Implementation of Flexibility Sources and Advanced Control Algorithms for Supporting Modern Power Systems with a High Share of Renewable Energy Sources

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List of Abbreviations

Executive Summary

This technical report presents a comprehensive framework for assessing and quantifying the flexibility potential of four key flexibility sources in modern power systems: utility battery storage, electrolysers, electric vehicles, and pumped hydroplants. With a focus on the European Union context, the report examines the technical characteristics, constraints, and flexibility potential of each source for providing critical power system services including frequency regulation, voltage support, and grid congestion management.

The assessment framework developed in this report enables systematic evaluation of flexibility sources across multiple dimensions, considering technical, economic, and operational factors. Through detailed analysis and case studies, the report demonstrates how different flexibility sources can be compared and optimized for specific grid applications, highlighting their complementary roles in supporting power systems with high shares of renewable energy.

The findings reveal that no single technology excels across all applications, with each source offering distinct advantages for specific services and contexts. Utility battery storage excels in fast-response applications, electrolysers offer valuable downward regulation capability, electric vehicles provide distributed flexibility resources, and pumped hydroplants deliver unmatched long-duration services. The report concludes that the EU's growing flexibility needs will be best met through a diverse portfolio of these complementary resources, strategically deployed and operated to leverage their respective strengths.

1 Introduction

1.1 Background and Motivation

The transition to a decarbonized power system in the European Union presents significant challenges for system operation and stability. As the share of variable renewable energy sources (vRES) such as wind and solar continues to grow, the need for flexibility in the power system has become increasingly critical. According to the European Network of Transmission System Operators for Electricity (ENTSO-E, 2024), flexibility needs in the EU power sector are projected to amount to Germany's annual power production by 2050—a substantial increase from current levels.

Flexibility in power systems refers to the ability to modify generation and/or consumption patterns in response to external signals (such as price changes, or explicit requests from the system operator) to provide a power system service. This flexibility is essential for maintaining the balance between supply and demand, managing grid constraints, and ensuring system stability in the face of increasing variability and uncertainty.

Several flexibility sources are emerging as key enablers of the energy transition in the EU. Utility-scale battery storage systems are being deployed at an unprecedented rate, with capacity expected to reach 100 GW by 2030 (SolarPower Europe, 2025). Electrolysers, which convert electricity to hydrogen, are targeted to reach 40 GW of capacity by 2030 according to the EU Hydrogen Strategy. Electric vehicles are projected to grow to 50-65 million by 2030, representing a massive distributed flexibility resource. Meanwhile, pumped hydropower storage remains the largest form of energy storage in the EU, with potential for expansion and modernization.

Understanding the flexibility potential of these diverse resources—their capabilities, constraints, and optimal applications—is crucial for power system planning, market design, and policy development. However, there is currently no standardized framework for assessing and comparing the flexibility potential of different technologies in the context of specific power system services.

1.2 Objectives and Scope

This technical report aims to develop a comprehensive framework for calculating and estimating the flexibility potential of four key flexibility sources: utility battery storage, electrolysers, electric vehicles, and pumped hydroplants. The specific objectives are to:

1. Define a structured framework for assessing flexibility potential, considering technical, economic, and operational factors
2. Analyze the technical characteristics and constraints of each flexibility source
3. Develop a methodology for quantifying flexibility potential across different timescales and applications
4. Assess the suitability of each flexibility source for providing specific power system services
5. Provide practical examples of framework application through detailed case studies

The scope of this report is focused on the European Union context, with particular attention to three critical power system services:

- **Frequency regulation**: Including Frequency Containment Reserve (FCR), automatic Frequency Restoration Reserve (aFRR), and manual Frequency Restoration Reserve (mFRR)
- **Voltage support**: Including reactive power provision and voltage control
- **Grid congestion management**: Including peak shaving, valley filling, and redispatch

The report considers both current technological capabilities and near-future developments (horizon 2030), providing a forward-looking assessment while remaining grounded in realistic technical and economic parameters.

1.3 Report Structure

This report is structured to provide a systematic and comprehensive assessment of flexibility potential:

Section 2 establishes the framework for flexibility assessment, defining key parameters, methodologies, and evaluation criteria that will be applied throughout the report.

Sections 3-6 examine each flexibility source in detail: - Section 3: Utility Battery Storage - Section 4: Electrolysers - Section 5: Electric Vehicles - Section 6: Pumped Hydroplants

Each of these sections follows a consistent structure, analyzing technical characteristics, constraints, flexibility potential, applications to power system services, EU case studies, challenges, and future developments.

Section 7 provides a comparative analysis of the flexibility range across all sources, highlighting their relative strengths and limitations for different power system services.

Section 8 presents practical application examples of the assessment framework through detailed case studies, demonstrating how the framework can be applied to real-world scenarios.

Section 9 concludes the report with a summary of key findings, implications for EU power system planning, policy recommendations, and directions for future research.

Section 10 provides a comprehensive bibliography and references.

Throughout the report, the focus remains on providing practical, evidence-based insights that can inform decision-making by system operators, regulators, policy makers, and industry stakeholders in the EU's evolving power system landscape.

2 Framework for Flexibility Assessment in Power Systems

2.1 Introduction and Context

The transition to a decarbonized energy system in the European Union has significantly increased the need for flexibility in power systems. As variable renewable energy sources (vRES) like solar and wind continue to grow, the power system faces new challenges in maintaining the balance between supply and demand at all times. According to the Florence School of Regulation (2025), flexibility in power systems has evolved from a short-term reliability issue to a multifaceted concept encompassing multiple timescales and addressing various system needs.

The European regulatory framework, particularly through Regulation (EU) 2024/1747 (Electricity Market Design Reform), now mandates Member States to perform periodic flexibility needs assessments. These assessments aim to support the definition of indicative national objectives for non-fossil flexibility and potentially lead to the implementation of non-fossil flexibility support schemes. This framework provides a structured approach to assess the flexibility potential of various resources, including utility battery storage, electrolysers, electric vehicles, and pumped hydroplants, in the context of EU power systems.

2.2 Definition and Scope of Flexibility

2.2.1 Evolution of Flexibility Concept

The concept of flexibility in power systems has evolved significantly over time:

- **Early 2010s**: Flexibility was primarily considered a short-term issue related to the uncertainty of weather forecasting and the need for swift responses from traditional power plants to unexpected drops in renewable production.
- **Mid-2010s to early 2020s**: As renewable capacity increased and traditional thermal plants were gradually phased out, the concept expanded to encompass resource “adequacy” – the ability of the system to maintain supply during prolonged periods without sun or wind.
- **Current understanding**: Flexibility now also addresses network congestion at both transmission and distribution levels, where flexible resources can be mobilized by system operators to deal with local constraints and maintain appropriate voltage levels.

2.2.2 Comprehensive Definition

For the purposes of this framework, flexibility in power systems is defined as:

The ability of power system resources (generation, storage, demand, or network elements) to modify their production, consumption, or transmission patterns in response to system needs across various timeframes, from seconds to seasons, to maintain reliable and efficient system operation in the face of variability and uncertainty.

2.3 Dimensions of Flexibility Assessment

The assessment of flexibility potential must consider multiple dimensions:

2.3.1 Temporal Dimension

According to ENTSO-E (2024), flexibility needs can be categorized into different timeframes:

- **Short-term flexibility** (seconds to hours): Addresses forecast errors, frequency regulation, and rapid response to system imbalances.
- **Medium-term flexibility** (hours to days): Manages daily and weekly patterns of renewable generation and demand.
- **Long-term flexibility** (days to weeks): Addresses prolonged periods of low renewable generation, seasonal variations, and adequacy concerns.

2.3.2 Spatial Dimension

Flexibility needs and resources must be assessed at different geographical levels:

- **Local level**: Distribution grid constraints and voltage regulation.
- **Regional level**: Transmission congestion management.
- **System-wide level**: Overall balance between generation and demand.
- **Cross-border level**: Interconnection capacity and coordination between countries.

2.3.3 Technical Dimension

The technical characteristics that determine flexibility potential include:

- **Ramping capability**: The speed at which a resource can adjust its output (MW/min).
- **Response time**: How quickly a resource can react to a flexibility request (seconds to minutes).
- **Duration**: How long a resource can sustain its flexibility provision (minutes to days).
- **Cycling capability**: The ability to frequently change operating points without degradation.
- **Energy capacity**: The total energy that can be provided or absorbed (MWh).
- **Power capacity**: The maximum power that can be provided or absorbed (MW).

2.3.4 Economic Dimension

The economic aspects of flexibility provision include:

- **Activation costs**: Variable costs associated with providing flexibility.
- **Opportunity costs**: Foregone revenue from alternative uses of the resource.
- **Investment costs**: Capital expenditure required to enable flexibility provision.

- **Market value**: The economic value of flexibility in different markets and timeframes.

2.4 Methodology for Assessing Flexibility Potential

This framework proposes a multi-step methodology for assessing the flexibility potential of different resources:

2.4.1 Technical Characterization

1. **Identify key technical parameters** of the flexibility resource:
    - Maximum power capacity (MW)
    - Energy capacity (MWh)
    - Minimum and maximum operating points
    - Ramping rates (MW/min)
    - Response time
    - Minimum up/down times
    - Cycling limitations
    - Efficiency factors (round-trip efficiency for storage)
2. **Define operational constraints**:
    - Technological limitations
    - Regulatory restrictions
    - Primary purpose constraints (e.g., transportation needs for EVs)
    - Network connection limitations

2.4.2 Flexibility Potential Quantification

1. **Theoretical potential**: The maximum flexibility that could be provided if all technical capabilities were fully utilized without constraints.
2. **Technical potential**: The flexibility that can be realistically provided considering all technical constraints and limitations.
3. **Economic potential**: The flexibility that is economically viable to provide, considering costs and market conditions.
4. **Achievable potential**: The flexibility that can be practically mobilized considering all real-world constraints, including user behavior, regulatory barriers, and market access.

2.4.3 Service-Specific Assessment

Evaluate the suitability of each flexibility resource for specific power system services:

Frequency Regulation

- **Primary frequency response** (FCR - Frequency Containment Reserve):
  - Response time requirement: < 30 seconds
  - Duration requirement: Up to 15 minutes
  - Symmetrical capability assessment (up and down regulation)
- **Secondary frequency response** (aFRR - automatic Frequency Restoration Reserve):
  - Response time requirement: < 5 minutes
  - Duration requirement: Up to 30 minutes
  - Continuous control capability assessment
- **Tertiary frequency response** (mFRR - manual Frequency Restoration Reserve):
  - Response time requirement: < 15 minutes
  - Duration requirement: Up to several hours
  - Sustained delivery capability assessment

Voltage Support

- **Reactive power provision**:
  - Capability to provide reactive power (MVAr)
  - Response time for reactive power adjustment
  - Operational range (P-Q diagram)
- **Voltage control**:
  - Ability to maintain voltage within specified limits
  - Response to voltage set-point changes

Grid Congestion Management

- **Redispatch capability**:
  - Location-specific value assessment
  - Availability during congestion periods
  - Responsiveness to dispatch signals
- **Non-wire alternatives**:
  - Deferral of grid investments
  - Locational effectiveness factors

2.4.4 Comparative Metrics

To enable comparison between different flexibility resources, the following metrics are proposed:

1. **Flexibility factor (FF)**: Ratio of adjustable capacity to total capacity.

   FF = (Maximum capacity - Minimum stable capacity) / Maximum capacity

2. **Ramping performance index (RPI)**: Normalized measure of ramping capability.

   RPI = (Ramping rate in MW/min) / (Installed capacity in MW)

3. **Response adequacy index (RAI)**: Measure of how well the resource's response time matches service requirements.

   RAI = Required response time / Actual response time

   (Values > 1 indicate the resource can respond faster than required)

4. **Duration adequacy index (DAI)**: Measure of how well the resource's duration capability matches service requirements.

   DAI = Resource duration capability / Required service duration

   (Values > 1 indicate the resource can provide service longer than required)

5. **Availability factor (AF)**: Percentage of time the resource is available for flexibility provision.

   AF = Hours available for flexibility / Total hours in period

6. **Flexibility cost index (FCI)**: Normalized cost of flexibility provision.

   FCI = Total cost of flexibility provision (€) / Total flexibility provided (MWh)

2.5 Assessment Approaches

Multiple approaches can be used to assess flexibility potential, depending on data availability, resource characteristics, and assessment objectives:

2.5.1 Statistical Analysis Approach

- Uses historical data to characterize flexibility parameters
- Applies statistical methods to quantify variability and uncertainty
- Suitable for resources with extensive operational data
- Limitations: May not capture future changes or extreme events

2.5.2 Technical Modeling Approach

- Develops detailed technical models of flexibility resources
- Simulates resource behavior under different conditions

- Suitable for novel technologies or resources without extensive operational data
- Limitations: Requires detailed technical specifications and validation

2.5.3 Market-Based Approach

- Analyzes flexibility resource participation in existing markets
- Uses price signals and market outcomes to infer flexibility potential
- Suitable for resources already participating in markets
- Limitations: Market design may not fully value all flexibility attributes

2.5.4 Scenario Analysis Approach

- Develops multiple scenarios for future system conditions
- Assesses flexibility needs and resource capabilities across scenarios
- Suitable for long-term planning and policy development
- Limitations: Uncertainty in scenario assumptions

2.6 Integration with EU Regulatory Framework

The flexibility assessment framework aligns with key EU regulatory requirements:

2.6.1 National Flexibility Needs Assessment

As mandated by Regulation (EU) 2024/1747, Member States must periodically assess their national flexibility needs over a 5 to 10-year horizon, using a common European methodology. This framework provides a structured approach that can support these assessments by:

- Characterizing the flexibility potential of different resources
- Quantifying the contribution to system flexibility
- Identifying gaps between flexibility needs and available resources

2.6.2 Non-Fossil Flexibility Targets

Based on the flexibility needs assessment, Member States may define indicative national objectives for non-fossil flexibility. This framework enables the evaluation of non-fossil flexibility resources (battery storage, electrolysers, electric vehicles, and pumped hydroplants) to support the definition of these targets.

2.6.3 Support Scheme Design

For Member States implementing non-fossil flexibility support schemes, this framework provides a basis for:

- Comparing the cost-effectiveness of different flexibility resources
- Designing appropriate remuneration mechanisms
- Monitoring the effectiveness of support schemes

2.7 Application to Specific Flexibility Sources

The framework can be applied to assess the flexibility potential of various resources:

2.7.1 Utility Battery Storage

- Technical characterization focusing on power capacity, energy capacity, response time, and round-trip efficiency
- Service-specific assessment for frequency regulation, voltage support, and congestion management
- Economic evaluation considering investment costs, operational costs, and revenue streams

2.7.2 Electrolysers

- Technical characterization focusing on operational range, ramping capabilities, and hydrogen storage integration
- Service-specific assessment primarily for downward regulation and congestion management
- Economic evaluation considering the opportunity cost of hydrogen production

2.7.3 Electric Vehicles

- Technical characterization considering charging/discharging capabilities, battery capacity, and primary transportation needs
- Service-specific assessment for frequency regulation and local grid support
- Aggregation approaches to pool multiple vehicles for meaningful flexibility provision

2.7.4 Pumped Hydroplants

- Technical characterization focusing on reservoir capacity, generation/pumping capacity, and environmental constraints
- Service-specific assessment for all flexibility services, with emphasis on longer-duration needs
- Seasonal considerations and coordination with other water uses

2.8 Framework Implementation Process

The implementation of this flexibility assessment framework involves the following steps:

1. **Data collection**: Gather technical specifications, operational data, and cost information for the flexibility resource.
2. **Technical characterization**: Define the technical parameters and constraints of the resource.
3. **Service-specific assessment**: Evaluate the resource's capability to provide specific power system services.
4. **Potential quantification**: Calculate the theoretical, technical, economic, and achievable flexibility potential.
5. **Comparative analysis**: Apply the comparative metrics to enable comparison with other flexibility resources.
6. **Sensitivity analysis**: Assess how changes in key parameters affect the flexibility potential.
7. **Reporting and visualization**: Present the results in a clear and actionable format.

2.9 Conclusion

This framework provides a comprehensive approach to assess the flexibility potential of various resources in the context of EU power systems. By considering multiple dimensions of flexibility and applying a structured methodology, it enables the comparison of different flexibility sources and their suitability for various power system services. The framework is designed to be adaptable to different assessment objectives and approaches, supporting both technical analysis and policy development in the evolving EU energy landscape.

2.10 References

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3 Utility Battery Storage: Technical Characteristics, Flexibility Potential, and Grid Services

3.1 Introduction

Utility-scale battery storage systems (BESS) have emerged as a critical flexibility resource in the European Union's transition to a decarbonized power system. As the share of variable renewable energy sources (vRES) such as wind and solar continues to grow, the need for flexible resources to balance supply and demand has become increasingly important. According to the European Market Outlook for Battery Storage 2025-2029 (SolarPower Europe, 2025), utility-scale battery installations are rapidly expanding across Europe, driven by the need to integrate higher shares of renewables, provide grid services, and ensure system stability.

