White Paper

Hydropower's key role in flexibility and storage for a safe, clean and secure European power system – today and tomorrow

ETIP HYDROPOWER

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Intended Purpose: This White Paper is part of a series developed by ETIP HYDROPOWER to support informed decision-making on hydropower in the context of the EU's energy, climate, and environmental objectives. It is addressed to European and national policymakers, especially those involved in research, energy and environmental policy. The aim is to provide expert-based insights and recommendations to guide the development and implementation of relevant EU strategies, research programmes and legislation.

Executive Summary

Europe's energy transition, driven by the European Green Deal and Clean Industrial Deal, relies heavily on the buildout of wind and solar generation. While essential for decarbonisation, these variable renewable energy (VRE) sources introduce challenges in ensuring security of supply. The growing need for flexibility, including storage technologies is clear: according to the Joint Research Centre, by 2050, daily flexibility requirements will be seven times higher than today [2].

Hydropower is uniquely positioned to address these challenges. It provides short-, medium-, and long-term flexibility, for example, by supporting frequency regulation and storing electricity. Today, pumped storage hydropower stands out as the leading technology for electricity storage, boasting the highest capacity of all available technologies. With considerable potential for expansion, it plays a crucial role in optimising the utilisation of surplus power generated from VRE sources.

However, several obstacles hinder hydropower's full potential: declining R&D investment, market distortions, support schemes that overlook hydropower's diverse contributions, inadequate remuneration for flexibility services, as well as complex, inconsistently implemented permitting frameworks.

Overcoming these obstacles requires targeted investment, predictable regulatory frameworks, and faster, streamlined permitting in line with Europe's climate goals – enabling a resilient energy future built on a balanced technology mix, with hydropower as a cornerstone of flexibility.

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What the European Power System needs

The European Union (EU) is a global leader in the efforts to combat climate change, with ambitious CO_2 emission reduction targets set in the European Green Deal and updated in the Clean Industrial Deal. Through the massive expansion of wind and solar power, the EU aims to reduce greenhouse gas emissions by 55% compared to 1990 levels by 2030. That number is proposed to jump to 90% by 2040, with the ultimate goal of climate neutrality – the 'Net Zero' target [1].

However, these initiatives aiming at combating climate change and reducing dependence on fossil imports also add uncertainty and increase the risk of instability of the power system. This is because power generation from wind and solar is inherently variable due to reliance on external factors such as weather conditions. To ensure security of supply while achieving the decarbonisation targets, increasing power system flexibility is becoming key. Fortunately, a variety of technologies and solutions are available [2].

When considering power systems, flexibility is the "ability of an electricity system to adjust to the variability of generation and consumption patterns and to grid availability" [3]. Presently, the increase in flexibility is primarily required in order to cope with the variability that the expansion of solar and wind sources introduces at different time scales, to avoid the curtailment of power from these variable renewable energy (VRE) sources, which jeopardises their economic viability, and to manage the increasing electrification of the energy demand.

Flexibility requirements resulting from power system fluctuations can be **short-, medium-, and long-term**. **Short-term** flexibility (milliseconds to hours) balances the system within the day and ensures system stability. **Medium-term** flexibility (hours to days) balances the electricity supply over daily variations. **Long-term** flexibility (up to months) addresses prolonged events [4].

Flexibility can be provided by a range of sources and technologies. To meet future flexibility needs, all sources – flexible consumption, flexible generation, and storage – will be needed. All technologies, as illustrated in Figure 1, will also be required in various combinations. These combinations will depend on local circumstances and the available resources and infrastructures. It is important to note that storage plays a particularly important role, as it provides the ability to both consume and generate electricity in a highly flexible manner.

