (art. 19e), indicative for MS (rec. 46)	Yes – CfDs (rec. 35), PPAs (rec. 28–30), peak shaving remuneration (art. 7a)	Mixed – mandatory for system operators (art. 19e), voluntary for providers (rec. 47)
Regulation (EU) 2019/943	Yes – demand response	Yes – flexibility sources	Yes – mentioned	Yes – intraday trading	Yes – long-term resource adequacy	Binding for operators; derogations	Yes – market mechanisms	Mandatory for operators; voluntary for
Directive (EU) 2019/944	Yes – active consumers	Yes – active consumers, flexibility services	Yes – mentioned	No – not mentioned	Yes – long-term flexibility services	Mixed – mandatory for Member States to set rules; derogations possible	Yes – market mechanism	Mandatory – Member States must establish proper regulations
Art. 19e (2024/1747)	Yes – demand response	Yes – flexibility sources	Yes – mentioned	Yes – intraday trading	Yes – long-term resource adequacy assessment	Binding for operators; derogation possible	Yes – market mechanisms	Mandatory for operators; voluntary for actors
ACER Dec. 03/2025	N/A	N/A	N/A	Yes – 15-min trading in SIDC	N/A	Binding – NEMOs/TSOs	N/A	Mandatory – for platform operators
ENTSO-E / DSO DR Code (Draft)	N/A	Yes – flexibility services	N/A	N/A	Yes – part of long-term planning & market structure	Binding – Member States must establish rules and platforms (art. 6, 45a)	N/A – registry enables access, not a compensation tool	Mixed – mandatory for operators; voluntary registration by flexibility providers

	Demand Side	Supply Side	Storage	Short-term (Hourly/Daily)	Long-term (Seasonal/Annual)	Binding	Compensation	Mandatory
Dir. 2024/1788 (Gas & H_2 Directive)	Yes – active consumers empowered to store/sell	Yes – hydrogen and renewable gas flexibility in system design	Yes – storage mentioned	Yes – switching and market access mechanisms	Yes – 2030/2035 objectives and regulated access	Mixed – binding for infrastructure; voluntary for market actors	Yes – compensation for regulated pricing	Mixed – obligations on operators; consumers remain voluntary
FNA Methodology	No – demand response	Yes – flexibility technologies	Yes – mentioned	Yes – 5–15 min to daily	Yes – 5–10y planning horizon	Binding – under art. 19e	N/A	Mandatory – for TSOs/DSOs
Letta Report (2024)	Yes – demand response	Yes – grid operators, flexibility solutions	Yes – mentioned	N/A	Yes – planning and long-term investments	Non-binding	Yes – market mechanisms	Voluntary
Draghi Report (2024)	Yes – demand response	Yes – EV fleets, flexibility solutions and infrastructures	Yes – mentioned	No – not mentioned	Yes – long-term planning and investments	Non-binding	Yes – compensation mechanisms for industrial flexibility; monetisation via CfDs, PPAs	Voluntary
Competitiveness Compass	Yes – demand response, demand	Yes – flex. services	N/A	N/A	N/A	Non-binding	N/A	Voluntary
Clean Industrial Deal	Yes – demand response	Yes – clean electrification	Yes – mentioned	N/A	Yes – strategic 2040 targets	Non-binding	Yes – CfDs, tax credits, support schemes, retail contracts	Voluntary
Action Plan for Affordable Energy	Yes – demand response, smart meters	Yes – grid infrastructure, power system flexibility	Yes – mentioned	Yes – pricing reform	Yes – infrastructure strategy	Non-binding	Yes – fiscal tools & remuneration	Voluntary

1. Legal Documents

Text 1. Electricity Market Design Reform

The EU regulation defines flexibility as '*the ability of an electricity system to adjust to the variability of generation and consumption patterns and grid availability across relevant market timeframes*.' The framework addresses this through three interconnected dimensions. Operational flexibility encompasses both demand-side measures (demand response, smart metering), supply-side, and energy storage, focusing on both short-term adjustments and long-term implementation through voluntary market participation. Non-fossil flexibility prioritises renewable energy sources through compensation mechanisms and support schemes, acknowledging the need to manage traditionally less flexible renewable sources in the market system. The regulatory framework requires Member States to conduct mandatory flexibility needs assessments and long-term reporting (5-10 years) based on ACER methodology. This includes setting indicative targets for non-fossil flexibility and implementing appropriate compensation solutions mechanisms, ensuring a balanced transition toward a more sustainable and adaptable energy system.