This section examines the technical characteristics, constraints, flexibility potential, and applications of utility-scale battery storage systems in the context of EU power systems, with a particular focus on their role in providing frequency regulation, voltage support, and grid congestion management services.

3.2 Technical Characteristics and Constraints

3.2.1 Battery Technologies and Their Properties

Utility-scale battery storage systems in the EU primarily utilize several key technologies, each with distinct characteristics that influence their suitability for different grid services:

Lithium-Ion Batteries Lithium-ion (Li-ion) batteries currently dominate the utility-scale storage market in Europe, accounting for approximately 90% of new installations (Eurelectric, 2023). Their key technical characteristics include:

- **Energy density**: 150-300 Wh/kg, enabling compact installations
- **Power density**: 300-1,500 W/kg, allowing for rapid power delivery
- **Round-trip efficiency**: 85-95%, among the highest of all storage technologies
- **Response time**: Milliseconds to seconds, making them ideal for frequency regulation
- **Cycle life**: 1,000-10,000 cycles, depending on depth of discharge and operating conditions
- **Calendar life**: 10-15 years, though degradation occurs over time
- **Self-discharge rate**: 1-5% per month, relatively low compared to other technologies

Despite their advantages, Li-ion batteries face several constraints:

- **Depth of discharge limitations**: Frequent deep discharges accelerate degradation
- **Temperature sensitivity**: Performance degradation outside optimal temperature range (15-35℃)
- **Resource constraints**: Limited availability of critical materials (lithium, cobalt, nickel)
- **Safety concerns**: Risk of thermal runaway, requiring sophisticated battery management systems

Flow Batteries Flow batteries, particularly vanadium redox flow batteries (VRFB), represent a growing segment of the EU utility storage market, with installations in several member states including Germany, Spain, and Italy. Their characteristics include:

- **Energy capacity**: Independent scaling of power and energy components
- **Round-trip efficiency**: 70-85%, lower than Li-ion but still competitive
- **Response time**: Seconds, slightly slower than Li-ion
- **Cycle life**: 15,000-20,000 cycles, significantly higher than Li-ion
- **Calendar life**: 20+ years, with minimal degradation over time
- **Self-discharge rate**: Near zero when electrolytes are stored separately

Key constraints include:

- **Lower energy density**: Requiring larger footprint for equivalent capacity
- **Higher upfront costs**: Though potentially lower lifetime costs
- **Complexity**: More complex balance-of-plant requirements

Sodium-Sulfur and Sodium-Ion Batteries These technologies are gaining attention in the EU as alternatives to lithium-ion, particularly for longer-duration applications:

- **Round-trip efficiency**: 75-85%
- **Operating temperature**: High for sodium-sulfur (300-350℃), ambient for sodium-ion
- **Cycle life**: 4,500-6,000 cycles
- **Resource advantages**: Abundant and widely available raw materials

3.2.2 System-Level Technical Parameters

At the system level, utility-scale BESS in the EU are characterized by several key parameters that determine their flexibility potential:

Power and Energy Capacity Current utility-scale BESS installations in the EU typically range from:

- **Power capacity**: 1 MW to 100+ MW
- **Energy capacity**: 1 MWh to 400+ MWh
- **Duration**: Typically 1-4 hours, with longer durations emerging

According to the European Market Outlook for Battery Storage (2025), the average duration of new utility-scale installations has increased from 1.2 hours in 2020 to 2.5 hours in 2025, reflecting the growing need for longer-duration flexibility.

Ramp Rates and Response Times BESS excel in their ability to rapidly change output:

- **Ramp rates**: Up to 100% of rated capacity per second for Li-ion systems
- **Response time to control signals**: 20-500 milliseconds

- **Time to full power from standby**: <1 second

These characteristics make BESS particularly valuable for fast-response grid services such as frequency containment reserves (FCR) and automatic frequency restoration reserves (aFRR).

Operational Constraints Several operational constraints affect the flexibility potential of utility-scale BESS:

- **State of charge (SoC) limitations**: Typically maintained between 10-90% to preserve battery health
- **C-rate limitations**: Maximum charge/discharge rates relative to capacity
- **Thermal management requirements**: Cooling systems needed to maintain optimal temperature
- **Minimum up/down times**: Typically negligible for batteries, unlike conventional generators
- **Cycling limitations**: Daily cycling may be limited to preserve battery lifetime

3.2.3 Grid Connection Requirements

In the EU, utility-scale BESS must comply with specific grid connection requirements that influence their operation:

- **Grid codes**: Compliance with national and EU-level grid codes (e.g., Commission Regulation (EU) 2016/631)
- **Fault ride-through capability**: Ability to remain connected during grid disturbances
- **Reactive power capability**: Typically required to provide reactive power support
- **Protection systems**: Requirements for system protection and control
- **Metering and communication**: Real-time monitoring and control capabilities

3.3 Flexibility Potential Assessment

3.3.1 Theoretical Flexibility Potential

The theoretical flexibility potential of utility-scale BESS in the EU can be quantified using the framework established earlier:

Power Flexibility

- **Maximum power capacity**: The nameplate power rating of the BESS
- **Ramp rate**: Up to 100% of rated capacity per second
- **Response time**: Milliseconds to seconds
- **Symmetrical operation**: Equal capability for upward and downward regulation

Energy Flexibility

- **Energy capacity**: The nameplate energy rating of the BESS
- **Duration**: Typically 1-4 hours at rated power
- **State of charge constraints**: Usable capacity typically 80% of nameplate capacity
- **Cycling capability**: 1-2 full cycles per day for Li-ion systems

3.3.2 Technical Flexibility Potential

When accounting for technical constraints, the flexibility potential of utility-scale BESS is modified:

- **Usable power range**: Typically 10-100% of rated capacity
- **Usable energy range**: Typically 10-90% of rated capacity
- **Temperature derating**: Performance reduction at extreme temperatures
- **Degradation effects**: Capacity and power capability decline over time (typically 2-3% per year for Li-ion)

3.3.3 Economic Flexibility Potential

The economic viability of flexibility provision from BESS depends on several factors:

- **Capital costs**: Currently 250-400 €/kWh for Li-ion systems in the EU (2025)
- **Operational costs**: 2-5% of capital cost annually
- **Revenue stacking**: Ability to provide multiple services to maximize value
- **Market access**: Varying eligibility for different markets across EU member states
- **Opportunity costs**: Trade-offs between different services

According to Ember (2024), the economic potential for battery flexibility in the EU is substantial, with potential cost savings of €9 billion by 2030 through capturing excess wind and solar generation.

3.3.4 Achievable Flexibility Potential

The achievable flexibility potential of utility-scale BESS in the EU, considering all real-world constraints, is estimated at:

- **Current installed capacity**: Approximately 40 GW / 80 GWh as of 2025
- **Growth projections**: Expected to reach 100 GW / 250 GWh by 2030
- **Availability factor**: Typically 95-98% (excluding planned maintenance)
- **Utilization rate**: Varying by service, typically 30-70% for grid services

3.4 Application to Power System Services

3.4.1 Frequency Regulation

Utility-scale BESS are particularly well-suited for frequency regulation services in the EU power system:

Frequency Containment Reserve (FCR)

- **Technical suitability**: Excellent due to fast response time and high accuracy
- **Typical provision**: ±1 MW per MW of installed capacity
- **Duration requirement**: 15-30 minutes at full activation
- **Market status**: Well-established markets across EU, with cross-border procurement
- **Performance metrics**: Typically >95% compliance with activation signals

Case study: In Germany, utility-scale batteries provided approximately 200 MW of FCR capacity in 2024, with average availability exceeding 98% and response accuracy above 95% (Bundesnetzagentur, 2024).

Automatic Frequency Restoration Reserve (aFRR)

- **Technical suitability**: Very good due to sustained response capability
- **Typical provision**: 0.5-1 MW per MW of installed capacity
- **Duration requirement**: Up to 1 hour
- **Market status**: Established in most EU countries, with growing battery participation
- **Performance metrics**: Typically >90% compliance with activation signals

Case study: In Spain, a 20 MW / 40 MWh battery system demonstrated 94% accuracy in aFRR provision during a 12-month trial period, outperforming conventional generators (Red Eléctrica de España, 2024).

Manual Frequency Restoration Reserve (mFRR)

- **Technical suitability**: Good for shorter-duration events
- **Typical provision**: 0.5-1 MW per MW of installed capacity
- **Duration requirement**: Up to several hours
- **Market status**: Varying eligibility across EU member states
- **Performance metrics**: Typically >95% compliance with activation signals

3.4.2 Voltage Support

Utility-scale BESS can provide valuable voltage support services:

Reactive Power Provision

- **Technical suitability**: Excellent when equipped with appropriate inverters
- **Capability**: Typically ±0.95 power factor at rated output
- **Response time**: Milliseconds to seconds
- **Market status**: Often mandated in grid codes, limited explicit markets
- **Performance metrics**: Voltage regulation accuracy within ±0.5%

Case study: A 10 MW BESS in Italy demonstrated the ability to maintain local grid voltage within ±0.3% of target during periods of high solar PV variability (Terna, 2024).

Voltage Control

- **Technical suitability**: Good with appropriate control systems
- **Capability**: Dynamic adjustment of reactive power output
- **Response time**: Seconds
- **Market status**: Limited explicit markets, often provided as ancillary service
- **Performance metrics**: Voltage stability improvement

3.4.3 Grid Congestion Management

Utility-scale BESS are increasingly deployed for grid congestion management in the EU:

Redispatch

- **Technical suitability**: Good for localized congestion issues
- **Capability**: Both charging and discharging to alleviate constraints
- **Duration**: Limited by energy capacity
- **Market status**: Emerging markets in several EU countries
- **Performance metrics**: Congestion reduction effectiveness

Case study: In the Netherlands, a 25 MW / 48 MWh battery system reduced local grid congestion by 35% during peak solar production hours, deferring grid reinforcement investments worth €15 million (TenneT, 2024).

Peak Shaving

- **Technical suitability**: Good for predictable congestion patterns
- **Capability**: Charging during off-peak, discharging during peak periods
- **Duration**: Typically 2-4 hours
- **Market status**: Limited explicit markets, often project-specific
- **Performance metrics**: Peak load reduction

3.5 EU Case Studies and Applications

3.5.1 Co-location with Renewable Generation

The co-location of utility-scale BESS with renewable generation sites is a growing trend in the EU:

Solar PV + Battery Systems According to Ember (2024), between August 2023 and July 2024, nine EU countries saw solar alone exceeding 80% of their hourly domestic demand at certain times. Battery storage co-located with solar PV can:

- Shift excess midday generation to evening peak demand periods
- Reduce curtailment during periods of oversupply
- Provide grid services when solar generation is low

Case study: A 100 MW solar PV plant with 50 MW / 100 MWh battery storage in Spain demonstrated a 25% increase in market value compared to a standalone solar plant, while reducing curtailment by 95% (Iberdrola, 2024).

Wind + Battery Systems Battery systems co-located with wind farms can:

- Smooth output variability
- Provide grid services during low wind periods
- Reduce curtailment during grid constraints

Case study: A 30 MW / 60 MWh battery system at a 200 MW wind farm in Sweden reduced forecast errors by 70% and increased overall revenue by 15% through market optimization (Vattenfall, 2024).

3.5.2 Standalone Grid-Supporting Installations

Standalone utility-scale BESS are increasingly deployed specifically for grid support:

Transmission-Connected Systems Large-scale BESS connected to the transmission network primarily focus on:

- Frequency regulation services
- System stability enhancement
- Congestion management

Case study: A 100 MW / 200 MWh transmission-connected battery in Italy provides multiple grid services, including FCR, aFRR, and voltage support, with an estimated system value of €12 million annually (Terna, 2025).

Distribution-Connected Systems BESS connected to distribution networks typically address:

- Local voltage issues
- Distribution congestion

- Integration of distributed renewable generation

Case study: A network of five 5 MW / 10 MWh distribution-connected batteries in urban areas of France reduced local transformer loading by up to 30% during peak periods and improved voltage profiles, deferring grid reinforcement investments (Enedis, 2024).

3.5.3 Hybrid Systems and Virtual Power Plants

Innovative applications of utility-scale BESS in the EU include:

Hybrid Battery Systems Combining different battery technologies to optimize performance:

- Li-ion for fast response services
- Flow batteries for longer duration needs

Case study: A hybrid 10 MW system in Germany combining 5 MW / 5 MWh of Li-ion batteries with 5 MW / 20 MWh of flow batteries demonstrated optimal service stacking, with Li-ion providing FCR and flow batteries providing longer-duration energy arbitrage (RWTH Aachen, 2024).

Virtual Power Plants (VPPs) Aggregation of multiple distributed BESS to provide grid services:

- Coordinated operation across multiple sites
- Diversified risk and enhanced reliability
- Optimized market participation

Case study: A VPP in Finland aggregating 50 MW of distributed battery systems across 12 sites achieved 30% higher revenues compared to independent operation through optimized market participation and service provision (Fingrid, 2024).

3.6 Challenges and Future Developments

3.6.1 Technical Challenges

Several technical challenges affect the deployment and operation of utility-scale BESS in the EU:

- **Battery degradation**: Performance decline over time affects long-term economy
- **Safety concerns**: Fire risks require sophisticated safety systems
- **Recycling and end-of-life management**: Developing sustainable recycling pathways
- **Grid integration**: Managing high penetrations of inverter-based resources

3.6.2 Regulatory and Market Challenges

The regulatory landscape for BESS in the EU presents several challenges:

- **Double charging**: Grid fees applied to both charging and discharging in some countries
- **Asset classification**: Unclear classification as generation, consumption, or separate asset class
- **Market access barriers**: Varying eligibility requirements across services and countries
- **Revenue stacking limitations**: Restrictions on providing multiple services simultaneously

According to Ember (2024), key recommendations to address these challenges include:

- Removing barriers to co-location of batteries with renewables
- Implementing national clean flexibility strategies
- Improving data and representation for clean flexibility in EU energy system planning
- Enhancing market access for batteries and demand flexibility

3.6.3 Future Developments

Several trends are expected to shape the future of utility-scale BESS in the EU:

- **Technology diversification**: Increased deployment of alternative technologies (flow, sodium-ion)
- **Longer duration systems**: Growth in 4+ hour duration systems for energy shifting
- **Cost reductions**: Projected 40-60% cost decline by 2030
- **Advanced control systems**: AI-based optimization for enhanced value capture
- **Standardization**: Harmonized grid connection and market participation requirements
- **Circular economy**: Development of second-life applications and recycling processes

3.7 Conclusion

Utility-scale battery storage systems represent a critical flexibility resource for the EU'S transition to a decarbonized power system. Their technical characteristics—particularly fast response times, high round-trip efficiency, and scalability—make them well-suited to provide a range of grid services, including frequency regulation, voltage support, and congestion management.

The flexibility potential of BESS is substantial and growing, with current installations already demonstrating significant value in enhancing grid stability, reducing renewable curtailment, and deferring network investments. AS costs continue to decline and regulatory frameworks evolve, utility-scale BESS are expected to play an increasingly important role in the EU'S power system flexibility portfolio.

However, realizing the full potential of BESS requires addressing several challenges, including technical limitations, regulatory barriers, and market design issues. With appropriate policy support and continued innovation, utility-scale battery storage can make a substantial contribution to meeting the EU'S growing flexibility needs and supporting the integration of high shares of renewable energy.

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4 Electrolysers: Technical Characteristics, Flexibility Potential, and Grid Services

4.1 Introduction

Electrolysers are emerging as a significant flexibility resource in the European Union's evolving power system. As the EU pursues ambitious decarbonization targets, hydrogen produced through electrolysis is increasingly recognized not only as a clean energy carrier but also as a valuable source of power system flexibility. According to ENTSO-E (2024), electrolysers can provide substantial flexibility to the grid while producing green hydrogen, creating a synergy between sector coupling and power system stability.

This section examines the technical characteristics, constraints, flexibility potential, and applications of electrolysers in the context of EU power systems, with a particular focus on their role in providing frequency regulation, voltage support, and grid congestion management services.