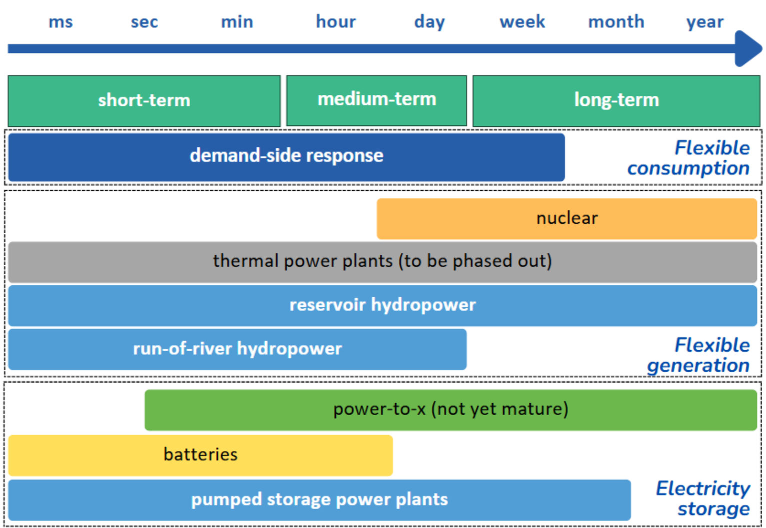

Figure 1. Flexibility sources and technologies [12]

Flexibility also has a geographic dimension that must be considered; namely, **local flexibility needs** at the distribution level and **regional flexibility needs** at the system level. Addressing both temporal and geographic flexibility needs requires the previously mentioned flexibility sources. In the current power system, from a generation perspective, these sources are mainly hydropower and gas, supported by baseload generators such as coal and nuclear power plants. However, a heavy reliance on gas, coal, and nuclear poses threats to Europe's energy security and import dependency, in addition to the significant CO_2 emissions associated with gas and coal.

Annex Box 1: Flexibility and Storage Services in Markets [5]*

SYNCHRONOUS INERTIA	0 s	This is the inherent capability of rotating machines directly connected to the power grid to store and inject their kinetic energy, which supports the frequency transient behaviour in the moments subsequent to an active power imbalance.
FAST FREQUENCY RESPONSE (FFR)	0.5 - 2 s	FFR is designed to provide a rapid active power response, typically within less than 2 seconds, following inertial response and before the activation of FCR.
FREQUENCY CONTAINMENT RESERVE (FCR)	< 30 s	FCR aims to contain system frequency after an active power imbalance by maintaining the balance between generation and demand.
AUTOMATIC FREQUENCY RESTORATION RESERVE (aFRR)	30 s - 15 min	aFRR is an automatic process that aims to restore system frequency to its set point and maintain power interchange among load-frequency control areas.
MANUAL FREQUENCY RESTORATION RESERVE (mFRR)	< 15 min	mFRR involves manual interventions to restore system frequency, typically fully activated within 15 minutes.
REPLACEMENT RESERVE (RR)	> 15 min	RR aims to replace or support frequency restoration processes, typically activated within 15 minutes to 1 hour.
VOLTAGE/VAR CONTROL	< 1 s	The Volt/var control process is implemented by manual or automatic control actions, designed to maintain the nominal set values for the voltage levels and/or reactive powers. This is critical when considering the impacts of VRE.
BLACK START	n/a	Black start is the process of restarting power plant operation during a grid blackout, from a completely non-energised state and without any power from the network.
STORAGE CAPACITY	hr - mths	Electricity storage provides grid stability by storing excess electricity and releasing it when needed. It helps balance supply and demand over different timescales, supports frequency regulation, and enhances grid reliability.

**For ancillary services with established markets in Europe, market names are used to describe them.*

Note: *This table is adapted from source* [5]*, with one additional row ("Storage Capacity") added by the authors.*

A growing share of VRE in Europe's electricity system will require greater flexibility to ensure a reliably functioning system. Compared to today, daily flexibility requirements in EU countries will more than double by 2030 and grow 7 times by 2050 (see Figure 2) to more than 900 TWh/yr [2]. When considering all time scales, flexibility requirements are expected to exceed 2000 TWh/yr by 2050 [2]. This number could be higher when considering other key partners in the European power system, such as the Balkans, the United Kingdom, Switzerland, and Norway [6].