Flexibility is mostly associated with: non-fossil, the idea of supply (services, solutions, provide, offer), and flexibility assessment.

Text 4. Article 19e of revised Electricity Regulation (EU) 2019/943 (as amended by 2024/1747)

This is an addendum to Electricity Market Design Reform. It builds on the same principle, and relative to its length, the concept of flexibility appears more concentrated.

Text 2. Electricity Regulation

The regulation views market participation as a key driver for electrical system flexibility, employing a dual approach: encouraging active consumer participation while integrating renewable energy sources and developing energy storage solutions. The market mechanism uses efficient pricing to send clear signals guiding investments toward more flexible solutions. While certain regulatory principles may have derogations, these exceptions must not compromise the overall goal of enhancing system flexibility. The regulation establishes ongoing monitoring requirements, with TSOs and DSOs submitting annual reports on their flexibility enhancement measures.

Flexibility is mostly associated with: signals, market signals, incentives, as well as assessments.

Text 3. Electricity Directive

The Directive (EU) 2019/944 frames flexibility as central to Europe's electricity market evolution. It positions consumers as key flexibility providers rather than passive users, enabling them to trade their flexibility through smart metering and data access. Member States must implement tariff structures that encourage flexibility and require Distribution System Operators to procure flexibility services under clear specifications. The regulatory framework prohibits barriers to flexibility development, with limited exceptions allowed only if they do not compromise system flexibility.

Flexibility is mostly associated with: 'rewards', 'incentives', 'trade their flexibility', 'to offer their flexibility'.

Text 5. ACER Decision 03-2025 on Intraday Market Coupling

The European Union Agency for Energy Regulators has approved amendments to electricity products in the single intraday market, introducing 15-minute trading intervals.

The document does not mention flexibility, but as an outcome increases short-run flexibility of the single intraday market.

Text 6. ENTSO-E & EU DSO Entity – Network Code on Demand Response

The regulation establishes a harmonised European framework for creating national 'flexibility registers' serving as centralised and standardised databases for the registration, qualification, and monitoring of flexible electricity resources, thus facilitating their participation in balancing and local services markets.

Flexibility is almost exclusively mentioned as ''flexibility registers'.

Text 7. Gas Package (Directive, December 2023)

Active consumers can produce, consume, store, and sell renewable gas, and participate in flexibility schemes, giving them a role in the market beyond traditional passive consumption. Third-party access will transition from optional negotiated arrangements (until 2032, to give Member States more flexibility) to mandatory regulated access afterward, ensuring all market participants can use hydrogen infrastructure under fair, transparent conditions set by regulators.

Flexibility is mostly associated with: active consumers and delayed application of the third-party access rule.

Text 8. FNA Methodology – ENTSO-E & DSO Entity

The national-level FNA methodology, pursuant to Article 19e of Regulation (EU) 2019/943 (as amended by Regulation 2024/1747), defines the data TSOs and DSOs must submit and prescribes a harmonised, quantitative, technology-neutral approach to identify electricity flexibility needs—covering renewable integration, rapid and intra-day ramping, and network constraints—across temporal scales from very-fast (5–15 min) to seasonal and spatial levels (transmission vs. distribution), distinguishing upward and downward flexibility. It sets an implementation timeline (roles in 3 months, data definitions in 4 months, full analyses in 10 months) and reporting requirements aligned with 5- to 10-year resource adequacy assessments to support national non-fossil flexibility targets.

The term mostly used in this document is flexibility needs due to the nature of the assessment.

2. Policy Reports

Texte 1. Letta Report (2024) – Much more than a market

The report advocates for cross-border cooperation to reduce costs associated with procuring flexibility across the Single Market, as current schemes are mostly confined to domestic operators. Enhanced interconnection between countries would increase system flexibility and mitigate price volatility. In this document, short run is defined as in a few years.

Flexibility is mostly associated with: eliminate barriers to interconnection in order to increase flexibility, cross-border flexibility, flexibility solutions.

Texte 9. Draghi Report (2024) – The Future of European Competitiveness

The Draghi report highlights that flexibility requirements will rise sharply — from covering just 11 % of EU electricity demand in 2021 to an estimated 30 % by 2050 — and calls for a full mapping of these needs alongside integrated planning of renewables, storage, hydrogen and grid upgrades. It recommends removing barriers and standardizing incentives — introducing flexible connection agreements, adapting network tariffs to true system costs, setting up a uniform compensation mechanism for industrial demand response, and fast-tracking the authorisation of capacity mechanisms and other flexibility instruments. Finally, it proposes harmonizing EU flexibility markets via cross-border auctions, locational price signals and digitalised permitting to contain system costs, curb price volatility and strengthen pan-European competitiveness.

