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Hydropower's key role in flexibility and storage for Europe – today and tomorrow

Working Group 1: Hydropower's role for flexibility and storage

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Nur für den internen Gebrauch - Internal

Executive Summary

Europe's energy transition, driven by the European Green Deal, relies heavily on wind and solar generation. While necessary for decarbonization, these sources introduce variability which may lead to grid instability. The growing need for flexibility and storage is clear: according to the Joint Research Centre, by 2050, daily flexibility requirements will be seven times higher than today [1].

Hydropower is uniquely positioned to meet these challenges. It provides short-, medium-, and long-term flexibility, for example, by supporting frequency regulation. Furthermore, hydropower offers the largest electricity storage capacity of any technology.

However, several barriers hinder hydropower's full potential. Investments in research and innovation are decreasing, permitting processes remain slow and inconsistent and remuneration for essential grid services is inconsistent and often fails to account for hydropower's value. Addressing these issues through targeted investment, regulatory reform, and fair market conditions is essential.

A resilient energy future requires a balanced technology mix, with hydropower as a cornerstone of flexibility and stability. To achieve this, Europe must improve policy frameworks, recognize hydropower's strategic role, and ensure its continued research, development and innovation.

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What the European Energy System needs

The European Union (EU) is a global leader in the efforts to combat climate change, with highly ambitious targets laid out in the European Green Deal to reduce CO_2 emissions significantly. By the end of the decade, the EU aims to reduce greenhouse gas emissions by 55% compared to 1990 levels. That number jumps to 90% by 2040, with the ultimate goal of climate neutrality by the year 2050 [2]. The EU plans to hit these targets all while remaining industrially competitive and energy secure [3].

Although aiming at combatting climate change, these initiatives also bring some unintended consequences for Europe's energy system. Power generation from wind and solar is inherently variable with uncertainties in the prediction as it relies on external factors such as weather conditions and atmospheric changes. These variable renewable energies (VRE) lead to a fluctuating electricity supply and a higher risk of grid instability, thus creating a less reliable system. This growing risk of instability and unreliability needs to be addressed if we are to safely reach the targets laid out in the European Green Deal. Luckily, there are existing solutions. Some technologies are **flexible** while other technologies can **store electricity** and thus address grid instability and increase the system reliability [1].

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, across relevant market timeframes" [4]. Presently, flexibility is primarily represented by the capability to (1) cope with the variability and uncertainty that solar and wind energy introduce at different time scales, from milliseconds to seasons, (2) avoid the curtailment of power from these VRE sources, which jeopardizes their economic viability, and (3) reliably supply all customers' electricity demand.

