White Paper

Hydropower & Climate Change

Strategic Role of Hydropower in Adapting to and Mitigating Climate Change Impacts

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

Climate change is reshaping Europe's hydropower landscape, presenting a unique opportunity to strengthen its role in the clean energy transition. Altered hydrological regimes, increased frequency of extreme weather events, and shifts in seasonal precipitation patterns pose risks to existing and future hydropower operations. However, hydropower is uniquely positioned to play a strategic role in Europe's clean energy transition, contributing not only to renewable electricity generation but also to energy storage, grid stability, and multi-purpose water management.

As a mature and reliable renewable source, hydropower provides flexible, dispatchable electricity, enabling the integration of variable renewables such as wind and solar. Its capacity for long-duration energy storage—particularly through pumped storage plants—supports system balancing and strengthens energy security. These system services are expected to become even more valuable under climate change scenarios, regardless of potential reductions in total generation.

The sector's resilience will depend on sustained investment in modernisation, adaptation of infrastructure, and optimisation of water management strategies. Reservoirs and multipurpose hydropower systems will be central in mitigating floods and droughts, ensuring water availability for energy production as well as environmental, agricultural, and urban needs. In regions like central and northern Europe, projected increases in winter precipitation may partially offset reductions elsewhere, underlining the need for site-specific and flexible management approaches.

Fully leveraging hydropower's contribution requires coordinated policy frameworks, ongoing research, and digital innovations. Modernisation of existing facilities combined with hybrid integration (hydro, wind, solar, or batteries) can enhance operational flexibility, mitigate climate impacts, and sustain hydropower's strategic role in Europe's pursuit of a carbon-neutral and water-secure future.

Hydropower should be recognised not merely as a sector facing climate risks, but as a critical enabler of Europe's energy resilience, adaptation capacity, and long-term sustainability.

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Hydropower and Climate Change: Current Status and Emerging Challenges

The European Union's installed hydropower capacity currently stands at approximately 152 GW, contributing around 12% of the EU's net electricity generation [1]. As a mature renewable energy source, hydropower plays a strategic role in Europe's clean energy transition—supporting the integration of variable renewables and reducing greenhouse gas emissions from the energy sector, which accounts for nearly 25% of the EU's total Greenhouse Gas (GHG) emissions [2].

Climate change is a defining global challenge, impacting both energy security and water management, but it is also a catalyst for innovation and transformation in the hydropower sector. Changing hydrological patterns, water scarcity, and extreme weather events threaten water resources availability and the operational sustainability of hydropower plants (HPPs) depending on their water storage capability (see Table 1 below showing different types of HPP and their role in terms of climate change). In this context, prioritising the water-energy-food-ecosystem nexus (WEFE Nexus), which describes the interdependence between energy and water systems, is essential to ensuring that hydropower contributes to climate change adaptation, strengthens water resilience, and helps reduce carbon emissions.

Type of HPP	Role in terms of climate change (i.e. adaptation and mitigation)
Reservoir hydropower	… they primarily provide flexible, dispatchable renewable electricity generation by regulating river discharge through water storage and release. This capability allows them to balance seasonal flow variations and meet peak electricity demands. Additionally, they offer critical water management services, including flood mitigation, drought management, and supporting other water uses.
Run-of-River (RoR) hydropower	… they enable continuous, electricity generation depending on river discharge. Due to their limited capacity to store water, they are directly dependent on real-time river flow, making them vulnerable to seasonal and climatic variations. However, large RoR can keep the water level high even at low river discharges due to their water level regulation capacities and can therefore support water uses such as navigation, irrigation, and water supply even during droughts.
Pumped storage hydropower (PSH)	… they have a crucial role in minimising freshwater withdrawal (i.e. when not permanently connected to a river body) while providing flexibility and long-duration electricity storage, hence support decarbonising peak hours, power system stability, and integrating Variable Renewable Energies (VREs) and reducing curtailment.

Table 1 - Reminder of the main types of HPPs and their respective objectives

Key impacts of climate change on hydropower

Climate change exerts a range of pressures on hydropower generation, leading to significant impacts worth highlighting:

- **Changing and increasingly variable flow regimes:** Climate change is reshaping hydrological patterns across Europe, with significant implications for hydropower operations. Southern Europe is likely to face reduced winter precipitation and intensified water scarcity, while Western, Central, and Eastern Europe may see earlier snowmelt and increased winter runoff due to more rainfall. Northern Europe could benefit from rising precipitation levels, enhancing hydropower potential. At the same time, more frequent and rapid flow variations—driven by both climatic shifts and operational demands—are leading to increased cycling of hydropower units (e.g. more starts and stops), accelerating equipment wear. These trends emphasise the need for region-specific adaptation strategies and investment in flexible, durable technologies and operational practices.