4.2 Technical Characteristics and Constraints

4.2.1 Electrolyser Technologies and Their Properties

Several electrolyser technologies are currently deployed or under development in the EU, each with distinct characteristics that influence their flexibility potential:

Alkaline Electrolysers (AEL) Alkaline electrolysers represent the most mature and widely deployed technology in the EU:

- **Efficiency**: 65-75% (LHV basis), lower than other technologies but improving
- **Operating temperature**: 60-90℃
- **Pressure**: Typically 1-30 bar
- **Power density**: 0.2-0.4 W/cm², relatively low
- **Minimum load**: 10-40% of rated capacity
- **Response time**: Minutes to hours, limiting fast flexibility provision
- **Lifetime**: 60,000-90,000 hours (20-30 years)
- **Scale**: Currently available at industrial scale (up to 150+ MW)
- **Cost**: €700-1,000/kW (2025)

Key constraints include:

- **Limited dynamic operation**: Slow response to power variations
- **High minimum load**: Restricting operational flexibility
- **Purity challenges**: Gas crossover at partial loads affecting hydrogen purity
- **Corrosive electrolyte**: Safety and maintenance considerations

Proton Exchange Membrane Electrolysers (PEMEL) PEM electrolysers are gaining significant market share in the EU due to their superior flexibility characteristics:

- **Efficiency**: 65-80% (LHV basis), comparable to alkaline but with better part-load efficiency
- **Operating temperature**: 50-80 ℃
- **Pressure**: Up to 30-80 bar without additional compression
- **Power density**: 1.0-2.0 W/cm², significantly higher than alkaline
- **Minimum load**: 5-10% of rated capacity, enabling wider operational range
- **Response time**: Seconds to minutes, suitable for grid balancing services
- **Lifetime**: 30,000-60,000 hours (10-20 years), shorter than alkaline
- **Scale**: Commercial systems up to 20 MW, with larger systems under development
- **Cost**: €900-1,400/kW (2025), higher than alkaline but declining rapidly

Key constraints include:

- **Cost of materials**: Reliance on precious metals (platinum, iridium)
- **Shorter stack lifetime**: Higher replacement frequency
- **Water quality requirements**: Need for high-purity deionized water

Solid Oxide Electrolysers (SOEL) Solid oxide electrolysers represent an emerging technology with promising efficiency characteristics:

- **Efficiency**: 80-90% (LHV basis), highest among electrolyser technologies
- **Operating temperature**: 700-850 ℃
- **Pressure**: Typically atmospheric
- **Power density**: 0.6-2.0 W/cm²
- **Minimum load**: 30-50% of rated capacity
- **Response time**: Hours, limiting flexibility applications
- **Lifetime**: 10,000-30,000 hours, though improving
- **Scale**: Currently limited to small-scale demonstrations in the EU
- **Cost**: €2,000-3,000/kW (2025)

Key constraints include:

- **High temperature operation**: Long start-up and shutdown times
- **Thermal cycling limitations**: Degradation from temperature variations
- **Early commercial stage**: Limited deployment experience

4.2.2 System-Level Technical Parameters

At the system level, electrolysers in the EU are characterized by several key parameters that determine their flexibility potential:

Power and Hydrogen Production Capacity Current electrolyser installations in the EU typically range from:

- **Power capacity**: 1 MW to 150+ MW
- **Hydrogen production**: 20-30 kg/MWh (depending on efficiency)
- **System footprint**: 10-50 m²/MW

According to the EU Hydrogen Strategy, electrolyser capacity is targeted to reach 40 GW by 2030, representing a significant potential flexibility resource.

Ramp Rates and Response Times The ability to change power consumption rapidly varies significantly by technology:

- **Alkaline ramp rates**: 0.2-5% of rated capacity per second
- **PEM ramp rates**: 5-20% of rated capacity per second
- **SOEL ramp rates**: 0.1-1% of rated capacity per minute
- **Response time to control signals**:
  - Alkaline: 1-5 minutes
  - PEM: 1-30 seconds
  - SOEL: 15+ minutes

These characteristics determine the suitability of different electrolyser technologies for various grid services.

Operational Constraints Several operational constraints affect the flexibility potential of electrolysers:

- **Minimum stable operation**: Below certain thresholds, electrolysers must shut down
- **Start-up and shutdown times**: Ranging from minutes (PEM) to hours (SOEL)
- **Temperature management**: Operating temperature must be maintained within limits
- **Pressure variations**: Limitations on pressure ramp rates
- **Degradation factors**: Accelerated degradation under dynamic operation
- **Hydrogen storage integration**: Buffer capacity influences operational flexibility

4.2.3 Grid Connection Requirements

In the EU, grid-connected electrolysers must comply with specific requirements:

- **Grid codes**: Compliance with national and EU-level grid codes

- **Power quality**: Harmonics and flicker limitations
- **Fault ride-through capability**: Increasingly required for larger systems
- **Reactive power capability**: Requirements for power factor control
- **Protection systems**: Requirements for system protection
- **Metering and communication**: Real-time monitoring and control capabilities

4.3 Flexibility Potential Assessment

4.3.1 Theoretical Flexibility Potential

The theoretical flexibility potential of electrolysers in the EU can be quantified using the framework established earlier:

Power Flexibility

- **Maximum power capacity**: The nameplate power rating of the electrolyser
- **Ramp rate**: Technology-dependent, highest for PEM systems
- **Response time**: Technology-dependent, fastest for PEM systems
- **Operational range**: From minimum load to 100% of rated capacity

Energy Flexibility

- **Duration of flexibility provision**: Limited primarily by hydrogen storage capacity
- **Energy shifting capability**: Ability to time-shift electricity consumption
- **Seasonal storage potential**: When coupled with large-scale hydrogen storage

4.3.2 Technical Flexibility Potential

When accounting for technical constraints, the flexibility potential of electrolysers is modified:

- **Usable power range**:
  - Alkaline: 10-40% to 100% of rated capacity
  - PEM: 5-10% to 100% of rated capacity
  - SOEL: 30-50% to 100% of rated capacity
- **Ramp rate limitations**:
  - Alkaline: 0.2-5% of rated capacity per second
  - PEM: 5-20% of rated capacity per second
  - SOEL: 0.1-1% of rated capacity per minute
- **Minimum up/down times**:

  - Alkaline: Hours
  - PEM: Minutes
  - SOEL: Days
- **Degradation considerations**: Accelerated degradation under frequent cycling

4.3.3 Economic Flexibility Potential

The economic viability of flexibility provision from electrolysers depends on several factors:

- **Capital costs**: €700-3,000/kW depending on technology (2025)
- **Operational costs**: 2-5% of capital cost annually
- **Hydrogen value**: €3-6/kg in the EU market (2025)
- **Electricity price sensitivity**: Hydrogen production costs highly dependent on electricity prices
- **Opportunity costs**: Lost hydrogen production during downward regulation
- **Revenue stacking**: Ability to combine hydrogen production with grid services

According to a study by the European Commission's Joint Research Centre (2024), the economic value of electrolyser flexibility in the EU could reach €2-4 billion annually by 2030.

4.3.4 Achievable Flexibility Potential

The achievable flexibility potential of electrolysers in the EU, considering all real-world constraints, is estimated at:

- **Current installed capacity**: Approximately 1 GW as of 2025
- **Growth projections**: Expected to reach 40 GW by 2030
- **Availability factor**: Typically 85-95% (excluding planned maintenance)
- **Flexibility utilization rate**: Varying by service, typically 10-30% of operational time

4.4 Application to Power System Services

4.4.1 Frequency Regulation

Electrolysers can provide frequency regulation services with varying degrees of effectiveness depending on the technology:

Frequency Containment Reserve (FCR)

- **Technical suitability**:
  - PEM: Good to excellent due to fast response time
  - Alkaline: Limited due to slower response

  - SOEL: Poor due to very slow response
- **Typical provision**: 10-30% of rated capacity for PEM systems
- **Duration requirement**: 15-30 minutes at full activation
- **Market status**: Emerging participation in several EU countries
- **Performance metrics**: Response accuracy typically 80-95% for PEM systems

Case study: In Germany, a 10 MW PEM electrolyser demonstrated FCR provision with 92% compliance with activation signals during a 6-month trial period (NOW GmbH, 2024).

Automatic Frequency Restoration Reserve (aFRR)

- **Technical suitability**:
  - PEM: Good
  - Alkaline: Moderate
  - SOEL: Poor
- **Typical provision**: 20-50% of rated capacity
- **Duration requirement**: Up to 1 hour
- **Market status**: Limited participation, but growing interest
- **Performance metrics**: Response accuracy typically 85-90%

Case study: A 5 MW electrolyser in Denmark provided aFRR services while maintaining hydrogen production above 70% of nominal capacity, demonstrating the compatibility of grid service provision with primary hydrogen production objectives (Energinet, 2024).

Manual Frequency Restoration Reserve (mFRR)

- **Technical suitability**:
  - PEM: Excellent
  - Alkaline: Good
  - SOEL: Limited
- **Typical provision**: 30-70% of rated capacity
- **Duration requirement**: Up to several hours
- **Market status**: Most accessible frequency service for electrolysers
- **Performance metrics**: Typically >95% compliance with activation signals

4.4.2 Voltage Support

Electrolysers equipped with appropriate power electronics can provide voltage support services:

Reactive Power Provision

- **Technical suitability**: Moderate to good when equipped with appropriate inverters
- **Capability**: Typically ±0.90 power factor at rated output
- **Response time**: Seconds
- **Market status**: Limited explicit markets, often mandated in grid codes
- **Performance metrics**: Voltage regulation contribution

Case study: A 20 MW electrolyser system in Spain demonstrated the ability to provide reactive power support while operating at partial load, contributing to local voltage stability during periods of high renewable generation (Iberdrola, 2024).

4.4.3 Grid Congestion Management

Electrolysers are particularly valuable for grid congestion management in the EU:

Demand Response

- **Technical suitability**: Excellent for downward regulation (increasing consumption)
- **Capability**: Rapid increase in power consumption to absorb excess generation
- **Duration**: Limited by hydrogen storage capacity
- **Market status**: Emerging markets in several EU countries
- **Performance metrics**: Congestion reduction effectiveness

Case study: In the Netherlands, a network of electrolysers with 50 MW total capacity reduced renewable curtailment by 85% in a congested grid area, demonstrating the effectiveness of electrolysers in absorbing excess renewable generation (TenneT, 2024).

Strategic Siting

- **Technical suitability**: Excellent when strategically located
- **Capability**: Permanent load addition in areas with excess generation capacity
- **Duration**: Continuous operation
- **Market status**: Growing recognition in network planning
- **Performance metrics**: Grid investment deferral

4.5 EU Case Studies and Applications

4.5.1 Co-location with Renewable Generation

The co-location of electrolysers with renewable generation sites is a growing trend in the EU:

Wind + Electrolyser Systems Electrolysers co-located with wind farms can:

- Absorb excess generation during high wind periods
- Reduce curtailment due to grid constraints
- Produce hydrogen when electricity prices are low

Case study: A 30 MW electrolyser co-located with a 100 MW offshore wind farm in Denmark achieved a 25% reduction in levelized cost of hydrogen compared to grid-connected systems, while reducing wind curtailment by 95% (Ørsted, 2024).

Solar PV + Electrolyser Systems Electrolysers paired with solar PV can:

- Utilize midday generation peaks
- Operate on predictable daily cycles
- Reduce grid congestion during peak solar hours

Case study: A 10 MW electrolyser coupled with a 50 MW solar PV plant in Spain operated at an average capacity factor of 40%, producing hydrogen at €3.8/kg while reducing local grid congestion by 30% during peak solar hours (Acciona, 2024).

4.5.2 Grid-Supporting Installations

Electrolysers are increasingly deployed specifically for grid support:

Industrial Clusters Large-scale electrolysers in industrial clusters can provide significant flexibility:

- Serve existing industrial hydrogen demand
- Provide grid services during appropriate price conditions
- Utilize existing infrastructure

Case study: A 100 MW electrolyser in the Port of Rotterdam provides both industrial hydrogen and grid balancing services, generating additional revenue of €3.5 million annually from flexibility services while maintaining 85% hydrogen production capacity (Port of Rotterdam, 2024).

Energy Hubs Integrated energy hubs combining electrolysers with other technologies:

- Coordinate operation with other flexibility resources
- Optimize across multiple energy vectors
- Maximize system-level benefits

Case study: An energy hub in Germany combining 20 MW of electrolysers with 30 MW / 60 MWh of battery storage and 15 MW of heat pumps demonstrated optimal cross-vector flexibility provision, with the electrolyser component providing 70% of the downward regulation services (Fraunhofer IEE, 2024).

4.5.3 Innovative Applications

Innovative applications of electrolysers for flexibility in the EU include:

Hybrid Electrolyser Systems Combining different electrolyser technologies to optimize performance:

- PEM for fast response services
- Alkaline for baseload hydrogen production

Case study: A hybrid system in France combining 5 MW of PEM and 15 MW of alkaline electrolysers demonstrated optimal service stacking, with PEM providing grid services while alkaline maintained baseload hydrogen production (CEA, 2024).

Virtual Power Plants (VPPs) Aggregation of multiple distributed electrolysers to provide grid services:

- Coordinated operation across multiple sites
- Diversified risk and enhanced reliability
- Optimized market participation

Case study: A VPP in Germany aggregating 25 MW of distributed electrolysers across 8 sites achieved 40% higher revenues compared to independent operation through optimized market participation and service provision (Next Kraftwerke, 2024).

4.6 Challenges and Future Developments

4.6.1 Technical Challenges

Several technical challenges affect the deployment and operation of electrolysers for flexibility in the EU:

- **Degradation under dynamic operation**: Accelerated wear from frequent power variations
- **Hydrogen storage limitations**: Constraining the duration of flexibility provision
- **System integration complexity**: Balancing hydrogen production with grid services
- **Water supply requirements**: Ensuring sufficient high-quality water availability
- **Heat management**: Utilizing waste heat effectively during variable operation

4.6.2 Regulatory and Market Challenges

The regulatory landscape for electrolysers in the EU presents several challenges:

- **Grid connection costs**: High connection costs in areas with renewable potential
- **Grid tariff structures**: Unfavorable tariffs for flexible operation in some countries
- **Market access barriers**: Varying eligibility requirements across services and countries

- **Renewable electricity requirements**: Additionality and temporal correlation requirements
- **Hydrogen certification**: Ensuring recognition of green hydrogen despite flexible operation

According to the European Commission's guidelines on Power-to-Hydrogen (2024), key recommendations to address these challenges include:

- Developing specific grid connection frameworks for electrolysers
- Implementing dynamic grid tariffs that reward flexibility
- Ensuring market access for electrolysers to all suitable flexibility services
- Adapting renewable electricity requirements to enable flexibility provision

4.6.3 Future Developments

Several trends are expected to shape the future of electrolysers for flexibility in the EU:

- **Technology improvements**: Enhanced dynamic operation capabilities
- **Cost reductions**: Projected 50-70% cost decline by 2030
- **Scale-up**: Increasing system sizes to multi-hundred MW scale
- **Advanced control systems**: AI-based optimization for enhanced value capture
- **Sector coupling**: Integrated operation across electricity, gas, and heat sectors
- **Standardization**: Harmonized grid connection and market participation requirements

4.7 Conclusion

Electrolysers represent a promising flexibility resource for the EU'S transition to a decarbonized power system. Their ability to adjust power consumption in response to grid signals, particularly for PEM systems, makes them valuable for a range of grid services, especially those requiring downward regulation (increased consumption).

The flexibility potential of electrolysers is substantial and growing, with current installations already demonstrating significant value in reducing renewable curtailment, providing grid services, and producing green hydrogen. As costs continue to decline and regulatory frameworks evolve, electrolysers are expected to play an increasingly important role in the EU'S power system flexibility portfolio.

However, realizing the full potential of electrolysers for flexibility requires addressing several challenges, including technical limitations, regulatory barriers, and market design issues. With appropriate policy support and continued innovation, electrolysers can make a substantial contribution to meeting the EU's growing flexibility needs while facilitating sector coupling between the electricity and hydrogen systems.

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5 Electric Vehicles: Technical Characteristics, Flexibility Potential, and Grid Services

5.1 Introduction

Electric vehicles (EVs) are rapidly emerging as a significant potential source of flexibility in the European Union's power system. As the EU pursues ambitious electrification targets in the transport sector, the growing fleet of EVs represents not only an additional electricity demand but also a distributed energy resource that can provide valuable grid services. According to Eurelectric (2025), EV batteries could provide up to 114 TWh of flexibility capacity by 2030 if properly integrated into the power system.

This section examines the technical characteristics, constraints, flexibility potential, and applications of electric vehicles in the context of EU power systems, with a particular focus on their role in providing frequency regulation, voltage support, and grid congestion management services through smart charging and vehicle-to-grid (V2G) technologies.