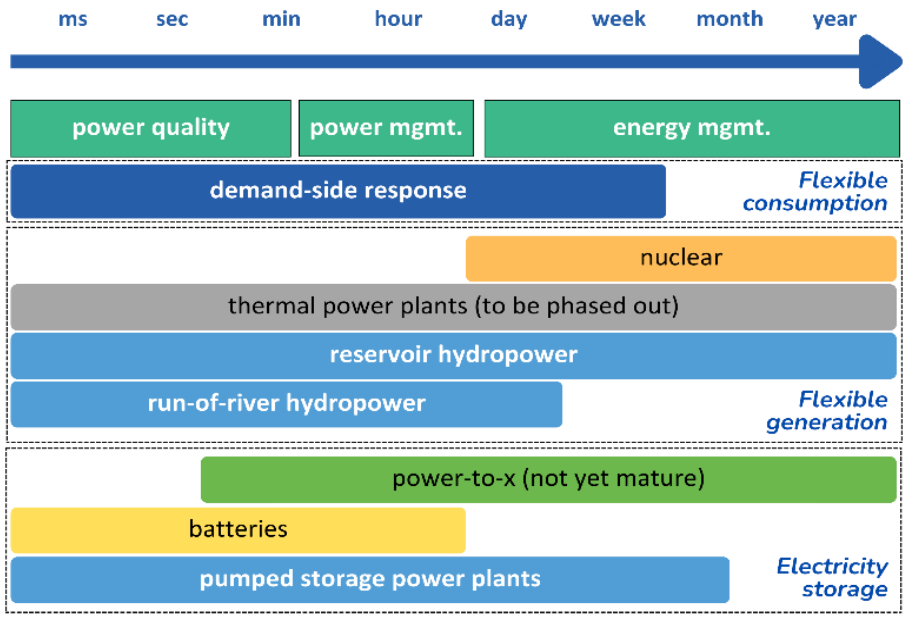

Figure 1. Flexibility sources and technologies [9]

Flexibility requirements stemming from grid fluctuations can be **short-, medium- and long-term** flexibility. **Short-term** (milliseconds up hours) balances the system within the day and ensures system stability. **Medium-term** (hours to days) balances the electricity supply over daily

variations. **Long-term** (up to months) compensates for long events such as shortages of wind and solar generation as well as seasonal changes [5]. Flexibility also has a geographic dimension that should be considered; namely **local flexibility** at the distribution level and **regional flexibility** at the system level. To deal with flexibility requirements, various services can be provided. In the current energy system, these services are mainly provided by hydropower and gas, supported by baseload generators coal and nuclear. However, being heavily reliant on gas and coal poses threats to Europe's security, in addition to generating CO_2.

Annex box: Flexibility and Storage Services in Markets [6]*

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-energized 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.
CURTAILMENT AVOIDANCE	min - hrs	Curtailment support utilizes storage capacity in the short term to reduce curtailment of wind and solar, ensuring the valuable power generated by these VRE is not wasted.

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

A growing share of VRE in Europe's electricity system will require higher flexibility to ensure a functioning system. Compared to today, daily flexibility requirements in EU countries will more than double by 2030 and grow 7 times by 2050 to more than 900 TWh/yr. When considering all time scales, the demand is expected to grow in excess of 2000 TWh/yr by 2050 [1]. This number is even larger when considering other key partners in the European grid, such as the Balkans, the UK, Switzerland, and Norway, which alone has roughly 10000 MW interconnectors to the EU [7].

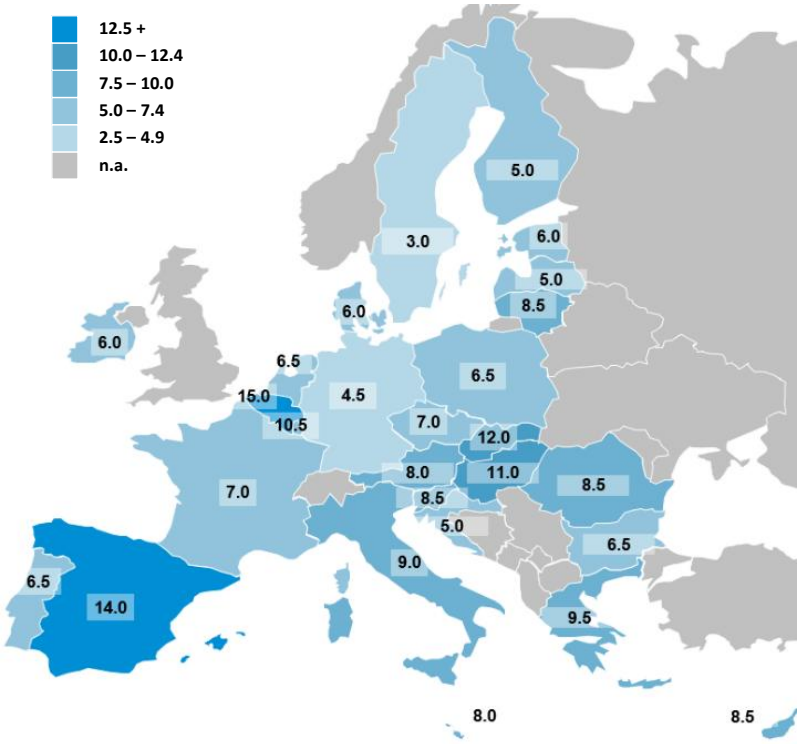

Figure 2. Growth factor of daily flexibility requirements in the EU [1]

Consider here the "**Dunkelflaute**" situation, periods when there is little to no electricity generation from wind or solar. If there are not enough flexibility providers

and stored electricity, the system can lack the needed electricity to meet consumer demands, become unstable and lead to a **blackout**.