Flexibility is mostly associated with: market-based approach, the idea of assessment of needs, investments, increase of interconnexion between MS, a tool that will reduce costs.

Texte 10. EC (2025) – A Competitiveness Compass for the EU, COM(2025) 30

Recommendation to accelerate the clean energy transition, by lowering its cost and promoting electrification. Demand flexibility plays a role in the long run to that end The word flexibility is also used to talk about the ability of the EU to adapt to its goal.

There is only one mention of flexibility directly related to energy (demand flexibility).

Texte 11. EC (2025) – The Clean Industrial Deal, COM(2025) 85

Europe’s grid still faces weak interconnections, poor integration, and low flexibility. To address this, the Clean Industrial Deal promotes AI-enabled smart grids and IoT monitoring to unlock demand-side flexibility and integrate renewables. The Commission will explore a PPA-based ‘clean flexibility’ tool to monetise consumption shifts, while new guidance by Q4 2025 will support remuneration of flexibility in retail contracts. The revised State Aid Framework also enables Member States to fund non-fossil flexibility solutions.

Flexibility is associated with: demand-side, development of tools to promote remuneration of flexibility, and funding non-fossil flexibility.

Texte 12. EC (2025) – Action Plan for Affordable Energy

System flexibility is key to integrating clean energy and cutting peak demand, with digitalisation, storage, and demand response potentially saving €12 billion annually. By mid-2025, the Commission will propose tariffs that reward load-shifting and electrification, clarify State aid for non-fossil flexibility, and issue guidance on promoting remuneration of flexibility in retail contracts. It will also consult on a PPA-based ‘clean flexibility’ instrument. Removing barriers for aggregators, speeding up permits, and deploying smart meters will be essential to unlock lower prices and avoid costly peak generation.

Flexibility is associated with: demand-side, system, lowering costs. Note : Here, there are several bibliographical references that mentions ‘flexibility’ but are not part of the text per se.

Appendix B- Regulatory Framework by Technology

Technology	Regulatory Framework	Details
Biomethane	Biomethane Industrial Partnership	Established on September 28, 2022, the BIP fosters collaboration among the European Commission, EU Member States, industry stakeholders, feedstock producers, academics, and NGOs. Its primary goal is to support the achievement of the 2030 biomethane production target and to create conditions for further expansion by 2050. The partnership also assists Member States in developing national biomethane strategies and promotes cooperation with neighbouring countries, including Ukraine. Source: https://bip-europe.eu/
	Methane Emissions Regulation (EU/2024/1787)	Effective from August 2024, this regulation mandates improved measurement, reporting, and verification of methane emissions in the energy sector. It enforces leak detection and repair programs and prohibits venting and flaring practices, aiming to minimise methane emissions associated with energy production, including biomethane. Source: https://energy.ec.europa.eu/topics/carbon-management-and-fossil-fuels/methane-emissions_en
	Renewable Energy Directive (RED III)	This directive sets binding targets for renewable energy consumption within the EU, including specific provisions for biomethane. It establishes sustainability criteria and greenhouse gas emission savings thresholds that biomethane must meet to be counted towards national renewable energy targets. Source: https://energy.ec.europa.eu/topics/renewable-energy/renewable-energy-directive-targets-and-rules/renewable-energy-directive_en
	REPowerEU Plan	Launched in May 2022, this strategic plan sets an ambitious target for the EU to produce 35 billion cubic meters (bcm) of sustainable biomethane annually by 2030. The plan outlines actions to scale up biomethane production, emphasizing the use of organic waste and residues over food and feedstocks to avoid land-use conflicts. It also highlights the need for investments in upgrading biogas to biomethane and facilitating its injection into the gas grid. Source: https://energy.ec.europa.eu/topics/renewable-