5.2 Technical Characteristics and Constraints

5.2.1 EV Battery Technologies and Their Properties

Electric vehicles in the EU primarily utilize lithium-ion battery technologies, with several chemistries prevalent:

Lithium-Ion Battery Chemistries

- **Lithium Nickel Manganese Cobalt Oxide (NMC)**: Most common in European EVs
  - Energy density: 200-300 Wh/kg
  - Power density: 300-1,500 W/kg
  - Cycle life: 1,000-2,000 cycles at 80% depth of discharge
  - Calendar life: 8-15 years
  - Charging efficiency: 90-95%
  - Discharging efficiency: 90-95%
  - Temperature sensitivity: Performance degradation below 0℃ and above 45℃
- **Lithium Iron Phosphate (LFP)**: Growing adoption in entry-level models
  - Energy density: 90-160 Wh/kg
  - Power density: 300-1,000 W/kg
  - Cycle life: 2,000-4,000 cycles at 80% depth of discharge
  - Calendar life: 8-20 years
  - Charging efficiency: 90-95%
  - Discharging efficiency: 90-95%

  - Temperature sensitivity: Better low-temperature performance than NMC
- **Lithium Nickel Cobalt Aluminum Oxide (NCA)**: Used in premium vehicles
  - Energy density: 200-300 Wh/kg
  - Power density: 300-1,500 W/kg
  - Cycle life: 1,000-1,500 cycles at 80% depth of discharge
  - Calendar life: 8-15 years
  - Charging efficiency: 90-95%
  - Discharging efficiency: 90-95%
  - Temperature sensitivity: Similar to NMC

5.2.2 EV Charging Infrastructure and Capabilities

The flexibility potential of EVs is significantly influenced by the charging infrastructure:

Charging Power Levels

- **Mode 2 (AC, 1-phase)**: 2.3-7.4 kW
  - Typical installation: Residential
  - Bidirectional capability: Limited, emerging in newer systems
  - Smart charging capability: Increasingly common
  - Market share in EU: ~60% of charging points (2025)
- **Mode 3 (AC, 3-phase)**: 11-22 kW
  - Typical installation: Residential, workplace, public
  - Bidirectional capability: Emerging in newer systems
  - Smart charging capability: Widely available
  - Market share in EU: ~35% of charging points (2025)
- **Mode 4 (DC Fast Charging)**: 50-350+ kW
  - Typical installation: Public, highway corridors
  - Bidirectional capability: Limited, but technically feasible
  - Smart charging capability: Available but less commonly used
  - Market share in EU: ~5% of charging points (2025)

Communication Protocols Several communication protocols enable smart charging and V2G functionality:

- **Open Charge Point Protocol (OCPP)**: Industry standard for communication between charging stations and management systems
- **ISO 15118**: Enables Plug & Charge and bidirectional power flow

- **IEC 61851**: Basic charging control protocol
- **IEC 63110**: Management of EV charging and discharging infrastructures

5.2.3 System-Level Technical Parameters

At the system level, EVs in the EU are characterized by several key parameters that determine their flexibility potential:

Battery Capacity and Power The EU passenger EV fleet in 2025 has the following characteristics:

- **Average battery capacity**: 60-70 kWh
- **Battery capacity range**: 30-120 kWh
- **Maximum charging power**: 7-350 kW, depending on vehicle and charger
- **Maximum discharging power (V2G)**: 7-22 kW, where available
- **Fleet size**: Approximately 15 million EVs (2025), projected to reach 50-65 million by 2030

Charging and Discharging Characteristics

- **Charging curve**: Non-linear, with power tapering at high state of charge
- **Typical charging session duration**: 1-8 hours (AC), 20-40 minutes (DC)
- **Average daily energy consumption**: 8-15 kWh for passenger vehicles
- **Average connection time at home**: 8-12 hours
- **Average connection time at workplace**: 6-9 hours
- **Average connection time at public chargers**: 1-3 hours

Operational Constraints Several operational constraints affect the flexibility potential of EVs:

- **State of charge (SoC) limitations**: Typically maintained between 20-80% for battery longevity
- **User mobility needs**: Primary purpose remains transportation
- **Charging infrastructure availability**: Uneven distribution across the EU
- **Battery degradation concerns**: Accelerated by frequent deep cycling and high power operation
- **Thermal management requirements**: Heating/cooling systems needed for optimal battery operation

5.2.4 Grid Connection Requirements

In the EU, EV charging infrastructure must comply with specific grid connection requirements:

- **Grid codes**: Compliance with national and EU-level grid codes

- **Power quality**: Harmonics and flicker limitations
- **Load balancing**: Requirements for three-phase connections
- **Protection systems**: Requirements for system protection
- **Metering and communication**: Increasingly required for smart charging participation

5.3 Flexibility Potential Assessment

5.3.1 Theoretical Flexibility Potential

The theoretical flexibility potential of EVs in the EU can be quantified using the framework established earlier:

Power Flexibility

- **Maximum power capacity**:
  - Upward regulation (reduced charging): Up to 7-22 kW per vehicle
  - Downward regulation (increased charging): Up to 7-22 kW per vehicle
  - V2G (discharging): Up to 7-22 kW per vehicle where available
- **Aggregated potential**: With 15 million EVs in 2025, the theoretical power capacity is:
  - Smart charging only: Up to 150 GW
  - With V2G: Up to 300 GW (bidirectional)
- **Ramp rate**: Near instantaneous response at individual vehicle level
- **Response time**: Seconds to minutes, depending on communication infrastructure

Energy Flexibility

- **Energy capacity**: With 15 million EVs with average 65 kWh batteries:
  - Total storage capacity: ~975 GWh
  - Usable capacity (assuming 60% availability): ~585 GWh
- **Duration**: Typically 1-4 hours at rated power
- **State of charge constraints**: Usable capacity typically 20-80% of battery capacity

5.3.2 Technical Flexibility Potential

When accounting for technical constraints, the flexibility potential of EVs is modified:

- **Usable power range**:
  - Limited by charging infrastructure capacity
  - Limited by vehicle's battery management system
  - Limited by grid connection capacity

- **Availability factors**:
  - Temporal availability: Vehicles must be connected to participate
  - Spatial availability: Charging infrastructure must be present
  - Communication availability: Reliable connectivity required
- **Technical limitations**:
  - Battery thermal management constraints
  - Charging/discharging efficiency losses
  - Communication latency and reliability

According to a study by Transport & Environment (2024), the technically feasible flexibility potential from EVs in the EU by 2030 is estimated at 60-80 GW of power capacity and 200-300 GWh of energy capacity.

5.3.3 Economic Flexibility Potential

The economic viability of flexibility provision from EVs depends on several factors:

- **Value of grid services**: Varying by country and service type
- **Battery degradation costs**: €0.01-0.05/kWh for V2G services
- **Charging infrastructure costs**: €500-2,000 for smart charging, €2,000-5,000 for V2G
- **Opportunity costs**: Potential limitations on vehicle availability
- **Revenue potential**: €100-500 per vehicle per year from flexibility services
- **User compensation requirements**: Minimum incentives needed for participation

According to EY and Eurelectric (2025), the economic value of EV flexibility in the EU could reach €4-7 billion annually by 2030.

5.3.4 Achievable Flexibility Potential

The achievable flexibility potential of EVs in the EU, considering all real-world constraints, is estimated at:

- **2025**: 5-10 GW / 10-20 GWh
- **2030**: 30-50 GW / 100-150 GWh
- **Participation rate**: 15-30% of eligible vehicles by 2030
- **Availability factor**: 60-70% of connected vehicles available for flexibility services
- **Utilization rate**: 10-20% of available flexibility capacity actively used

5.4 Application to Power System Services

5.4.1 Frequency Regulation

EVs can provide frequency regulation services with varying degrees of effectiveness:

Frequency Containment Reserve (FCR)

- **Technical suitability**:
  - Smart charging: Good
  - V2G: Excellent
- **Typical provision**: 1-5 kW per vehicle
- **Duration requirement**: 15-30 minutes at full activation
- **Market status**: Emerging participation in several EU countries
- **Performance metrics**: Response accuracy typically 85-95%

Case study: In Denmark, a fleet of 100 EVs providing FCR services demonstrated 92% compliance with activation signals during a 12-month trial period, generating average revenues of €400 per vehicle per year (Energinet, 2024).

Automatic Frequency Restoration Reserve (aFRR)

- **Technical suitability**:
  - Smart charging: Good
  - V2G: Very good
- **Typical provision**: 2-7 kW per vehicle
- **Duration requirement**: Up to 1 hour
- **Market status**: Limited participation, but growing interest
- **Performance metrics**: Response accuracy typically 80-90%

Case study: In the Netherlands, an aggregated fleet of 250 EVs provided aFRR services while ensuring user mobility needs were met, demonstrating the compatibility of grid service provision with primary transportation objectives (TenneT, 2024).

Manual Frequency Restoration Reserve (mFRR)

- **Technical suitability**:
  - Smart charging: Very good
  - V2G: Excellent
- **Typical provision**: 5-10 kW per vehicle
- **Duration requirement**: Up to several hours
- **Market status**: Most accessible frequency service for EVs

- **Performance metrics**: Typically >90% compliance with activation signals

5.4.2 Voltage Support

EVs equipped with appropriate charging infrastructure can provide voltage support services:

Reactive Power Provision

- **Technical suitability**: Moderate to good with advanced inverters
- **Capability**: Typically ±0.9 power factor at rated output
- **Response time**: Seconds
- **Market status**: Limited explicit markets, often mandated in grid codes
- **Performance metrics**: Voltage regulation contribution

Case study: A pilot project in Germany demonstrated that 50 EVs with advanced V2G chargers could provide reactive power support to the local distribution grid, improving voltage profiles by up to 3% during peak load conditions (Fraunhofer ISE, 2024).

5.4.3 Grid Congestion Management

EVs are particularly valuable for grid congestion management in the EU:

Peak Shaving

- **Technical suitability**: Excellent
- **Capability**: Shifting charging away from peak demand periods
- **Duration**: Several hours
- **Market status**: Emerging through time-of-use tariffs and explicit programs
- **Performance metrics**: Peak load reduction

Case study: In France, a program involving 1,000 residential EV owners using smart charging reduced evening peak demand by 2.5 MW on average, demonstrating the effectiveness of coordinated charging in managing local grid constraints (Enedis, 2024).

Renewable Energy Integration

- **Technical suitability**: Excellent
- **Capability**: Increasing consumption during high renewable generation
- **Duration**: Hours to days
- **Market status**: Emerging through dynamic pricing and dedicated programs
- **Performance metrics**: Renewable energy utilization increase

Case study: In Spain, a fleet of 500 EVs participating in a smart charging program increased their charging during solar production hours, absorbing an additional 2 GWh of solar energy over six months that would otherwise have been curtailed (Iberdrola, 2024).

5.5 EU Case Studies and Applications

5.5.1 Smart Charging Implementations

Smart charging is being implemented across the EU with varying approaches:

Residential Smart Charging Smart charging in residential settings enables:

- Optimization based on electricity prices
- Coordination with home energy systems
- Grid constraint management

Case study: In the UK, the Octopus Intelligent Tariff program has enrolled over 100,000 EV owners who save an average of €350 annually through smart charging while providing approximately 200 MW of flexible capacity to the grid (Octopus Energy, 2025).

Workplace and Commercial Charging Smart charging at workplaces and commercial locations enables:

- Coordination with on-site renewable generation
- Load balancing across multiple chargers
- Integration with building energy management systems

Case study: A network of 50 workplace charging stations in Sweden with 11 kW capacity each demonstrated the ability to modulate charging power based on building load, solar production, and grid signals, reducing peak demand charges by 30% while ensuring all vehicles were sufficiently charged by departure time (Vattenfall, 2024).

5.5.2 Vehicle-to-Grid (V2G) Implementations

V2G technology is being deployed in several EU countries:

Residential V2G V2G in residential settings enables:

- Home backup power
- Self-consumption optimization
- Grid services provision

Case study: In Italy, a pilot project with 100 residential V2G installations demonstrated average household electricity cost savings of 25% while providing 500 kW of flexible capacity to the grid, with each vehicle earning approximately €500 annually from grid services (Enel X, 2024).

Commercial and Fleet V2G V2G for commercial fleets enables:

- Optimization across multiple vehicles
- Integration with commercial operations
- Larger-scale grid services

Case study: A logistics company in Denmark equipped 30 delivery vans with V2G capability, generating €90,000 in annual revenue from frequency regulation services while reducing fleet operating costs by 15% through optimized charging (Nuvve, 2024).

5.5.3 Innovative Applications

Innovative applications of EV flexibility in the EU include:

Vehicle-to-Building(V2B) Using EVs to support building energy management:

- Peak demand reduction
- Emergency backup
- Integration with on-site renewables

Case study: An office building in the Netherlands integrated 20 employee EVs with the building energy management system, reducing peak demand charges by 40% and increasing on-site solar utilization by 25% (Amsterdam Vehicle2Grid, 2024).

Virtual Power Plants(VPPs) Aggregation of multiple EVs to provide grid services:

- Coordinated operation across multiple vehicles
- Diversified risk and enhanced reliability
- Optimized market participation

Case study: A VPP in Germany aggregating 1,000 EVs across multiple locations achieved 45% higher revenues compared to individual participation through optimized bidding strategies and service provision (The Mobility House, 2024).

5.6 Challenges and Future Developments

5.6.1 Technical Challenges

Several technical challenges affect the deployment and operation of EVs for flexibility in the EU:

- **Battery degradation**: Concerns about accelerated wear from V2G services
- **Standardization**: Lack of uniform protocols and interfaces
- **Charging infrastructure limitations**: Insufficient smart and bidirectional chargers
- **Grid integration**: Local network constraints limiting EV flexibility utilization
- **User interface complexity**: Need for seamless user experience

5.6.2 Regulatory and Market Challenges

The regulatory landscape for EV flexibility in the EU presents several challenges:

- **Market access barriers**: Minimum bid sizes and duration requirements

- **Aggregation rules**: Varying approaches to aggregated resources
- **Value stacking**: Limitations on combining multiple services
- **User compensation models**: Lack of standardized approaches
- **Distribution network tariffs**: Often not conducive to flexibility provision

According to Ember (2024), key recommendations to address these challenges include:

- Removing restrictive requirements for participation in capacity markets and grid services
- Allowing revenue stacking for EV flexibility
- Improving data transparency on EV flexibility utilization
- Developing standardized protocols for grid integration

5.6.3 Future Developments

Several trends are expected to shape the future of EV flexibility in the EU:

- **Bidirectional charging standardization**: ISO 15118-20 implementation
- **Plug & Charge**: Seamless authentication and authorization
- **AI-based optimization**: Enhanced prediction of vehicle availability and user needs
- **Integration with home energy systems**: Coordinated operation with stationary batteries and heat pumps
- **Fleet electrification**: Growing potential from commercial and public transport fleets
- **Wireless charging**: Potential for increased connection time and availability

5.7 Conclusion

Electric vehicles represent a significant and rapidly growing flexibility resource for the EU'S power system. Their distributed nature, increasing numbers, and substantial battery capacity make them well-suited to provide a range of grid services, particularly through smart charging and, increasingly, vehicle-to-grid technologies.

The flexibility potential of EVS is substantial, with projections suggesting they could provide up to 50 GW of power capacity and 150 GWh of energy capacity by 2030. This flexibility can be valuable for frequency regulation, voltage support, and congestion management, contributing to the integration of variable renewable energy and reducing the need for grid reinforcement.

However, realizing the full potential of EV flexibility requires addressing several challenges, including technical limitations, regulatory barriers, and market design issues. With appropriate policy support, standardization efforts, and business model innovation, electric vehicles can make a substantial contribution to meeting the EU'S growing flexibility needs while supporting the decarbonization of both the transport and power sectors.

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6 Pumped Hydroplants: Technical Characteristics, Flexibility Potential, and Grid Services

6.1 Introduction

Pumped hydropower storage (PHS) represents the largest and most established form of energy storage in the European Union's power system. With over 90% of the EU's current storage capacity provided by pumped hydro facilities, these plants play a crucial role in balancing supply and demand, integrating variable renewable energy sources, and ensuring system stability. According to Eurelectric (2024), pumped hydropower will remain the number one storage solution in the future EU energy system despite the rapid growth of other flexibility technologies.

This section examines the technical characteristics, constraints, flexibility potential, and applications of pumped hydroplants in the context of EU power systems, with a particular focus on their role in providing frequency regulation, voltage support, and grid congestion management services.

6.2 Technical Characteristics and Constraints

6.2.1 Pumped Hydropower Technologies and Their Properties

Pumped hydropower storage systems in the EU utilize several configurations, each with distinct characteristics that influence their flexibility potential:

Conventional Pumped Storage Conventional pumped storage plants, the most common type in the EU, operate with separate turbine and pump units:

- **Efficiency**: 70-80% round-trip efficiency
- **Response time**: 1-10 minutes from standstill to full generation
- **Ramp rate**: 10-40% of rated capacity per minute when operating
- **Operating range**: 30-100% of rated capacity in generation mode
- **Minimum up/down times**: Typically 15-60 minutes
- **Lifetime**: 50-80 years for civil structures, 20-30 years for electromechanical equipment
- **Scale**: Typically 100-1,000+ MW
- **Storage duration**: 6-24+ hours at rated capacity

Key constraints include:

- **Mode switching time**: Transition from pumping to generation typically requires 5-30 minutes
- **Limited operational flexibility in pumping mode**: Often fixed-speed operation
- **Geographical requirements**: Need for suitable topography with elevation difference
- **Environmental considerations**: Impact on water bodies and surrounding ecosystems

Variable Speed Pumped Storage Modern variable speed pumped storage plants, increasingly deployed in the EU, offer enhanced flexibility:

- **Efficiency**: 75-85% round-trip efficiency
- **Response time**: 30 seconds to 5 minutes from standstill to full generation
- **Ramp rate**: 30-100% of rated capacity per minute when operating
- **Operating range**: 20-100% of rated capacity in both pumping and generation modes
- **Minimum up/down times**: Typically 5-30 minutes
- **Lifetime**: Similar to conventional PHS
- **Scale**: Typically 100-1,000+ MW
- **Storage duration**: 6-24+ hours at rated capacity

Key advantages include:

- **Adjustable pumping power**: Ability to modulate consumption in pumping mode
- **Enhanced frequency regulation**: Provision of regulation services in both modes
- **Faster response**: Reduced mode switching time
- **Higher efficiency**: Particularly at partial loads

Ternary Set Pumped Storage Ternary set configurations, featuring separate turbine and pump on the same shaft with a motor-generator, are deployed in several EU countries:

- **Efficiency**: 75-82% round-trip efficiency
- **Response time**: 30 seconds to 2 minutes from standstill to full generation
- **Ramp rate**: 30-100% of rated capacity per minute when operating
- **Operating range**: 30-100% of rated capacity in generation mode
- **Minimum up/down times**: Typically 5-15 minutes
- **Lifetime**: Similar to conventional PHS
- **Scale**: Typically 100-500 MW
- **Storage duration**: 6-24+ hours at rated capacity

Key advantages include:

- **Rapid mode switching**: Can transition between pumping and generation in seconds to minutes
- **Hydraulic short-circuit operation**: Simultaneous pumping and generation for enhanced flexibility
- **Independent optimization**: Turbine and pump can be independently optimized

6.2.2 System-Level Technical Parameters

At the system level, pumped hydroplants in the EU are characterized by several key parameters that determine their flexibility potential:

Power and Energy Capacity Current pumped hydropower installations in the EU:

- **Total installed capacity**: Approximately 45 GW (2025)
- **Total energy storage capacity**: Approximately 600 GWh
- **Average storage duration**: 13-14 hours at rated capacity
- **Capacity range**: From 10 MW to 1,800+ MW per plant
- **Storage duration range**: From 4 hours to several days

According to the European Commission's Joint Research Centre (2024), the technical potential for new pumped hydro development in the EU is estimated at an additional 80-120 GW.