During "**Dunkelflaute**" periods, when there is little to no electricity generation from wind and solar, the electricity system may face challenges in meeting demand if sufficient flexible sources, such as flexible generation and storage, are not available, which, in extreme cases, can increase the potential of **blackout scenarios**.

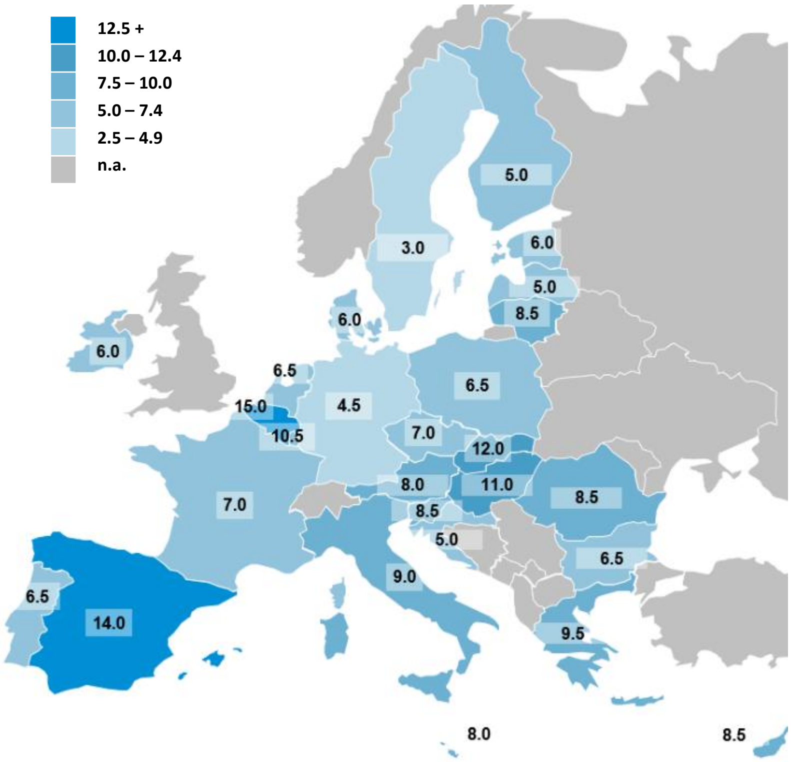

Figure 2. Growth factor of daily flexibility requirements in the EU [2]

With such rapid growth in flexibility demands, **interconnection capacity** across Europe is also essential for the secure operation of the electricity system. Expanding interconnections between regions enhances power system flexibility and enables the sharing of flexible sources and renewable energy across broader geographic areas.

How hydropower can support Europe's need for flexibility and storage

Hydropower stands out among electricity technologies due to its exceptional ability to provide flexibility across all time frames, as illustrated in Annex Box 2, particularly through flexible generation and large-scale storage capacities, which are essential for ensuring a stable and reliable electricity supply. It achieves this while also being one of the least expensive technologies in terms of levelized cost of energy (LCOE), and among the most reliable forms of power generation and storage technologies [7].

Annex Box 2: Flexibility and Storage Services in Markets Provided by Hydropower [5]

		Run-of-River	Reservoir	Pumped Storage
SYNCHRONOUS INERTIA	0 ms	x	x	x
FAST FREQUENCY RESPONSE (FFR)	0.5 s - 2 s	o	o	o
FREQUENCY CONTAINMENT RESERVE (FCR)	< 30 s	x	x	x
AUTOMATIC FREQUENCY RESTORATION RESERVE (aFRR)	30 s - 15 min	x	x	x
MANUAL FREQUENCY RESTORATION RESERVE (mFRR)	< 15 min	x	x	x
REPLACEMENT RESERVE (RR)	> 15 min	x	x	x
VOLTAGE/VAR CONTROL	< 1 s	x	x	x
BLACK START	N/A	c	c	c
STORAGE CAPACITY	hr - mths		x	x

x: hydropower provides this …… c: hydropower can provide this …… o: hydropower is innovating to provide this
Note: *This table is adapted from source* [5]*, with one additional row ("Storage Capacity") added by the authors.*