With such a growth in flexibility demand, **interconnection capacity** across Europe is also essential for the secure operation of the electricity system. Expanding interconnection between regions enhances grid flexibility and enables the sharing of storage capacity and renewable energy across wider areas.

Hydropower is a unique technology because, in its various forms, it can address these two key grid services, **flexibility** and **storage**, in a **cost-effective, renewable and sustainable** manner [7].

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

Hydropower stands out among electricity technologies due to its exceptional ability to provide grid flexibility, particularly through operational flexibility and large-scale storage capacities, which are essential for ensuring a stable and reliable electricity supply. All this while being one of the least expensive, by levelized cost of energy (LCOE), and highly reliable power generation technologies, helping to reduce price fluctuations in the electricity market [8].

Annex box: Flexibility and Storage Services in Markets Provided by Hydropower [6]

		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
CURTAILMENT AVOIDANCE	min - hrs	x	x	x

x: hydropower provides this …… c: hydropower can provide this …… o: hydropower is innovating to provide this

One of the key strengths of hydropower is its ability to provide operational flexibility, which allows it to respond to fluctuations in electricity demand almost instantaneously. Unlike conventional thermal and nuclear power plants that require significant startup times, hydropower facilities can achieve **fast starting and ramp-up/down** within seconds, with **highly adaptable machines**, making them ideal for maintaining grid stability during sudden changes, as demonstrated by 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 grid demand. Some hydropower plants can also perform **load shifting**, helping balance supply and demand by storing water and generating electricity when needed. Furthermore, even where hydropower is not currently providing large-scale support, notably FFR, the industry is actively innovating in order to meet future market demands.

Another valuable feature of hydropower is the possibility of **Black Start capability**, which enables it to restore power to the grid in the event of a complete blackout without relying on external power sources. Furthermore, due to their nature, hydropower plants located on or close to borders can not only support **local and regional flexibility** but also **support interconnection capacity**, keeping power flowing smoothly between countries.

Example 1: Kops II – Austria – illwerke vkw

Since 2008 Kops II has been providing peak load and balancing electricity 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 storage pump, a hydraulic clutch, a motor generator and a six-nozzled Pelton turbine each. To be able to ensure load shifting in a range between 0% and 100% in turbine and pump mode, the principle of the "hydraulic short circuit" is used (for further details see the XFLEX HYDRO project [6]).

Hydropower also offers by far the largest **storage capacity** among all electricity technologies, with the ability to provide storage across seasonal timescales. This makes it a crucial resource for managing both short- and long-duration electricity needs, particularly when VRE sources are unavailable or producing excess power that would otherwise be curtailed. Unlike batteries, which are typically used for short-term balancing, hydropower's scale, longevity (50-100 years and longer), and use of existing infrastructure enables it to store vast amounts of electricity over extended periods, ensuring reliability and reducing the risk of electricity shortages.

Example 2: Serre-Ponçon – France – EDF

The Serre-Ponçon reservoir dam on the Durance River stores 1 billion m^3 of water, powering a 380 MW plant and 15 downstream stations generating 3.8 TWh annually. Beyond electricity, it secures 200 Mm^3 for seasonal irrigation, supplies drinking and industrial cooling water, and ensures flood protection. It also drives tourism, generating 400 million euros annually.