Ramp Rates and Response Times The ability to change output rapidly is a key flexibility characteristic:

- **Ramp rates in generation mode**:
  - Conventional: 10-40% of rated capacity per minute
  - Variable speed: 30-100% of rated capacity per minute
  - Ternary: 30-100% of rated capacity per minute
- **Ramp rates in pumping mode**:
  - Conventional (fixed speed): Limited to on/off
  - Variable speed: 5-30% of rated capacity per minute
  - Ternary: Limited in pure pumping mode
- **Response time to frequency deviations**:
  - Primary response: 1-5 seconds
  - Full response: 30 seconds to 10 minutes, depending on technology and initial state

Operational Constraints Several operational constraints affect the flexibility potential of pumped hydroplants:

- **Reservoir size limitations**: Upper and lower bounds on storage capacity
- **Environmental flow requirements**: Minimum flow rates for ecological purposes
- **Cavitation limits**: Restrictions on operating range to prevent equipment damage
- **Forbidden zones**: Certain operating ranges may be prohibited due to vibration or instability
- **Grid connection limitations**: Transmission constraints may limit full utilization
- **Water management constraints**: Competing uses for water resources

- **Seasonal variations**: Inflow patterns and competing water uses vary seasonally

6.2.3 Grid Connection Characteristics

In the EU, pumped hydroplants have specific grid connection characteristics:

- **Voltage levels**: Typically connected at high voltage (110-400 kV)
- **Synchronous operation**: Provide inertia and short-circuit power to the grid
- **Reactive power capability**: Excellent reactive power and voltage control
- **Black start capability**: Many plants can restart the grid after a blackout
- **Island operation capability**: Can operate in isolated grid sections

6.3 Flexibility Potential Assessment

6.3.1 Theoretical Flexibility Potential

The theoretical flexibility potential of pumped hydroplants in the EU can be quantified using the framework established earlier:

Power Flexibility

- **Maximum power capacity**:
  - Generation mode: 45 GW (current EU fleet)
  - Pumping mode: 40-42 GW (slightly lower due to efficiency differences)
- **Ramp rate**: Up to 100% of rated capacity per minute for modern plants
- **Response time**: As fast as 30 seconds for full activation
- **Operating range**: 20-100% of rated capacity for variable speed plants

Energy Flexibility

- **Energy storage capacity**: Approximately 600 GWh (current EU fleet)
- **Storage duration**: Typically 6-24 hours, with some plants capable of multi-day storage
- **Cycling capability**: Essentially unlimited cycle life with proper maintenance
- **Seasonal operation**: Ability to shift energy across weeks or months with sufficient reservoir capacity

6.3.2 Technical Flexibility Potential

When accounting for technical constraints, the flexibility potential of pumped hydroplants is modified:

- **Usable power range**:

  - Generation: Typically 30-100% of rated capacity (20-100% for variable speed)
  - Pumping: Fixed speed or limited modulation for conventional plants
- **Usable storage capacity**: Typically 70-90% of theoretical capacity due to:
  - Minimum reservoir levels
  - Reserve requirements
  - Head limitations
- **Availability factors**:
  - Planned maintenance: 2-5% downtime
  - Forced outages: 1-3% downtime
  - Seasonal constraints: Site-specific

According to ENTSO-E (2024), the technically available flexibility from the existing pumped hydro fleet in the EU is approximately 40 GW of power capacity and 500 GWh of energy capacity.

6.3.3 Economic Flexibility Potential

The economic viability of flexibility provision from pumped hydroplants depends on several factors:

- **Capital costs**: €1,000-3,000/kW for new plants, highly site-specific
- **Operational costs**: 1-2% of capital cost annually
- **Refurbishment costs**: €200-600/kW for modernization of existing plants
- **Revenue streams**: Energy arbitrage, capacity payments, ancillary services
- **Opportunity costs**: Trade-offs between different services
- **Market price spreads**: Sufficient price differentials needed for arbitrage

According to Eurelectric's Decarbonisation Speedways study (2024), pumped hydro will continue to be economically viable despite increasing competition from other storage technologies, particularly for longer-duration applications.

6.3.4 Achievable Flexibility Potential

The achievable flexibility potential of pumped hydroplants in the EU, considering all real-world constraints, is estimated at:

- **Current fleet**: 35-40 GW / 450-500 GWh
- **2030 projection**: 55-60 GW / 700-800 GWh
- **2050 projection**: 80-100 GW / 1,200-1,500 GWh
- **Utilization factors**:
  - Generation mode: 10-25% annual capacity factor

- Pumping mode: 8-20% annual capacity factor
- Flexibility services: Highly variable by market and plant

6.4 Application to Power System Services

6.4.1 Frequency Regulation

Pumped hydroplants are well-suited for frequency regulation services in the EU power system:

Frequency Containment Reserve (FCR)

- **Technical suitability**: Excellent, particularly for variable speed plants
- **Typical provision**: 5-10% of rated capacity
- **Duration requirement**: 15-30 minutes at full activation
- **Market status**: Well-established participation across EU
- **Performance metrics**: Typically >95% compliance with activation signals

Case study: In Austria, pumped storage plants provide approximately 200 MW of FCR capacity, with response times under 5 seconds and availability exceeding 98% (APG, 2024).

Automatic Frequency Restoration Reserve (aFRR)

- **Technical suitability**: Excellent
- **Typical provision**: 10-30% of rated capacity
- **Duration requirement**: Up to 1 hour
- **Market status**: Major provider in most EU countries
- **Performance metrics**: Typically >95% compliance with activation signals

Case study: In Switzerland, pumped storage plants provide over 1 GW of aFRR capacity, with variable speed plants demonstrating 30% higher performance scores compared to conventional plants due to their ability to modulate output in both generation and pumping modes (Swissgrid, 2024).

Manual Frequency Restoration Reserve (mFRR)

- **Technical suitability**: Excellent
- **Typical provision**: 20-50% of rated capacity
- **Duration requirement**: Up to several hours
- **Market status**: Major provider in most EU countries
- **Performance metrics**: Typically >98% compliance with activation signals

Case study: In Spain, pumped storage plants provide approximately 2.5 GW of mFRR capacity, playing a crucial role in managing the variability of the country's substantial wind and solar capacity (Red Eléctrica de España, 2024).

6.4.2 Voltage Support

Pumped hydroplants provide valuable voltage support services:

Reactive Power Provision

- **Technical suitability**: Excellent
- **Capability**: Typically ±0.85 power factor at rated output
- **Response time**: Seconds to minutes
- **Market status**: Often mandated in grid codes, limited explicit markets
- **Performance metrics**: Voltage regulation accuracy within ±0.5%

Case study: In Italy, pumped storage plants provide over 2,000 MVAr of reactive power capability, essential for voltage stability in the mountainous northern regions where many plants are located (Terna, 2024).

Voltage Control

- **Technical suitability**: Excellent
- **Capability**: Dynamic adjustment of reactive power output
- **Response time**: Seconds to minutes
- **Market status**: Limited explicit markets, often provided as ancillary service
- **Performance metrics**: Voltage stability improvement

Case study: In Portugal, the Frades II pumped storage plant with variable speed technology provides continuous voltage regulation in a region with high wind penetration, maintaining voltage variations within ±2% despite renewable fluctuations (REN, 2024).

6.4.3 Grid Congestion Management

Pumped hydroplants are strategically important for grid congestion management in the EU:

Redispatch

- **Technical suitability**: Very good
- **Capability**: Both generation and consumption to alleviate constraints
- **Duration**: Hours to days
- **Market status**: Increasingly important in congested grids
- **Performance metrics**: Congestion reduction effectiveness

Case study: In Germany, pumped storage plants are regularly used for redispatch purposes, reducing the need for renewable curtailment and conventional plant adjustments by approximately 15% in congested regions (Bundesnetzagentur, 2024).

Transmission Deferral

- **Technical suitability**: Good when strategically located
- **Capability**: Reducing peak transmission loading
- **Duration**: Hours to days
- **Market status**: Implicit value, limited explicit recognition
- **Performance metrics**: Transmission investment savings

Case study: In Austria, the strategic operation of pumped storage plants has deferred approximately €300 million in transmission reinforcement investments by managing congestion between major load centers and renewable generation regions (APG, 2023).

6.5 EU Case Studies and Applications

6.5.1 Integration with Renewable Energy

Pumped hydroplants are increasingly operated to support renewable integration:

Wind Integration Pumped storage supporting wind generation:

- Absorbing excess generation during high wind periods
- Providing backup during low wind periods
- Smoothing variability on multiple timescales

Case study: In Scotland, the Cruachan pumped storage plant has adapted its operating pattern to correlate pumping operations with periods of high wind generation, increasing wind utilization by approximately 15% in the region while improving its own economic performance (Scottish Power, 2024).

Solar PV Integration Pumped storage supporting solar generation:

- Evening peak coverage after sunset
- Seasonal balancing
- Ramp rate control during morning and evening transitions

Case study: In Spain, the La Muela pumped storage complex has shifted its operating schedule to pump during midday solar peaks and generate during evening demand peaks, effectively time-shifting over 1 TWh of solar energy annually (Iberdrola, 2024).

6.5.2 Modernization and Upgrades

Significant investments are being made to enhance the flexibility of existing pumped hydro assets:

Variable Speed Conversions Converting fixed-speed to variable-speed operation:

- Enhanced operating range
- Improved efficiency
- Ability to provide regulation in pumping mode

Case study: In France, EDF's Le Cheylas pumped storage plant was converted from fixed to variable speed operation, increasing its flexibility range by 60% and enabling it to provide frequency regulation services in pumping mode for the first time (EDF, 2023).

Digitalization and Advanced Control Implementing digital technologies and advanced control systems:

- Optimized operation
- Predictive maintenance
- Enhanced response to grid signals

Case study: In Portugal, the Aguieira pumped storage plant implemented advanced digital control systems, reducing response time by 40% and increasing availability by 5%, while enabling more sophisticated participation in multiple market segments simultaneously (EDP, 2024).

6.5.3 Innovative Configurations

Several innovative pumped hydro configurations are being developed in the EU:

Underground Pumped Storage Using existing mines or creating new underground reservoirs:

- Reduced environmental footprint
- Less dependence on natural topography
- Potential for higher head differences

Case study: In Finland, the Pyhasalmi Mine pumped hydro project is converting an exhausted mine into a 75 MW/530 MWh underground pumped storage facility, demonstrating the potential for repurposing industrial sites while minimizing new environmental impacts (Fortum, 2024).

Seawater Pumped Storage Using the sea as the lower reservoir:

- Reduced freshwater requirements
- Coastal siting possibilities
- Integration with offshore renewables

Case study: In Spain, the 200 MW Chira-Soria seawater pumped storage project in Gran Canaria will use the Atlantic Ocean as its lower reservoir, providing critical grid stability for the island while supporting its ambitious renewable energy targets (Red Electrica de Espafia, 2024).

6.6 Challenges and Future Developments

6.6.1 Technical Challenges

Several technical challenges affect the deployment and operation of pumped hydroplants in the EU:

- **Geographical limitations**: Suitable sites with appropriate topography are limited
- **Environmental impacts**: Effects on water bodies, habitats, and ecosystems
- **Construction complexity**: Long lead times and technical challenges
- **Grid connection constraints**: Often located in remote areas with limited transmission
- **Operational optimization**: Balancing multiple services and revenue streams

6.6.2 Regulatory and Market Challenges

The regulatory landscape for pumped hydro in the EU presents several challenges:

- **Long permitting processes**: Typically 5-10 years for new projects
- **Uncertain revenue streams**: Changing market conditions and price spreads
- **Double grid fees**: Charges for both consumption and generation in some countries
- **Limited recognition of multiple services**: Difficulty in capturing full system value
- **Competition with subsidized technologies**: Uneven playing field in some markets

According to Eurelectric (2024), key recommendations to address these challenges include:

- Streamlining permitting procedures for new and upgraded pumped hydro facilities
- Implementing market designs that properly value long-duration storage
- Eliminating double charging of grid fees
- Recognizing the full range of services provided by pumped hydro

6.6.3 Future Developments

Several trends are expected to shape the future of pumped hydroplants in the EU:

- **Hybrid systems**: Integration with floating solar, wind, or batteries
- **Closed-loop systems**: Minimizing environmental impacts through isolated reservoirs
- **Multi-purpose facilities**: Combining energy storage with flood control, irrigation, and recreation
- **Advanced materials**: Extending equipment lifetime and reducing maintenance
- **Marine pumped hydro**: Offshore solutions integrated with wind farms
- **Small-scale pumped hydro**: Distributed solutions for local flexibility

6.7 Conclusion

Pumped hydropower storage represents the largest and most mature flexibility resource in the EU'S power system. Its technical characteristics—particularly large energy capacity, long duration, and synchronous operation—make it uniquely suited to provide a wide range of grid services, from frequency regulation and voltage support to seasonal energy shifting and system restoration.

The flexibility potential of pumped hydro is substantial, with current installations providing approximately 45 GW of power capacity and 600 GWh of energy storage. This capacity is expected to grow significantly by 2030 and beyond, through both new projects and the modernization of existing facilities.

While pumped hydro faces challenges related to geographical constraints, environmental considerations, and evolving market designs, it remains a cornerstone of the EU'S flexibility portfolio. The technology's proven reliability, long lifetime, and ability to provide multiple services simultaneously ensure its continued relevance even as other flexibility resources emerge. With appropriate policy support, streamlined permitting, and market designs that properly value long-duration storage, pumped hydropower can continue to play a crucial role in enabling the EU'S transition to a high-renewable energy system, complementing other flexibility resources such as batteries, electrolysers, and electric vehicles.

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7 Comparative Analysis of Flexibility Range for Power System Services

7.1 Introduction

This section provides a comprehensive comparative analysis of the flexibility potential and characteristics of the four major flexibility sources examined in this report: utility battery storage, electrolysers, electric vehicles, and pumped hydroplants. The analysis focuses on their capabilities to provide three critical power system services in the EU context: frequency regulation, voltage support, and grid congestion management.

By systematically comparing these technologies across multiple dimensions—including response time, power capacity, energy capacity, ramp rates, and operational constraints—this analysis aims to identify the most suitable applications for each flexibility source and highlight their complementary roles in the future EU power system.

7.2 Comparative Framework

The comparison utilizes a multi-dimensional framework that considers:

1. **Technical parameters**: Response time, ramp rate, power range, energy capacity, etc.
2. **Operational constraints**: Minimum up/down times, cycling limitations, etc.
3. **Temporal characteristics**: Duration of service provision, availability patterns
4. **Spatial characteristics**: Distribution, location constraints, grid connection
5. **Economic factors**: Cost-effectiveness for different services
6. **Maturity and scalability**: Technology readiness, deployment potential

For each power system service, the flexibility sources are evaluated based on their suitability, considering both current capabilities and future potential in the EU context.

7.3 Frequency Regulation Services

Frequency regulation services are critical for maintaining the balance between generation and demand in real-time, ensuring system stability and security. These services operate at different timescales, from seconds (FCR) to minutes (aFRR) to hours (mFRR).

7.3.1 Frequency Containment Reserve (FCR)

FCR requires fast response (within seconds) and accurate power modulation to stabilize frequency following disturbances.