One of the key strengths of hydropower is its ability to provide flexible generation, enabling it to respond to fluctuations in electricity demand almost instantaneously. Unlike many conventional thermal and nuclear power plants that can require significant startup times, hydropower facilities can **ramp-up and ramp-down** capacity very fast, within seconds, thanks to **highly adaptable machines**. In addition to providing flexible power generation, pumped storage hydropower plants can function as flexible consumers by pumping water, reversing the generation process. Thus, electricity is stored in a highly efficient manner and can be fed back into the system as needed. This capability is demonstrated by, for example, Kops II, a pumped storage hydropower plant in Austria that was designed to perform up to 30 start-stop-cycles per day, adapting to rapid changes in the power system, a reflection of the broader industry's continuous innovation to meet the needs of the future power system [8].

Another valuable feature of hydropower is the possibility of **black start capability**, which enables it to restore power to the system in the event of a complete blackout without relying on external power sources. This capability was crucial during the widespread blackout that affected Spain, Portugal and France on April 28, 2025, as hydropower plants played a key role in initiating the grid restoration process [9].

Example 1: Kops II – Austria – illwerke vkw

Since 2008, Kops II has been providing peak load and flexibility with a total capacity of 525 MW in turbine and 480 MW in pump mode. Kops II operates three highly flexible ternary machinery sets consisting of a three-stage radial pump, a hydraulic clutch, a motor generator and a six-nozzled Pelton turbine each. To be able to ensure full regulating capability in a range between 0% and 100% in turbine and pump mode, the principle of the "hydraulic short circuit" is used (for further details on this principle, see the XFLEX HYDRO project [5]).

Pumped storage hydropower in Europe is the largest source of electricity **storage** among all available technologies, with the ability to provide storage capacities across all timescales. Variable-speed reversible pump-turbines also further enhance flexibility by enabling fast-response frequency regulation in both pump and turbine modes, and by providing FFR. This makes pumped storage a crucial technology for the efficient utilisation of available resources, particularly when VRE sources are either unavailable or generating excess power that would otherwise be curtailed. Unlike batteries, which are typically used for short-term balancing, hydropower's scale and use of existing infrastructure enable it to store vast amounts of electricity over extended periods up to several months, thereby ensuring reliability and security of supply.

Example 2: Grand'Maison – France – EDF

Since 1985, Grand'Maison has been the largest pumped-storage hydropower plant in France and one of the most important in Europe, with a total capacity of 1,800 MW. Located in the French Alps, the plant uses a head of roughly 900 meters between its upper and lower reservoirs to generate electricity. Grand'Maison is equipped with 8 reversible pump-turbine units and 4 pelton turbines, allowing it to switch rapidly between pumping and generation modes. Thanks to its high storage capacity and fast start-up time, Grand'Maison plays a crucial role in integrating VRE sources and delivering both flexibility and peak-load electricity to the French power system.

What hydropower needs

While the importance of hydropower in Europe has been proven, hydropower must be enabled in several specific areas to ensure that it continues to play this vital role. Hydropower is a mature technology, but it must be allowed, encouraged, and incentivised to evolve in line with emerging challenges, such as growing flexibility demands, more stringent policy requirements, changing societal expectations, and the impacts of climate change.

A key priority is **sustained investment in Research, Development, and Innovation (R&D&I)**. Maintaining Europe's global leadership in hydropower technology requires continuous innovation to deliver more flexible and sustainable solutions, while addressing emerging operational challenges and modern sustainability standards. For example, shifts in system requirements have altered hydropower's operating patterns, resulting in increased wear and tear on equipment and higher maintenance costs. R&D&I efforts must focus not only on enhancing hydropower's efficiency and flexibility, but also on quantifying and mitigating its impacts. The Hydropower Europe Research and Innovation Agenda (RIA) offers a comprehensive roadmap to guide such efforts.