What hydropower needs

While the importance of hydropower in Europe has been demonstrated, ensuring it continues to play this vital role requires targeted enablement in several areas. Hydropower is a mature technology, but it must be allowed, encouraged, and financed to evolve in line with emerging challenges, such as increased flexibility demands, stricter policy requirements, changing societal expectations and 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 investment innovation to develop more flexible and sustainable solutions while addressing new operational challenges and modern sustainability standards. For example, shifts in system requirements have altered hydropower's operating patterns, leading to increased wear and tear on equipment and drastically reduced equipment lifetimes. R&D&I efforts must focus not only on enhancing hydropower's efficiency and flexibility but also on quantifying and mitigating such impacts. The Hydropower Europe **Research and Innovation Agenda (RIA)** provides a comprehensive roadmap for such efforts.

Another significant barrier is the **complex permitting (and re-permitting) process**. Inefficient and inconsistent application of permitting regulations slows down modernization and innovation efforts, making it difficult for hydropower to adapt to new demands and the rapid uptake of VRE. Ensuring clarity and consistency in interpretation of regulations at European, national and regional levels is vital to hydropower's success, through supporting project development and contributing to improving public acceptance of hydropower projects.

Remuneration for flexibility services is another critical area requiring improvement [10]. Hydropower has long provided essential services such as frequency control and voltage regulation, some of which, in principle, have been remunerated for decades. However, many flexibility services at time scales ranging from milliseconds to seasons still remain uncompensated in most countries, despite their growing importance. Furthermore, delivering flexibility services to meet the growing demand increases operational costs and accelerates machine wear, reducing the operational lifespan of critical equipment, which is not sufficiently covered by current market structures [10]. This is clearly visible in periods when the major supply from wind and solar pushes electricity prices to low values or even negative. Adaptation of remuneration schemes is necessary to reflect these additional costs and to ensure hydropower operators have fair access to capacity mechanisms, alongside other technologies, in countries that have implemented this support mechanism. Another challenge specific to the remuneration of hydropower is the return on investment for modernization and refurbishment of existing hydropower plants. These can be capital-intensive projects, which might not be realized on a purely merchant market basis. Above all, the market design should allow for competition-based remuneration, providing fair compensation for flexibility services while supporting investment in modernization and refurbishment.

Finally, **regulatory framework stability and fair market conditions** are essential for the long-term sustainability of hydropower. Large-scale strategic investments face significant funding difficulties if their business model is based solely on volatile market revenues, particularly given the highly uncertain future of power system transformation. Fluctuating price forecasts and evolving market structures make long payback periods increasingly risky, further complicating investment decisions. The shift in distribution and medium-voltage transportation networks, which are increasingly becoming collectors of VRE, further underscores the need for a market framework that properly values distributed hydropower flexibility. Additionally, the new Electricity Market Design as stipulated within Regulation (EU) 2024/1747 does not fully consider hydropower and its unique offers, as hydropower is not included as a technology that benefits from direct support schemes and must go through an additional Flexibility Needs Assessment. Future amendments should adequately recognize hydropower's unique contributions—particularly its high dynamics, such as fast start-stop and rapid ramping capabilities—as crucial for securing its role in future energy systems. Revising these provisions to ensure a level playing field, also considering hydropower's multipurpose benefits, would allow hydropower to contribute fully to grid flexibility while securing fundability and the stability investors need.

Conclusions

Europe is at a crossroads in its energy transition. As VRE sources like wind and solar rapidly grow, the need for reliable flexibility and storage solutions needs to keep up. Meeting these demands requires a balanced technology mix, one that considers a hybrid model of hydropower together with other low-carbon sources, to ensure stability, sustainability, and security of supply.

Hydropower is a key piece in this puzzle, being uniquely positioned to provide both the flexibility and long-term storage essential for a resilient grid. However, unlocking its full potential requires decisive action: accelerating R&D&I, improving permitting processes, ensuring fair remuneration for flexibility services, and creating stable regulatory frameworks and fair market conditions that support investment.

By recognizing hydropower's strategic role and addressing key barriers, Europe can strengthen its energy system while advancing climate goals. With the right policies and market frameworks, hydropower will continue to be a cornerstone of the clean energy transition, delivering reliability, sustainability, and long-term value for future generations.

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