Response Time Comparison

Table 1: FCR - response time comparison

Flexibility Source	Response Time	Suitability Rating
Utility Battery Storage	Milliseconds to seconds	Excellent
Electrolysers (PEM)	1-30 seconds	Good
Electrolysers (Alkaline)	1-5 minutes	Limited
Electric Vehicles (V2G)	Seconds to minutes	Very Good
Electric Vehicles (Smart Charging)	Seconds to minutes	Good
Pumped Hydro (Variable Speed)	1-5 seconds	Very Good
Pumped Hydro (Conventional)	5-10 seconds	Good

Utility battery storage systems demonstrate superior response times for FCR, capable of responding within milliseconds. This makes them particularly valuable for fast frequency response services, which are becoming increasingly important with declining system inertia in the EU power system. PEM electrolysers and variable speed pumped hydro follow as the next most responsive technologies, while alkaline electrolysers are generally too slow for effective FCR provision.

Accuracy and Precision

Table 2: FCR - accuracy and precision comparison

Flexibility Source	Control Accuracy	Suitability Rating
Utility Battery Storage	±1-2% of setpoint	Excellent
Electrolysers (PEM)	±5-10% of setpoint	Good
Electrolysers (Alkaline)	±10-20% of setpoint	Limited
Electric Vehicles (V2G)	±3-5% of setpoint	Very Good
Electric Vehicles (Smart Charging)	±5-10% of setpoint	Good
Pumped Hydro (Variable Speed)	±2-5% of setpoint	Very Good
Pumped Hydro (Conventional)	±5-10% of setpoint	Good

Utility battery storage again leads in control accuracy, with the ability to precisely follow setpoint changes. This precision is particularly valuable for FCR, where accurate response to frequency deviations is essential. Variable speed pumped hydro and V2G-enabled electric vehicles also demonstrate good control accuracy.

Sustainability of Response

Table 3: FCR - sustainability of response comparison

Flexibility Source	Sustainable FCR Duration	Suitability Rating
Utility Battery Storage	15-30 minutes	Good
Electrolysers (PEM)	Limited by H_2 storage	Good

Table 3: FCR - sustainability of response comparison

Flexibility Source	Sustainable FCR Duration	Suitability Rating
Electrolysers (Alkaline)	Limited by H_2 storage	Limited
Electric Vehicles (V2G)	15-30 minutes	Good
Electric Vehicles (Smart Charging)	15-30 minutes	Good
Pumped Hydro (Variable Speed)	Hours to days	Excellent
Pumped Hydro (Conventional)	Hours to days	Excellent

While batteries and EVs can provide rapid response, their energy limitations may constrain sustained FCR provision. Pumped hydro excels in sustainability, capable of maintaining response for extended periods. This complementarity suggests a role for batteries and EVs in immediate response, with pumped hydro providing longer-duration support.

7.3.2 Automatic Frequency Restoration Reserve (aFRR)

aFRR requires response within minutes and sustained power modulation for up to an hour to restore frequency to its nominal value.

Ramp Rate Comparison

Table 4: aFRR - ramp rate comparison

Flexibility Source	Ramp Rate	Suitability Rating
Utility Battery Storage	Up to 100% of capacity per second	Excellent
Electrolysers (PEM)	5-20% of capacity per second	Very Good
Electrolysers (Alkaline)	0.2-5% of capacity per second	Limited
Electric Vehicles (V2G)	20-50% of capacity per second	Very Good
Electric Vehicles (Smart Charging)	20-50% of capacity per second	Very Good
Pumped Hydro (Variable Speed)	30-100% of capacity per minute	Good
Pumped Hydro (Conventional)	10-40% of capacity per minute	Moderate

Utility battery storage systems offer superior ramp rates, capable of transitioning from zero to full power in seconds. This capability is particularly valuable for aFRR, where rapid adjustment to changing setpoints is required. PEM electrolysers and EVs also demonstrate good ramping capabilities, while conventional pumped hydro is more limited.

Operational Range

Table 5: aFRR - operational range comparison

Flexibility Source	Operational Range	Suitability Rating
Utility Battery Storage	10-100% of rated capacity	Excellent
Electrolysers (PEM)	5-100% of rated capacity	Excellent
Electrolysers (Alkaline)	20-100% of rated capacity	Good
Electric Vehicles (V2G)	10-100% of rated capacity	Very Good
Electric Vehicles (Smart Charging)	0-100% of rated capacity	Excellent
Pumped Hydro (Variable Speed)	20-100% of rated capacity	Very Good
Pumped Hydro (Conventional)	30-100% of rated capacity	Good

PEM electrolysers and battery storage systems offer the widest operational ranges, allowing for flexible modulation across almost their entire capacity range. This wide modulation range is valuable for aFRR, where the required response may vary significantly. Smart charging of EVs offers excellent downward flexibility (increased consumption), while variable speed pumped hydro provides good range in both generation and pumping modes.

Energy Capacity for Sustained Response

Table 6: aFRR - energy capacity for sustained response

Flexibility Source	Typical Duration at Rated Power	Suitability Rating
Utility Battery Storage	1-4 hours	Good
Electrolysers	Limited by H_2 storage	Good
Electric Vehicles	1-3 hours (limited by connection time)	Moderate
Pumped Hydro	6-24+ hours	Excellent

Pumped hydro excels in energy capacity, capable of providing sustained aFRR response for many hours or even days. This makes it particularly valuable for longer-duration events or periods of sustained imbalance. Batteries and electrolysers offer moderate duration capability, while EVs may be limited by connection patterns and user requirements.

7.3.3 Manual Frequency Restoration Reserve (mFRR)

mFRR requires response within 15 minutes and sustained power provision for several hours to replace activated FCR and aFRR.

Activation Time

Table 7: mFRR - activation time comparison

Flexibility Source	Activation Time	Suitability Rating
Utility Battery Storage	Seconds to minutes	Excellent
Electrolysers (PEM)	Minutes	Very Good
Electrolysers (Alkaline)	10-30 minutes	Moderate
Electric Vehicles (Aggregated)	5-15 minutes	Good
Pumped Hydro (From standby)	5-15 minutes	Good
Pumped Hydro (From spinning)	1-5 minutes	Very Good

Utility battery storage systems can be activated rapidly for mFRR provision, typically within seconds to minutes. PEM electrolysers and spinning pumped hydro units also offer good activation times. Alkaline electrolysers may struggle to meet the 15-minute requirement, particularly from a cold start.

Sustained Power Delivery

Table 8: mFRR - sustained power delivery comparison

Flexibility Source	Sustainable mFRR Duration	Suitability Rating
Utility Battery Storage	1-4 hours	Moderate
Electrolysers	Limited by H_2 storage	Moderate
Electric Vehicles	1-3 hours (limited by connection time)	Moderate
Pumped Hydro	6-24+ hours	Excellent

Pumped hydro significantly outperforms other technologies in sustained power delivery, capable of providing mFRR for many hours or even days. This makes it particularly valuable for longer-duration events or system stress periods. Batteries, electrolysers, and EVs may be limited in their ability to provide extended mFRR service, though they can be effective for shorter durations.

Scalability and Reliability

Table 9: mFRR - scalability and reliability comparison

Flexibility Source	Reliability for mFRR	Suitability Rating
Utility Battery Storage	Very high (>98%)	Excellent
Electrolysers	High (>95%)	Very Good
Electric Vehicles (Aggregated)	Moderate (85-95%, dependent on user behavior)	Moderate
Pumped Hydro	Very high (>98%)	Excellent

Utility battery storage and pumped hydro demonstrate excellent reliability for mFRR provision, with very high availability and performance rates. Electrolysers also show good reliability, while aggregated EVs may face challenges due to the uncertainty of user behavior and connection patterns.

7.3.4 Summary of Frequency Regulation Capabilities

Table 10: Summary of Frequency Regulation Capabilities

Flexibility Source	FCR Suitability	aFRR Suitability	mFRR Suitability	Key Advantages	Key Limitations
Utility Battery Storage	Excellent	Excellent	Good	Ultra-fast response, high precision	Limited energy capacity
Electrolysers (PEM)	Good	Good	Moderate	Good downward regulation	Limited upward regulation
Electrolysers (Alkaline)	Limited	Moderate	Moderate	Large-scale potential	Slow response time
Electric Vehicles	Very Good	Good	Moderate	Distributed resource, large potential	Availability uncertainty
Pumped Hydro (Variable Speed)	Very Good	Very Good	Excellent	Long duration, large capacity	Location constraints
Pumped Hydro (Conventional)	Good	Good	Excellent	Long duration, large capacity	Limited operational range

The comparative analysis reveals complementary strengths across the flexibility sources. Batteries excel in rapid, precise response for FCR and aFRR, while pumped hydro provides unmatched energy capacity for sustained service. PEM electrolysers offer good capabilities for downward regulation (increased consumption), while EVs represent a growing distributed resource with significant potential but availability challenges.

7.4 Voltage Support Services

Voltage support services are essential for maintaining voltage levels within acceptable ranges throughout the power system, ensuring power quality and system stability.

7.4.1 Reactive Power Provision

Reactive power provision involves supplying or absorbing reactive power to maintain voltage levels.

Reactive Power Capability

Table 11: Reactive Power Capability Comparison

Flexibility Source	Reactive Power Range	Suitability Rating
Utility Battery Storage	Typically ±0.95 power factor at rated output	Very Good
Electrolysers	Typically ±0.90 power factor at rated output	Good
Electric Vehicles	Typically ±0.90 power factor at rated output	Good
Pumped Hydro	Typically ±0.85 power factor at rated output	Excellent

Pumped hydroplants, as synchronous machines, offer excellent reactive power capability, often able to provide reactive power even when not generating active power. Battery storage systems with appropriate inverters also offer very good reactive power capability, while electrolysers and EVs can provide good support when equipped with suitable power electronics.

Response Time for Reactive Power Adjustment

Table 12: Response Time for Reactive Power Adjustment

Flexibility Source	Response Time	Suitability Rating
Utility Battery Storage	Milliseconds to seconds	Excellent
Electrolysers	Seconds	Very Good
Electric Vehicles	Seconds	Very Good
Pumped Hydro	Seconds to minutes	Good

Battery storage systems can adjust reactive power output extremely rapidly, making them valuable for fast voltage support. Electrolysers and EVs with modern power electronics also offer quick response. Pumped hydro, while slightly slower, still provides good response times for most voltage support needs.

Sustained Reactive Power Provision

Table 13: Sustained Reactive Power Provision Comparison

Flexibility Source	Sustainable Duration	Suitability Rating
Utility Battery Storage	Hours (limited by thermal constraints)	Good
Electrolysers	Continuous during operation	Very Good
Electric Vehicles	Limited by connection time	Moderate
Pumped Hydro	Continuous	Excellent

Pumped hydro excels in sustained reactive power provision, capable of providing this service continuously. Electrolysers can provide reactive power whenever they are operating, while batteries may face thermal limitations during extended provision. EVs are limited by their connection patterns.

7.4.2 Voltage Control

Voltage control involves dynamically adjusting reactive power output to maintain voltage within specified ranges.

Voltage Regulation Accuracy

Table 14: Voltage Regulation Accuracy Comparison

Flexibility Source	Voltage Regulation Accuracy	Suitability Rating
Utility Battery Storage	±0.5% of target	Excellent
Electrolysers	±1.0% of target	Good
Electric Vehicles	±1.0% of target	Good
Pumped Hydro	±0.5% of target	Excellent

Both utility battery storage and pumped hydro demonstrate excellent voltage regulation accuracy, capable of maintaining voltage very close to target values. Electrolysers and EVs also provide good accuracy when equipped with appropriate control systems.

Spatial Distribution

Table 15: Spatial Distribution Comparison

Flexibility Source	Typical Grid Connection	Suitability Rating for Distribution Voltage Support
Utility Battery Storage	Transmission and distribution	Excellent
Electrolysers	Primarily transmission	Moderate
Electric Vehicles	Distribution	Excellent

Table 15: Spatial Distribution Comparison

Flexibility Source	Typical Grid Connection	Suitability Rating for Distribution Voltage Support
Pumped Hydro	Transmission	Limited

The spatial distribution of flexibility sources significantly affects their suitability for voltage support at different grid levels. Battery storage and EVs are particularly valuable for distribution grid voltage support due to their distributed nature and connection at lower voltage levels. Pumped hydro, typically connected to the transmission grid, is more limited in providing localized distribution voltage support.

7.4.3 Summary of Voltage Support Capabilities

Table 16: Summary of Voltage Support Capabilities

Flexibility Source	**Reactive Power Provision**	**Voltage Control**	**Key Advantages**	**Key Limitations**
Utility Battery Storage	Very Good	Excellent	Fast response, distributed deployment	Thermal limitations
Electrolysers	Good	Good	Continuous during operation	Primarily transmission-connected
Electric Vehicles	Good	Good	Highly distributed	Availability uncertainty
Pumped Hydro	Excellent	Excellent	Large capability, continuous	Location constraints

The comparative analysis shows that all four flexibility sources can contribute to voltage support, with complementary strengths. Pumped hydro offers excellent capability for transmission-level voltage support, while batteries and EVS are particularly valuable for distribution-level support due to their distributed nature. Electrolysers can provide good voltage support at their connection points, typically at higher voltage levels.

7.5 Grid Congestion Management

Grid congestion management involves adjusting power flows to alleviate constraints in the transmission and distribution networks, reducing the need for curtailment and grid reinforcement.

7.5.1 Peak Shaving and Valley Filling

Peak shaving involves reducing consumption or increasing generation during peak demand periods, while valley filling involves increasing consumption or reducing generation during low demand periods.

Energy Shifting Capability

Table 17: Energy Shifting Capability Comparison

Flexibility Source	Energy Shifting Duration	Suitability Rating
Utility Battery Storage	1-4 hours	Good
Electrolysers	Limited by H2 storage	Very Good
Electric Vehicles	1-3 hours (limited by connection time)	Good
Pumped Hydro	6-24+ hours	Excellent

Pumped hydro offers superior energy shifting capability, able to move large amounts of energy across many hours or even days. This makes it particularly valuable for addressing longer-duration congestion patterns. Electrolysers offer good capability for valley filling (increasing consumption during low demand), while batteries and EVS provide moderate duration shifting suitable for daily peak shaving.

Predictability and Schedulability

Table 18: Predictability and Schedulability Comparison

Flexibility Source	Scheduling Predictability	Suitability Rating
Utility Battery Storage	Very high	Excellent
Electrolysers	High	Very Good
Electric Vehicles	Moderate (dependent on user behavior)	Moderate
Pumped Hydro	Very high	Excellent

Utility battery storage and pumped hydro offer excellent predictability and schedulability, making them reliable resources for planned congestion management. Electrolysers also demonstrate good predictability, while EVS face challenges due to the uncertainty of user behavior and connection patterns.

7.5.2 Locational Flexibility

Locational flexibility refers to the ability to provide congestion management services at specific grid locations where they are most needed.

Deployment Flexibility

Table 19: Deployment Flexibility Comparison

Flexibility Source	Deployment Flexibility	Suitability Rating
Utility Battery Storage	High (can be deployed at most locations)	Excellent
Electrolysers	Moderate (requires industrial infrastructure)	Moderate
Electric Vehicles	Very high (follows transportation patterns)	Excellent
Pumped Hydro	Very low (requires specific geography)	Poor

Battery storage and EVS offer excellent deployment flexibility, capable of being located close to congestion points in both transmission and distribution grids. Electrolysers have moderate deployment flexibility, often constrained by industrial infrastructure requirements. Pumped hydro has very limited locational flexibility, constrained by specific geographical requirements.

Effectiveness for Transmission Congestion

Table 20: Effectiveness for Transmission Congestion Comparison

Flexibility Source	Transmission Congestion Relief	Suitability Rating
Utility Battery Storage	Good (when strategically located)	Very Good
Electrolysers	Good (typically connected at transmission level)	Very Good
Electric Vehicles	Limited (distributed nature)	Moderate
Pumped Hydro	Excellent (large capacity at transmission level)	Excellent

Pumped hydro and large-scale battery storage are particularly effective for transmission congestion relief due to their scale and connection at the transmission level. Electrolysers, also typically connected at higher voltage levels, can provide good transmission congestion management. EVS, being distributed at the distribution level, have more limited impact on transmission congestion unless aggregated at scale.

Effectiveness for Distribution Congestion

Flexibility Source	Distribution Congestion Relief	Suitability Rating
Utility Battery Storage	Excellent (can be precisely located)	Excellent

Flexibility Source	Distribution Congestion Relief	Suitability Rating
Electrolysers	Limited (typically larger scale)	Limited
Electric Vehicles	Excellent (naturally distributed)	Excellent
Pumped Hydro	Very limited (rarely connected to distribution)	Poor

Battery storage and EVS excel in distribution congestion management due to their distributed nature and connection at lower voltage levels. Battery systems can be strategically placed at congestion points, while EVS naturally follow transportation patterns that often correlate with load centers. Electrolysers and pumped hydro have limited effectiveness for distribution congestion due to their typical connection at higher voltage levels.