- **Increased flood risk:** More intense rainfall and extreme weather events pose challenges to infrastructure and operational budgets. Yet, large hydropower reservoirs can play a vital role in flood mitigation, thanks to their capacity to store excess water and regulate flow, offering a valuable service to surrounding communities.

- **Glacier retreat:** The retreat of Alpine glaciers is altering seasonal water availability and increasing the risk of Glacial Lake Outburst Floods. While this presents challenges, it also opens opportunities for innovation in water resource management. For example, new artificial reservoirs could be considered to replace the current water stores held in glaciers, where opportunities exist to construct dams for this purpose. This is evidenced by recent assessments of glacial storage replacement in the Alpine context [3], and recent real projects are ongoing in Switzerland [4].

- **Rising temperatures and water demand:** Higher temperatures are increasing demand for water in industry and residential cooling as well as irrigation and for ecosystems needs, which may reduce availability for hydropower. However, this also highlights the importance of integrated water-energy planning and the potential for hydropower to support resilient, multi-use water systems.

- **Droughts:** As water demand grows across sectors during dry periods, hydropower may face increased competition for resources. This underscores the need for collaborative water governance and adaptive management strategies to ensure sustainable energy and water supply.

- **More severe and more frequent heat waves** can accelerate the aging of civil structures and equipment, raising operational costs. Proactive maintenance and modernisation efforts can help extend asset lifespans and improve resilience.

- **More frequent debris flow and higher sediment yield** can damage infrastructure and reduce reservoir capacity. These risks particularly affect aging assets, but they also present a strong case for modernisation. Upgrading existing facilities can enhance resilience, reduce downtime, and support long-term cost-efficiency. Adaptation strategies are already being implemented in many regions, showcasing the sector's capacity to respond proactively to climate challenges.

Hydropower's strategic role in addressing climate change

Adaptation challenges and opportunities

Hydropower is inherently dependent on the availability of water resources, which are increasingly affected by climate change. While this poses challenges, it also presents opportunities: although every HPP is site-specific in terms of type, size, and location, there is the possibility to adapt their operating patterns to accommodate changes in flow regimes. Such adaptations may influence annual hydropower generation compared to historical levels, to meet a new balance among all water uses—including environmental needs.

Balancing water use, cost-effectiveness and climate resilience in decision-making processes requires advanced tools and expertise, which adds complexity to the management of hydropower systems. Effective adaptation of hydropower depends to a large extend on knowledge of future climate conditions, which in turn depend on future emissions and socio-economic scenarios, as well as the availability of high-quality, spatially and temporally resolved hydro-meteorological data. Such data may not be available in all regions or at the appropriate scale, leading to uncertainty and data dependency issues.

When necessary for hydropower systems to adapt to climate change (particularly in case of increased flood risk), structural adaptations, though requiring investment and planning, offer long-term benefits in resilience, safety, and operational efficiency.

Engaging stakeholders and communities is essential for building support for adaptation investments that enhance safety and sustainability, especially as dam opponents often lobby for their decommissioning rather than their adaptation. It is important to highlight that hydropower reservoirs already help ensure water flow during droughts and reduce flood risks, particularly when operated using real-time flow forecast and supported by preventive measures.

The *How-to Guide on Hydropower Climate Change Resilience* developed by the Hydropower Sustainability Alliance is widely recognised as the foundational resource on the topic of adaptation and resilience and provides detailed guidance for stakeholders [5].

Mitigation

Hydropower also plays a crucial role in reducing GHG emissions by 1) providing low-carbon renewable electricity generation and storage, 2) supporting the integration of other variable renewables and 3) supporting power system stability. As wind and solar energy face integration challenges due to their variability and intermittency, hydropower is uniquely positioned to provide the flexibility needed across all timeframes—from milliseconds to months—to ensure system stability and reliability. This includes electricity storage, frequency regulation, and rapid response capabilities.