		energy/bioenergy/biomethane_en
	Standardisation Efforts	The EU is actively working on harmonizing gas quality standards to facilitate biomethane integration and cross-border trade. The European Committee for Standardisation (CEN) has developed standards such as EN 16726, which aims to enhance the interoperability of gas systems across Member States. However, challenges persist due to variations in permissible oxygen levels and other parameters across countries. Revisions to these standards are underway to address these discrepancies and support the sector's growth. Source: https://www.europeanbiogas.eu/overview-on-key-eu-policies-for-the-biogas-sector/
Hydropower	Water Framework Directive (2000/60/EC)	This directive aims to achieve 'good ecological status' for all EU water bodies. It establishes strict environmental objectives to ensure sustainable water use while protecting aquatic ecosystems. Hydropower projects must comply with its requirements by minimizing ecological impacts, such as altered river flow, fish migration barriers, and sediment transport disruption. The directive encourages river basin management planning to balance renewable energy generation with water conservation. Source: https://environment.ec.europa.eu/topics/water/water-framework-directive_en
	Renewable Energy Directive (RED II) (2018/2001/EU) and its amendment (EU/2023/2413)	The main target of this set of framework interventions is to promote the use of renewable energy across the EU, including hydropower, by achieving at least 42.5% renewable energy in the EU's overall energy mix by 2030. The amendment (EU/2023/2413) strengthens these commitments, introducing streamlined permitting procedures for renewable projects, including hydropower, in designated renewables acceleration areas. It emphasises sustainability by requiring hydropower projects to comply with environmental safeguards, such as fish migration measures and ecological flow requirements, ensuring that hydropower expansion does not compromise water ecosystems while supporting the EU's clean energy transition. Source: https://energy.ec.europa.eu/topics/renewable-energy/renewable-energy-directive-targets-and-rules/renewable-energy-directive_en
	Environmental Impact Assessment	The main goal of this intervention is to ensure that environmental considerations are integrated into the decision-making process for projects that may have significant effects on

	(EIA) Directive (2011/92/EU)	the environment. It requires developers to assess and report potential environmental impacts before obtaining approval, allowing authorities to evaluate risks and implement mitigation measures. The directive promotes public participation, transparency, and sustainable development, ensuring that projects, including those related to energy, infrastructure, and industry, minimise negative environmental consequences while balancing economic and social needs. Source: https://environment.ec.europa.eu/law-and-governance/environmental-assessments/environmental-impact-assessment_en
	Guidance document on the requirements for hydropower in relation to EU nature legislation	The document provides practical recommendations to ensure hydropower projects align with the EU's environmental directives, particularly the Habitats and Birds Directives. It emphasises the need for thorough assessments of potential impacts on protected species and habitats, advocating for measures to prevent or minimise adverse effects. Source: https://op.europa.eu/en/publication-detail/-/publication/b0279310-a5b4-11e8-99ee-01aa75ed71a1/language-en
Green Hydrogen	EU Hydrogen Strategy (2020)	This strategy defines the EU's vision for hydrogen as a key driver in achieving climate neutrality. It prioritises the production and deployment of renewable hydrogen to decarbonise multiple sectors, setting ambitious targets for scaling up hydrogen technologies and infrastructure. Meeting the deployment goals set for 2024 and 2030 necessitates a robust investment agenda that maximises synergies, ensures coherence across various EU funding mechanisms and EIB financing, leverages private investment, and prevents excessive public support. Source: https://energy.ec.europa.eu/topics/eus-energy-system/hydrogen_en?utm_source
	Hydrogen and Decarbonised Gas Market Package (2024)	This legislative package, consisting of Directive (EU) 2024/1788 and Regulation (EU) 2024/1789, aims to accelerate the adoption of renewable and low-carbon gases, including hydrogen. It establishes a comprehensive regulatory framework for dedicated hydrogen infrastructure and markets, fostering the integration of green hydrogen into the EU energy system. Source: https://energy.ec.europa.eu/topics/markets-and-consumers/hydrogen-and-decarbonised-gas-market_en
	Delegated Acts on Renewable	In June 2023, the European Commission adopted two delegated acts to define the production criteria for renewable hydrogen.