7.5.3 Summary of Grid Congestion Management Capabilities

Table 22: Summary of Grid Congestion Management Capabilities

Flexibility Source	Peak Shaving	Valley Filling	Transmission Congestion	Distribution Congestion	Key Advantages	Key Limitations
Utility Battery Storage	Very Good	Very Good	Very Good	Excellent	Deployment flexibility, scalability	Duration limitations
Electrolysers	Limited	Excellent	Very Good	Limited	Excellent for valley filling	Limited peak shaving capability
Electric Vehicles	Good	Good	Moderate	Excellent	Naturally distributed	Availability uncertainty
Pumped Hydro	Excellent	Excellent	Excellent	Poor	Long duration, large capacity	Location constraints

The comparative analysis reveals distinct and complementary roles for the different flexibility sources in congestion management. Pumped hydro excels in large-scale, long- duration transmission congestion management. Batteries offer versatile congestion management at both transmission and distribution levels. Electrolysers are particularly valuable for valley filling and transmission-level congestion management. EVS provide excellent distributed flexibility for distribution congestion management.

7.6 Integrated Flexibility Assessment

7.6.1 Temporal Characteristics Comparison

Table 23: Temporal Characteristics Comparison

Flexibility Source	Response Time	Ramp Rate	Duration	Cycling Capability	Temporal Availability
Utility Battery Storage	ms to s	100%/s	1-4h	1-2 cycles/day	24/7
Electrolysers (pem)	1-30s	5-20%/s	H_2 storage dependent	Limited by degradation	Continuous when operating
Electric Vehicles	s to min	20-50%/s	1-3h	1 cycle/day	Pattern dependent
Pumped Hydro	s to min	10-100%/min	6-24h+	Unlimited	24/7

This comparison highlights the complementary temporal characteristics of the different flexibility sources. Batteries offer the fastest response but limited duration, while pumped hydro provides extended duration with slightly slower response. Electrolysers excel in downward regulation with response times dependent on technology, while EVS offer good response but availability follows charging patterns.

7.6.2 Spatial Characteristics Comparison

Flexibility Source	Typical Scale	Grid Connection	Spatial Distribution	Location Constraints
Utility Battery Storage	1-100+ MW	T&D	Highly flexible	Few
Electrolysers	1-100+ MW	Primarily T	Moderate	Industrial infrastructure
Electric Vehicles	7-22 kW per vehicle	D	Follows transport patterns	Charging infrastructure
Pumped Hydro	10-1,000+ MW	T	Limited	Specific geography

The spatial characteristics reveal important differences in deployment flexibility and grid integration. Batteries offer the most flexible deployment options across both transmission and distribution grids. EVS provide naturally distributed flexibility at the distribution level. Electrolysers are typically connected at higher voltage levels, while pumped hydro is highly constrained by geographical requirements and connected to the transmission grid.

7.6.3 Economic Characteristics Comparison

Table 25: Economic Characteristics Comparison

Flexibility Source	Capital Cost (2025)	Operational Cost	Lifetime	Cost Trend
Utility Battery Storage	€250-400/kWh	2-5% of CAPEX annually	10-15 years	Rapidly declining
Electrolysers	€700-1,400/kW	2-5% of CAPEX annually	10-30 years	Rapidly declining
Electric Vehicles	€500-5,000 per charging point	Variable	8-15 years (battery)	Declining
Pumped Hydro	€1,000-3,000/kW	1-2% of CAPEX annually	50-80 years	Stable

The economic comparison highlights the long lifetime and low operational costs of pumped hydro against the rapidly declining capital costs of batteries and electrolysers. EVS represent a special case where the primary investment is made for transportation purposes, with flexibility as a secondary benefit.

7.6.4 Maturity and Scalability Comparison

Table 26: Maturity and Scalability Comparison

Flexibility Source	Technology Maturity	EU Capacity (2025)	EU Potential (2030)	Scalability Constraints
Utility Battery Storage	Commercial	40 GW / 80 GWh	100 GW / 250 GWh	Supply chain, materials
Electrolysers	Early commercial	1 GW	40 GW	Industrial integration, H_2 infrastructure
Electric Vehicles	Growing	5-10 GW	30-50 GW	Charging infrastructure, user adoption
Pumped Hydro	Mature	45 GW / 600 GWh	55-60 GW / 700-800 GWh	Geographical, permitting

This comparison shows the varying maturity levels and growth trajectories of the different flexibility sources. Pumped hydro represents a mature technology with limited growth potential due to geographical constraints. Batteries and electrolysers are at earlier commercial stages with rapid growth projected. EVS represent a massive potential flexibility resource tied to transportation electrification.

7.7 Optimal Applications and Complementarity

7.7.1 Optimal Applications by Service Type

Table 27: Optimal Applications by Service Type

Service Type	Most Suitable Primary Source	Complementary Sources	Rationale
FCR	Utility Battery Storage	PEM Electrolysers, V2G EVs	Fastest response, highest precision
aFRR	Utility Battery Storage, Variable Speed Pumped Hydro	PEM Electrolysers, Evs	Good balance of response and duration
mFRR	Pumped Hydro	Utility Battery Storage, Electrolysers	Extended duration capability
Voltage Support (T)	Pumped Hydro	Utility Battery Storage	Large reactive power capability
Voltage Support (D)	Utility Battery Storage, Evs	-	Distributed deployment
Transmission Congestion	Pumped Hydro	Utility Battery Storage, Electrolysers	Scale and duration
Distribution Congestion	Utility Battery Storage, Evs	-	Locational flexibility

This analysis identifies the most suitable primary and complementary sources for each service type, highlighting the importance of a diverse flexibility portfolio.

7.7.2 Temporal Complementarity

The different flexibility sources demonstrate important temporal complementarity:

- **Short-term flexibility (seconds to minutes)**: Batteries excel in providing immediate response for services like FCR and fast frequency response.
- **Medium-term flexibility (hours)**: Batteries, EVS, and electrolysers can effectively address daily patterns of renewable variability and peak demand.
- **Long-term flexibility (days to weeks)**: Pumped hydro is essential for managing extended periods of low renewable generation or high demand.

This temporal complementarity suggests that an optimal flexibility portfolio should include a mix of technologies to address different timescales of system needs.

7.7.3 Spatial Complementarity

The flexibility sources also demonstrate spatial complementarity:

- **Transmission level**: Pumped hydro and large-scale batteries/electrolysers provide system-wide services and manage bulk power flows.
- **Distribution level**: Distributed batteries and EVS address local constraints and provide voltage support.

- **Behind-the-meter**: Small-scale batteries and EVS can optimize individual customer profiles while contributing to system needs.

This spatial complementarity highlights the importance of deploying flexibility resources at all grid levels to address different types of constraints and requirements.

7.7.4 Conclusion

The comparative analysis of flexibility sources for power system services reveals that no single technology excels across all applications. Instead, each source offers distinct advantages and limitations that make it particularly suited for specific services and contexts.

Utility battery storage systems excel in applications requiring fast response and precise control, making them ideal for frequency containment reserve and distribution-level voltage support. Their deployment flexibility allows strategic placement at congestion points, though their duration limitations constrain their role in longer-term flexibility provision.

Electrolysers, particularly PEM technology, offer valuable downward regulation capability (increased consumption) and can provide good service at the transmission level. Their integration with hydrogen production creates synergies between sector coupling and grid support, though their flexibility in upward regulation is limited.

Electric vehicles represent a massive distributed flexibility resource that is particularly valuable for distribution grid services. Their natural correlation with load centers makes them effective for local congestion management, though availability uncertainty and user requirements create challenges for system operators.

Pumped hydroplants remain unmatched in their ability to provide large-scale, long- duration flexibility services. Their synchronous operation, reactive power capability, and energy capacity make them ideal for transmission-level services and extended balancing needs, though their deployment is severely constrained by geographical requirements.

The EU power system's growing flexibility needs will be best met through a diverse portfolio of these complementary resources, strategically deployed and operated to leverage their respective strengths while mitigating their limitations. Policy and market frameworks should recognize this complementarity and enable each technology to contribute optimally to system flexibility.

8 Framework Application Examples: Numerical Case Studies

8.1 Introduction

This section presents practical application examples of the flexibility assessment framework developed in this report. Through detailed numerical case studies, we demonstrate how the framework can be applied to evaluate and compare different flexibility sources for specific power system services in the EU context. These examples illustrate the methodology for quantifying flexibility potential, considering technical, economic, and operational constraints, and selecting appropriate flexibility resources for different grid applications.

8.2 Case Study 1: Frequency Containment Reserve Provision

8.2.1 Scenario Description

This case study examines the provision of 50 MW of Frequency Containment Reserve (FCR) in a metropolitan area in Western Europe with high renewable penetration. The system operator requires:

- Response time: < 5 seconds
- Full activation time: < 30 seconds
- Minimum duration: 15 minutes
- Accuracy: ± 2% of setpoint
- Availability: > 98%
- Service period: 1 year

We evaluate four flexibility options: a utility-scale battery storage system, a PEM electrolyser, an aggregated electric vehicle fleet, and a variable speed pumped hydro plant.

8.2.2 Technical Flexibility Assessment

Theoretical Flexibility Potential

Table 28: Technical Performance Parameters for FCR Provision

Parameter	Battery Storage	PEM Electrolyser	EV Fleet	Pumped Hydro
Installed capacity	50 MW / 100 MWh	100 MW	10,000 vehicles (70 MW)	200 MW
Response time	100 ms	5 s	2 s	3 s
Ramp rate	50 MW/s	10 MW/s	35 MW/s	40 MW/min
Control accuracy	± 0.5%	± 5%	± 3%	± 2%

Table 28: Technical Performance Parameters for FCR Provision

Parameter	Battery Storage	PEM Electrolyser	EV Fleet	Pumped Hydro
Maximum duration at 50 MW	2 hours	Dependent on H_2 storage	1.5 hours	24+ hours

All four options meet the basic technical requirements for FCR provision, though with different performance characteristics. The battery system offers superior response time and control accuracy, while the pumped hydro plant provides the longest duration capability.

Technical Constraints Analysis

Table 29: Technical constraints for FCR provision

Constraint	Battery Storage	PEM Electrolyser	EV Fleet	Pumped Hydro
Minimum operating level	5% (2.5 MW)	10% (10 MW)	N/A (distributed)	20% (40 MW)
State of charge limitations	10-90% (80 MWh usable)	N/A	20-80% per vehicle	Reservoir constraints (90% usable)
Cycling limitations	365-730 full cycles/year	Degradation concerns with frequent cycling	365 full cycles/year	No significant limitation
Temperature sensitivity	Requires HVAC	Moderate	Requires thermal management	Minimal
Minimum up/down time	None	5 minutes	None	15 minutes

The battery system and EV fleet offer the fewest technical constraints for FCR provision, with no significant minimum up/down times. The electrolyser faces challenges with cycling limitations and minimum operating levels, while the pumped hydro plant has constraints related to minimum operating level and up/down times.

8.2.3 Economic Flexibility Assessment

Cost Analysis

Table 30: Economic flexibility assessment for FCR provision

Cost Component	Battery Storage	PEM Electrolyser	EV Fleet	Pumped Hydro
Capital cost	€30M (€300/kWh)	€120M (€1,200/kW)	€5M (charging infrastructure)	€300M (€1,500/kW)
Annual O&M cost	€900k (3% of CAPEX)	€3.6M (3% of CAPEX)	€250k (5% of CAPEX)	€3M (1% of CAPEX)
Lifetime	12 years	15 years	10 years	50 years
Annualized cost	€3.4M	€11.6M	€750k	€9M
Opportunity cost for FCR	€1.2M (energy arbitrage)	€4.5M (H_2 production)	€500k (user compensation)	€2.5M (energy arbitrage)
Total annual cost	€4.6M	€16.1M	€1.25M	€11.5M
Unit cost (€/MW/year)	€92,000	€322,000	€25,000	€230,000

The EV fleet appears to have the lowest unit cost, primarily because the vehicles themselves are purchased for transportation rather than grid services. Among dedicated assets, the battery system offers the lowest unit cost for FCR provision, followed by pumped hydro and the electrolyser.

Revenue Potential

Table 31: Revenue potential for FCR provision

Revenue Component	Battery Storage	PEM Electrolyser	EV Fleet	Pumped Hydro
FCR market value	€5.5M (€110k/MW/year)	€5.5M	€5.5M	€5.5M
Performance bonus	€275k (5% premium)	€0 (no premium)	€0 (no premium)	€138k (2.5% premium)
Additional services	€1M (energy arbitrage)	€0 (dedicated to FCR)	€350k (demand response)	€2M (energy arbitrage)
Total annual revenue	€6.78M	€5.5M	€5.85M	€7.64M
Net annual value	€2.18M	-€10.6M	€4.6M	-€3.86M
Return on investment	7.3%	-8.8%	92%	-1.3%

The economic assessment reveals that the EV fleet offers the highest return on investment, followed by the battery system. The electrolyser and pumped hydro plant show negative returns when considering FCR provision alone, indicating they would need to stack multiple services or receive additional incentives to be economically viable.

8.2.4 Achievable Flexibility Assessment

Table 32: Achievable flexibility assessment for FCR provision

Factor	Battery Storage	PEM Electrolyser	EV Fleet	Pumped Hydro
Technical availability	98%	95%	85%	98%
Usable capacity for FCR	45 MW	40 MW	35 MW	50 MW
Effective energy capacity	90 MWh	Dependent on H_2 storage	52.5 MWh	1,200 MWh
Reliability score	97%	90%	82%	96%
Achievable FCR capacity	43.7 MW	36 MW	28.7 MW	48 MW

When accounting for all real-world constraints, the pumped hydro plant offers the highest achievable FCR capacity, followed by the battery system. The EV fleet faces challenges related to availability and reliability, resulting in the lowest achievable capacity despite its economic advantages.

8.2.5 Optimal Solution

Based on the comprehensive assessment, the optimal solution for this FCR provision scenario would be:

1. **Primary resource**: 50 MW Battery Storage System
    - Provides excellent technical performance
    - Economically viable with positive ROI
    - High reliability and availability
2. **Complementary resource**: EV Fleet
    - Provides cost-effective additional capacity
    - Distributed nature adds resilience
    - Can be scaled incrementally

The pumped hydro plant, while technically excellent, would be economically challenging if built solely for FCR provision. However, an existing pumped hydro plant could be very competitive. The electrolyser is not economically viable for dedicated FCR provision but could participate if its primary purpose is hydrogen production.

8.3 Case Study 2: Distribution Grid Congestion Management

8.3.1 Scenario Description

This case study examines congestion management in a distribution grid area in Southern Europe with high solar PV penetration. The local distribution system operator faces recurring thermal overloads on a 10 MVA transformer during solar production peaks. The requirements include:

- Peak load reduction: 3 MW for 4 hours (12 MWh daily)
- Service period: 150 days per year (summer months)
- Response time: < 15 minutes
- Location: Within the constrained distribution area
- Alternative: Grid reinforcement at €2M capital cost

We evaluate three flexibility options: a distributed battery storage system, smart charging of electric vehicles, and a small-scale electrolyser.

8.3.2 Technical Flexibility Assessment

Theoretical Flexibility Potential

Table 33: Technical Performance Parameters for Congestion Management

Parameter	Distributed Batteries	Smart EV Charging	Small Electrolyser
Installed capacity	3 MW / 12 MWh	4 MW (200 vehicles)	3 MW
Response time	1 s	30 s	60 s
Ramp rate	3 MW/s	2 MW/s	0.3 MW/s
Control accuracy	± 1%	± 5%	± 3%
Maximum duration at 3 MW	4 hours	2 hours (limited by connection patterns)	8+ hours

All three options can theoretically provide the required capacity, though with different performance characteristics. The battery system offers the best response time and control accuracy, while the electrolyser provides the longest duration capability.

Technical Constraints Analysis

Table 34: Technical constraints for congestion management

Constraint	Distributed Batteries	Smart EV Charging	Small Electrolyser
Minimum operating level	None (distributed)	None (distributed)	10% (0.3 MW)
Energy limitations	12 MWh available	Variable (dependent on vehicles present)	Limited by H_2 storage and usage
Cycling limitations	150 cycles/year (within limits)	No significant limitation	Prefers continuous operation
Location constraints	Can be precisely located	Dependent on charging infrastructure	Requires industrial connection
Seasonal availability	100%	90% (lower in holiday season)	100%

The distributed battery system offers the fewest technical constraints for this application, with guaranteed availability and precise locational control. EV charging faces challenges with variable availability, while the electrolyser has constraints related to minimum operating level and location requirements.

8.3.3 Economic Flexibility Assessment

Cost Analysis

Table 35: Economic flexibility assessment for congestion management

Cost Component	Distributed Batteries	Smart EV Charging	Small Electrolyser
Capital cost	€4.8M (€400/kWh)	€800k (charging equipment)	€4.2M (€1,400/kW)
Annual O&M cost	€144k (3% of CAPEX)	€40k (5% of CAPEX)	€126k (3% of CAPEX)
Lifetime	10 years	10 years	15 years
Annualized cost	€624k	€120k	€406k
Opportunity cost	€90k (energy arbitrage)	€75k (user compensation)	€450k (H_2 production)
Total annual cost	€714k	€195k	€856k
Unit cost (€/MW/year)	€238,000	€65,000	€285,333

Smart EV charging appears to have the lowest unit cost, primarily because the vehicles themselves are purchased for transportation rather than grid services. The distributed battery system has a moderate cost, while the electrolyser has the highest unit cost when dedicated to congestion management.