The market interventions in several European countries in response to the 2022 surge in energy prices have had profound impacts on the power sector, creating a heightened sense of uncertainty for investors. This comes at a critical time, as the sector pursues the refurbishment and upgrading of its fleet to enhance both firmness and flexibility in support of a progressively decarbonised power system. Meeting these demands requires large-scale, capital-intensive investment. To enable such investments, a stable, predictable, and technology-neutral legal framework is essential, one that offers long-term confidence to project developers and investors alike.

Avoiding market distortions and ensuring a level playing field is essential for hydropower's further success. Member States should work to reduce the strain of discriminatory taxes, levies, grid fees, or other additional costs for hydropower. To support this, the European Commission could lead a comprehensive EU-wide review of these burdens, while also highlighting best practices and successful approaches as models for broader implementation.

In countries where signals from the electricity wholesale market may be inadequate to stimulate investments in flexibility, support schemes—such as those outlined in the recent revision of the Electricity Market Design—can play a key role in driving long-term investment in hydropower. However, it is crucial that these schemes remain consistent with existing regulatory frameworks and enable flexible hydropower plants to optimise revenues across various markets. In addition, the emphasis should not solely be on prioritising new constructions but also on upgrading and expanding the existing hydropower fleet.

In the case of pumped storage, effective national-level implementation of the 2019 Electricity Market Design Reform is critically important. This reform formally recognises storage as its own market role, acknowledging its unique dual function as both an electricity consumer and producer. To safeguard the value of renewable electricity throughout the entire storage cycle, it is essential to establish a standardised, EU-wide certification methodology.

Remuneration of flexibility services, which fall outside the scope of the electricity wholesale market, is another critical area in need of improvement [10]. Although hydropower has long supported essential grid stability through frequency control, voltage regulation, and fast ramping, some of the services remain under-compensated or entirely uncompensated. This is particularly concerning given the additional operational costs and accelerated equipment wear and tear, which are rarely addressed by current market structures [11]. In addition, some Member States still restrict revenue stacking, limiting hydropower's ability to capture the full value of its services. To safeguard the long-term availability of these essential flexibility services, marketbased remuneration schemes must reflect full cost and incentivise continued investment and modernisation.

Flexible hydropower, including both pumped storage and reservoir plants, requires a stable investment environment underpinned by clear, long-term signals. Where offered by Member States, support schemes should not be restricted to new-built capacity, but also enable upgrades and efficiency improvements across the existing fleet.

Another significant obstacle is the generally **complex and lengthy permitting and authorisation process**. The insufficient and ambiguous implementation of EU regulations at the Member State level slows down modernisation and innovation efforts, making it difficult for hydropower to adapt to evolving requirements and the rapid expansion of VRE.

The latest revision of the Renewable Energy Directive (RED III) was a positive step towards accelerating the permitting procedures. However, it remains at the discretion of Member States to exempt hydropower from the presumption of overriding public interest, in addition to the designated acceleration areas. The permitting process in Member States can take several years, sometimes up to a decade, in addition to the outcome being uncertain and the profitability of the investment potentially changing over time. Furthermore, another central issue persists: the different types of hydropower plants and their different roles within the electricity system are still not sufficiently recognised or taken into account.

Key Takeaways

- Europe's demand for flexibility will continue to grow rapidly with the continued uptake of volatile renewable energy (VRE) sources.
- Hydropower is uniquely positioned to meet Europe's flexibility needs by providing both flexible generation and flexible electricity storage through offers such as:
  - pumped storage hydropower's vast electricity storage capacity
  - fast ramp-up/ramp-down capacity from highly adaptable machines
  - black start capabilities
- To unlock hydropower's full potential requires decisive action:
  - R&D&I investments need to be accelerated to foster innovation
  - Hydropower needs a level playing field, free from market distortions
  - Flexibility support schemes must reflect hydropower's contributions to providing flexibility across all time frames through flexible generation and large-scale electricity storage
  - Remuneration schemes should reflect the true value of providing flexibility as it increases operational costs and accelerates equipment wear
  - Member States need to implement EU regulations in a clear, streamlined and legally sound manner to reduce permitting complexity

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