	Hydrogen (2023)	The first act specifies the conditions under which hydrogen can be classified as renewable, focusing on additionality, temporal, and geographical correlation of renewable electricity used in electrolysis. The second act outlines a methodology for calculating the life-cycle greenhouse gas emissions of RFNBOs to ensure they meet the required emission reduction thresholds. Source: https://www.europarl.europa.eu/RegData/etudes/BRIE/2023/747085/EPRS_BRI%282023%29747085_EN.pdf
Solar PV	European Solar Charter (2024)	Signed on April 15, 2024, the European Solar Charter establishes a set of voluntary commitments aimed at strengthening the EU's photovoltaic sector. It fosters collaboration among Member States and industry stakeholders to accelerate solar energy adoption while ensuring a resilient and sustainable supply of high-quality solar PV products in Europe. The charter also emphasises the expansion of renewable energy auctions and other support mechanisms, along with the swift implementation of the relevant provisions of the Net-Zero Industry Act to enhance Europe's solar manufacturing capabilities. Source: https://www.solarpowereurope.org/advocacy/position-papers/european-solar-charter
	EU Solar Energy Strategy (2022)	As part of the REPowerEU plan, the European Commission adopted this strategy in May 2022, targeting over 320 GW of newly installed solar PV capacity by 2025 and nearly 600 GW by 2030. The strategy identifies barriers and proposes initiatives to accelerate solar energy deployment, including the European Solar Rooftops Initiative, which aims to make rooftop solar installations mandatory for new buildings within a specific timeframe. Source: https://energy.ec.europa.eu/topics/renewable-energy/solar-energy_en
	Eco-design and Energy Labelling Regulations (Proposed 2023)	The European Commission plans to introduce regulations focusing on the efficiency, durability, reparability, and recyclability of solar PV modules, inverters, and systems sold within the EU. These measures aim to ensure environmental sustainability and consumer transparency in the solar energy market. Source: https://commission.europa.eu/news/ecodesign-and-energy-labelling-working-plan-2022-2024-2022-04-06_en?utm_source=chatgpt.com
	Renewable	The interventions focused on the use of solar energy introduce

	Energy Directive (RED II) (2018/2001/EU)	measures to streamline permitting processes for renewable energy projects, facilitating faster implementation of solar installations. Additionally, the directive encourages Member States to promote energy communities and enhance cooperation with local authorities, aiming to integrate more solar energy into buildings and urban areas. These initiatives are designed to harness the potential of solar energy, contributing significantly to the EU's decarbonisation and energy transition goals. Source: https://energy.ec.europa.eu/document/download/efcd200c-b9ae-4a9c-98ab-73b2fd281fcc_en?filename=C_2024_5041_1_EN_ACT_part1_v10.pdf
Onshore/Offshore Wind	Trans-European Networks for Energy (TEN-E) Regulation	Revised in 2022, the TEN-E Regulation aims to modernise and expand Europe's energy infrastructure. It provides a framework for the identification and development of Projects of Common Interest (PCIs), which are essential for integrating renewable energy sources like wind into the EU's energy grid. The regulation also establishes regional cooperation structures to support the creation of integrated and efficient offshore and onshore grids, including hybrid projects that involve Member States and offshore wind installations. Source: https://www.europarl.europa.eu/RegData/etudes/BRIE/2024/757628/EPRS_BRI%282024%29757628_EN.pdf
	Offshore Renewable Energy Strategy (2020)	This strategy outlines the EU's plan to harness the potential of offshore wind and other marine renewable energy sources. Adopted by the European Commission in 2020, it aims to significantly expand Europe's offshore renewable energy capacity to support climate neutrality by 2050. The strategy sets ambitious targets to increase offshore wind capacity from 12 GW in 2020 to at least 60 GW by 2030 and 300 GW by 2050, complemented by 40 GW of ocean energy and other emerging technologies, such as floating wind and solar, by mid-century. To achieve these goals, the strategy proposes measures including maritime spatial planning to identify suitable sites, coordinated grid planning and development, enhancing the regulatory framework, mobilizing public and private investments, and fostering research and innovation. These initiatives aim to harness the vast potential of Europe's five sea basins, promoting sustainable and inclusive growth within the EU. Source: https://energy.ec.europa.eu/topics/renewable-energy/offshore-renewable-energy_en

	North Seas Energy Cooperation	This is a regional framework established to advance the development of offshore renewable energy and grid infrastructure in the North Sea region, encompassing the North Sea, Irish Sea, and Celtic Sea. Comprising nine countries—Belgium, Denmark, France, Germany, Ireland, Luxembourg, the Netherlands, Norway, and Sweden—along with the European Commission, this cooperation aims to facilitate cost-effective and sustainable energy production through collaborative efforts. Key objectives include coordinating the planning and construction of offshore wind farms, developing an integrated energy grid, and enhancing cross-border energy trade. In October 2024, NSEC members convened in Odense Port, Denmark, to adopt the 2025-2027 work programme, reaffirming their commitment to transforming the North Seas into 'Europe's green power plant. Source: https://energy.ec.europa.eu/topics/infrastructure/high-level-groups/north-seas-energy-cooperation_en

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