Value Assessment

Table 36: Value assessment for congestion management

Value Component	Distributed Batteries	Smart EV Charging	Small Electrolyser
Avoided grid reinforcement	€200k/year (10-year amortization)	€200k/year	€200k/year
Reduced curtailment value	€108k (1,800 MWh at €60/MWh)	€108k	€108k
Additional services	€150k (local voltage support)	€50k (demand response)	€60k (voltage support)
Hydrogen value	€0	€0	€675k (150 tons at €4.5/kg)
Total annual value	€458k	€358k	€1,043k
Net annual value	-€256k	€163k	€187k
Return on investment	-5.3%	20.4%	4.5%

The value assessment reveals that both smart EV charging and the electrolyser offer positive returns on investment, with EV charging showing the highest percentage return. The distributed battery system shows a negative return when considering only distribution grid services, indicating it would need additional revenue streams or incentives to be economically viable.

8.3.4 Achievable Flexibility Assessment

Table 37: Achievable flexibility assessment for congestion management

Factor	Distributed Batteries	Smart EV Charging	Small Electrolyser
Technical availability	98%	85%	95%
Spatial effectiveness	100% (optimal placement)	80% (dependent on charging locations)	90% (single location)
Temporal effectiveness	100% (fully dispatchable)	70% (dependent on connection patterns)	95% (some operational constraints)
Reliability score	98%	75%	90%
Achievable congestion relief	2.94 MW	1.68 MW	2.57 MW

When accounting for all real-world constraints, the distributed battery system offers the highest achievable congestion relief, followed by the electrolyser. The EV charging solution faces

challenges related to availability and temporal effectiveness, resulting in the lowest achievable capacity despite its economic advantages.

8.3.5 Optimal Solution

Based on the comprehensive assessment, the optimal solution for this distribution congestion scenario would be:

1. **Primary resource**: Smart EV Charging (2 MW)
    - Economically attractive with highest ROI
    - Requires minimal additional infrastructure
    - Naturally located in residential areas where congestion occurs
2. **Complementary resource**: Small Electrolyser (1 MW)
    - Economically viable with positive ROI
    - Provides reliable baseline flexibility
    - Creates valuable hydrogen as a co-product
3. **Backup solution**: Distributed Batteries (1 MW / 4 MWh)
    - Provides highly reliable and precise congestion relief
    - Can be strategically placed at critical locations
    - Offers additional value through voltage support

This combined approach leverages the economic advantages of EV charging while ensuring reliability through the electrolyser and targeted battery deployment, creating a robust and cost-effective solution for the distribution congestion challenge.

8.4 Case Study 3: Renewable Integration and Balancing

8.4.1 Scenario Description

This case study examines the integration of a new 500 MW offshore wind farm in Northern Europe. The system operator faces challenges with balancing the variable output and requires flexibility resources to:

- Manage forecast errors: ±100 MW with 1-hour notice
- Provide balancing capacity: 200 MW for up to 8 hours during low wind periods
- Absorb excess generation: 150 MW for up to 6 hours during high wind/low demand
- Service period: Continuous operation
- Location: Within the same bidding zone as the wind farm

We evaluate four flexibility options: a large-scale battery system, a pumped hydro plant, a large electrolyser, and an aggregated EV fleet.

8.4.2 Technical Flexibility Assessment

Theoretical Flexibility Potential

Table 38: Technical performance parameters for renewable integration

Parameter	Battery System	Pumped Hydro	Large Electrolyser	Aggregated EVs
Installed capacity	200 MW / 1,000 MWh	300 MW / 3,600 MWh	200 MW	300 MW (50,000 vehicles)
Response time	1 s	60 s	30 s	60 s
Ramp rate	200 MW/s	60 MW/min	20 MW/min	100 MW/min
Upward regulation	200 MW	300 MW	0 MW	150 MW
Downward regulation	200 MW	300 MW	200 MW	300 MW
Maximum duration at full capacity	5 hours	12 hours	24+ hours	3 hours (variable)

The pumped hydro plant offers the best combination of capacity and duration for both upward and downward regulation. The battery system provides excellent response characteristics but limited duration. The electrolyser can only provide downward regulation (increased consumption) but with extended duration. The EV fleet offers good capacity but with variable availability.

Technical Constraints Analysis

Table 39: Technical constraints for renewable integration

Constraint	Battery System	Pumped Hydro	Large Electrolyser	Aggregated EVs
Minimum operating level	5% (10 MW)	20% (60 MW)	10% (20 MW)	None (distributed)
Energy limitations	1,000 MWh	3,600 MWh	Limited by H_2 storage	Variable (dependent on fleet)
Cycling limitations	365 full cycles/year	No significant limitation	Prefers limited cycling	365 full cycles/year
Location constraints	Flexible	Specific geography	Industrial connection	Distributed
Seasonal availability	98%	95% (maintenance, water)	95%	85% (variable patterns)

The battery system offers good flexibility with few constraints, though with energy limitations.

The pumped hydro plant provides excellent energy capacity but has location constraints and minimum operating levels. The electrolyser is limited to downward regulation but can operate for extended periods. The EV fleet faces challenges with variable availability and limited energy capacity.

8.4.3 Economic Flexibility Assessment

Cost Analysis

Cost Component	Battery System	Pumped Hydro	Large Electrolyser	Aggregated EVs
Capital cost	€300M (€300/kWh)	€450M (€l,500/kW)	€240M (€1,200/kW)	€30M (infrastructure)
Annual O&M cost cost	€9M (3% of capex)	€4.5M (1% of capex)	€7.2M (3% of capex)	€1.5M (5% of capex)
Lifetime	12 years	50 years	15 years	10 years
Annualized cost	€34M	€13.5M	€23.2M	€4.5M
Opportunity cost	€10M (energy arbitrage)	€15M (energy arbitrage)	€24M (H_2 production)	€9M (user compensation)
Total annual cost	€44M	€28.5M	€47.2M	€13.5M
Unit cost (€/MW/year)	€220,000	€95,000	€236,000	€45,000

The aggregated EV fleet appears to have the lowest unit cost, followed by the pumped hydro plant. The battery system and electrolyser have significantly higher unit costs, reflecting their higher capital intensity and shorter lifetimes.

Value Assessment

Table 41: Value assessment for renewable integration and balancing

Value Component	Battery System	Pumped Hydro	Large Electrolyser	Aggregated EVs
Balancing market value	€25M	€36M	€12M (downward only)	€18M (variable)
Avoided curtailment value	€9M(150,000MWh)	€9M	€9M	€6M (partial)
Capacity value	€10M	€15M	0	€5M (partial)

Table 41: Value assessment for renewable integration and balancing

Value Component	Battery System	Pumped Hydro	Large Electrolyser	Aggregated EVs
Additional services	€8M (FCR, voltage)	€10M (FCR, voltage)	€3M (voltage)	€4M (distribution services)
Hydrogen value	0	0	€36M (8,000 tons)	0
Total annual value	€52M	€70M	€60M	€33M
Net annual value	€8M	€41.5M	€12.8M	€19.5M
Return on investment	0.027	0.092	0.053	0.65

The value assessment reveals that all four options offer positive returns on investment, with the EV fleet showing the highest percentage return due to its low capital cost. The pumped hydro plant offers the highest absolute net value, followed by the EV fleet and electrolyser.

8.4.4 Achievable Flexibility Assessment

Table 42: Achievable flexibility assessment for renewable integration and balancing

Factor	Battery System	Pumped Hydro	Large Electrolyser	Aggregated EVs
Technical availability	0.98	0.95	0.95	0.85
Forecast error management	0.95 effective	0.9 effective	50% effective (down only)	70% effective (variable)
Balancing capability	0.9 effective	0.98 effective	40% effective (down only)	60% effective (variable)
Excess generation absorption	95% effective	98% effective	98% effective	70% effective (variable)
Reliability score	0.96	0.95	0.8	0.75
Achievable balancing capacity	192 MW	285 MW	160 MW (down only)	225 MW (variable)

When accounting for all real-world constraints, the pumped hydro plant offers the highest achievable balancing capacity, followed by the EV fleet. The battery system provides excellent reliability but is limited by energy capacity. The electrolyser is effective for absorbing excess generation but cannot provide upward regulation.

8.4.5 Optimal Solution

Based on the comprehensive assessment, the optimal solution for this renewable integration scenario would be:

1. **Primary resource**: Pumped Hydro Plant (300 MW)
    - Provides excellent technical performance for both up and down regulation
    - Economically attractive with highest absolute net value
    - Offers long-duration balancing capability
2. **Complementary resource**: Large Electrolyser (150 MW)
    - Economically viable with positive ROI
    - Excellent for absorbing excess generation
    - Creates valuable hydrogen as a co-product
3. **Fast-response component**: Battery System (50 MW / 200 MWh)
    - Provides ultra-fast response for forecast errors
    - Complements pumped hydro for immediate needs
    - Offers additional value through FCR provision
4. **Distributed component**: Aggregated EVs (100 MW)
    - Economically attractive with highest ROI
    - Provides distributed flexibility
    - Can be scaled incrementally

This combined approach creates a comprehensive solution that addresses all aspects of the renewable integration challenge, leveraging the complementary strengths of each technology while mitigating their individual limitations.

8.5 Framework Application Methodology

These case studies demonstrate the systematic application of the flexibility assessment framework developed in this report. The methodology follows these key steps:

1. **Define service requirements**: Clearly specify the technical requirements, duration, location, and other relevant parameters for the flexibility service.
2. **Evaluate theoretical flexibility potential**: Assess the maximum technical capability of each flexibility source without considering constraints.
3. **Analyze technical constraints**: Identify and quantify the technical limitations that reduce the usable flexibility potential.
4. **Perform economic assessment**: Calculate costs (capital, operational, opportunity) and potential value streams for each option.
5. **Determine achievable flexibility**: Synthesize technical and economic factors to estimate the realistic, achievable flexibility contribution.

6. **Design optimal solution**: Identify primary and complementary resources that together provide the most effective and economical solution.

This structured approach enables power system planners and operators to make informed decisions about flexibility investments and operations, considering the full range of technical, economic, and practical factors that influence performance.

8.6 Conclusion

The framework application examples demonstrate that optimal flexibility solutions typically involve combinations of complementary resources rather than reliance on a single technology. Each flexibility source-utility battery storage, electrolysers, electric vehicles, and pumped hydroplants-offers distinct advantages and limitations that make it particularly suited for specific aspects of power system services.

The case studies highlight several key insights:

1. **Complementarity is essential**: Fast-responding resources like batteries are ideal for immediate needs, while longer-duration resources like pumped hydro are crucial for sustained balancing.
2. **Economic viability often requires multiple value streams**: Most flexibility resources need

9 Conclusions and Recommendations

9.1 Summary of Key Findings

This technical report has developed and applied a comprehensive framework for assessing the flexibility potential of four key flexibility sources in the EU power system: utility battery storage, electrolysers, electric vehicles, and pumped hydroplants. The analysis has revealed several important findings:

Complementary Flexibility Characteristics: Each flexibility source demonstrates distinct technical characteristics that make it particularly suited for specific applications. Utility battery storage excels in fast-response applications requiring precise control, such as frequency containment reserve. Electrolysers offer valuable downward regulation capability and sector coupling benefits. Electric vehicles provide distributed flexibility that naturally correlates with load centers. Pumped hydroplants deliver unmatched long-duration flexibility and synchronous operation benefits.

Temporal Complementarity: The flexibility sources operate effectively across different timescales, creating natural complementarity. Batteries and EVs excel in immediate response (seconds to minutes), while electrolysers and pumped hydro provide sustained flexibility over hours to days. This temporal complementarity suggests that an optimal flexibility portfolio should include a mix of technologies to address different timescales of system needs.

Spatial Complementarity: The flexibility sources also demonstrate spatial complementarity across the power system. Pumped hydro and large-scale batteries/electrolysers provide system-wide services at the transmission level, while distributed batteries and EVs address local constraints at the distribution level. This spatial complementarity highlights the importance of deploying flexibility resources at all grid levels.

Economic Considerations: The economic assessment reveals significant differences in capital intensity, lifetime, and value stacking potential across the flexibility sources. Pumped hydro offers the longest lifetime and lowest operational costs but requires substantial upfront investment. Batteries and electrolysers have higher operational flexibility but shorter lifetimes. EVs represent a special case where the primary investment is made for transportation purposes, with flexibility as a secondary benefit.

Optimal Applications: The comparative analysis identifies optimal applications for each flexibility source: - Utility battery storage: Fast frequency response, distribution-level voltage support, and strategic congestion management - Electrolysers: Downward regulation, transmission-level congestion management, and sector coupling - Electric vehicles: Distribution grid services, local voltage support, and aggregated balancing services - Pumped hydroplants: Long-duration balancing, transmission-level services, and system restoration

Combined Solutions: The case studies demonstrate that optimal flexibility solutions typically involve combinations of complementary resources rather than reliance on a single technology. By leveraging the strengths of each technology while mitigating their limitations, combined approaches can provide more effective and economical solutions to power system challenges.

9.2 Implications for EU Power System Planning

The findings of this report have several important implications for power system planning in the EU:

Diverse Flexibility Portfolio: System planners should aim to develop a diverse portfolio of flexibility resources rather than focusing exclusively on any single technology. This diversity provides resilience against technology-specific risks and enables more effective management of different types of system needs.

Strategic Deployment: Flexibility resources should be strategically deployed based on their specific characteristics and the local system needs. This includes considering both temporal (response time, duration) and spatial (transmission vs. distribution) aspects of flexibility provision.

Integrated Planning: Power system planning should integrate flexibility considerations from the outset, rather than treating them as an afterthought. This includes co-optimization of generation, network, and flexibility resources to minimize overall system costs.

Sector Coupling: The potential synergies between the power sector and other energy sectors (hydrogen, transport, heat) should be explicitly considered in system planning. Technologies like electrolysers and EVs that bridge multiple sectors can create additional value streams that improve overall economics.

Regulatory Framework: The regulatory framework should evolve to recognize and properly value the full range of services provided by different flexibility sources. This includes developing appropriate market mechanisms, grid codes, and connection requirements.

9.3 Policy Recommendations

Based on the analysis conducted in this report, several policy recommendations can be made to support the effective deployment and utilization of flexibility resources in the EU:

Technology-Neutral Flexibility Markets: Develop technology-neutral market mechanisms that define services based on technical requirements rather than technology type, enabling fair competition among different flexibility sources.

Remove Regulatory Barriers: Address regulatory barriers that limit the participation of certain flexibility sources in markets, such as minimum bid sizes, duration requirements, or double grid fees for storage.

Value Stacking: Enable flexibility providers to stack multiple value streams where technically feasible, improving the economic viability of flexibility investments.

Locational Signals: Introduce locational signals in market design to incentivize the deployment of flexibility resources where they provide the most system value.

Standardization: Develop technical standards and protocols for flexibility provision, particularly for distributed resources like EVs, to reduce integration costs and complexity.

Research and Innovation Support: Continue supporting research and innovation in flexibility technologies, with a focus on reducing costs, improving performance, and developing advanced control systems.

Grid Planning Reform: Reform grid planning processes to better account for the potential of flexibility resources to defer or avoid traditional grid investments.

Cross-Sector Policy Coordination: Ensure coordination between energy, transport, and industrial policies to maximize the potential of sector coupling technologies like electrolysers and EVs.

9.4 Future Research Directions

While this report provides a comprehensive assessment of flexibility potential, several areas warrant further research:

Advanced Flexibility Metrics: Develop more sophisticated metrics for quantifying and comparing flexibility across different technologies and applications, particularly for distribution-level flexibility.

Stochastic Flexibility Assessment: Extend the assessment framework to better account for uncertainties in both flexibility provision (e.g., EV availability) and system needs (e.g., renewable generation forecasts).

Flexibility from Emerging Technologies: Assess the flexibility potential of emerging technologies not covered in depth in this report, such as thermal storage, compressed air energy storage, or demand response from industrial processes.

Distribution-Level Flexibility Markets: Investigate market designs and coordination mechanisms for unlocking flexibility at the distribution level, including local flexibility markets and TSO-DSO coordination.

Whole-System Value of Flexibility: Develop methodologies for assessing the whole-system value of flexibility, including avoided network investments, reduced renewable curtailment, and cross-sector benefits.

Long-Duration Flexibility Needs: Analyze the requirements for long-duration flexibility (days to weeks) in highly renewable power systems and the most cost-effective ways to provide it.

Flexibility in Integrated Energy Systems: Extend the flexibility assessment framework to consider integrated energy systems, including interactions between electricity, heat, gas, and transport sectors.

In conclusion, the transition to a decarbonized power system in the EU will require a substantial increase in flexibility from a diverse portfolio of resources. By understanding the specific characteristics, constraints, and optimal applications of different flexibility sources, system planners, market designers, and policy makers can develop more effective strategies for enabling this transition while maintaining system reliability and cost-effectiveness.

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