Hydropower technologies deliver essential power system services, such as synchronous inertia, voltage/VAR (Volt-Ampere Reactive), and high fault current, which are critical for integrating inherently VREs like wind and solar. Thanks to its flexible generation and large-scale storage capacity, hydropower can absorb surplus electricity from VREs during periods of high generation, and then can release it as dispatchable power when demand is high or VRE output is low. This not only reduces curtailment of renewables but also enhances overall system resilience and reliability – all of which are essential for reducing greenhouse gas emissions and accelerating climate change mitigation. This capability is particularly evident in PSH, which can mitigate VREs' fluctuations through reservoir management and reversible pump-turbine operations. PSH also supports fast frequency response (FFR) and automatic frequency restoration reserve (aFRR), making it indispensable for balancing the grid and ensuring climate-resilient energy infrastructure [6]. Large PSH plants offer high installed capacity and long-duration electricity storage, making them ideal for energy shifting and ensuring infrastructure robustness under increasing climate stress. Smaller hydropower systems, including reservoir and RoR plants, can provide similar services to battery energy storage systems, while supporting EU strategic autonomy, as they rely on domestically sourced equipment and materials. The long service life of hydropower assets, often exceeding 100 years, allows for the amortisation of investments related to adaptation over an extended period. As most of the emissions are produced during construction, this long lifespan also results in low carbon emission factors, making hydropower a highly relevant option for rehabilitation and re-concessioning. The existing data, frameworks, and regulations governing reservoir hydropower, PSH, and RoR plants, such as the EU taxonomy [7], acknowledge hydropower's potential role in climate change mitigation while imposing strict environmental criteria to ensure sustainability.

The *How-to Guide on Hydropower Climate Change Mitigation* developed by the Hydropower Sustainability Alliance is widely recognised as the foundational resource on the topic of mitigation and provides detailed guidance for stakeholders [8].

WEFE Nexus to support climate change adaptation

Climate change will affect water availability for both human activities and ecosystems, energy needs and the resilience of infrastructure. Hydropower plants are already supporting multipurpose water use and intersectoral collaboration, contributing to electricity generation, irrigation, navigation, water supply, flood and drought management. They also support ecosystem services by providing seasonal water regulation, which can contribute to preserve existing ecosystems, in particular during floods and droughts, and to improve ecosystems—or potentially develop new ones—in case of river restoration (i.e. supports new aquatic and riparian ecosystems). [9]

Advanced modelling in regulated basins continue to offer strong short-term predictability for operational planning. This reliability in water resources is a key advantage for electricity generation planning, contributing to greater water and electricity supply security. Hence, reservoirs will play a critical role in adapting to climate change impacts by efficiently balancing water resources across various sectors.

Innovations and opportunities for adaptation, mitigation and the WEFE Nexus

Modernisation and resilience of hydropower

Hydropower presents significant opportunities to enhance resilience, efficiency, and sustainability in the face of climate change. Upgrading existing small hydropower plants[1] (up to 10 MW as typically defined in EU taxonomy or national regulations) can improve their ability to withstand extreme weather events and fluctuating water availability.

> Refurbishing existing hydropower plants is key to offset projected climate-related losses in generation. For instance, in Italy, long-term studies predict up to a 22% reduction in hydropower potential by 2070, primarily due to declining summer runoff in the Alps. However, these losses are expected to be largely mitigated by additional generation achieved through modernisation and efficiency upgrades of current installations [10].

Modernisation and upgrading efforts should target hydropower plants of all sizes. While small-scale plants often face structural and operational limitations that can be addressed through targeted upgrades, large-scale hydropower plants—despite their generally robust infrastructure—can also benefit from efficiency improvements, digitalisation, and adaptive management strategies to enhance climate resilience and operational flexibility.

Modernisation efforts, including the integration of hybrid hydro-wind-solar systems (potentially combined with batteries), seawater pumped storage, and coupling with desalination technologies [11], can significantly enhance both energy and water security. Expanding water and electricity storage capacities helps buffer surplus generation and better align supply with demand. In densely populated areas facing increasing freshwater scarcity due to climate change, hybrid systems that combine energy generation with freshwater production offer a strategic solution to address both energy and water challenges simultaneously.

Modernisation strategies[2] should also address safety considerations, especially for aging hydropower infrastructure exposed to climate-induced stress factors such as increased flood volumes, sedimentation, and structural fatigue. Ensuring the structural integrity and operational safety of both small and large hydropower plants under evolving climate conditions is paramount[3].

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[1] This action is also covered by the EU Social Fund: European Commission. (2025). Guidance on the Social Climate Plans (C (2025) 881 final). Brussels. Retrieved from https://climate.ec.europa.eu/document/download/9fbce2e3-5052-4d61-874a-54af0c7dbf55_en?filename=c_2025_881_par [climate.ec.europa.eu]

[2] Modernisation strategy refers to a systematic plan that includes technological, social, environmental, and climate resilience aspects to improve hydroelectric assets.

[3] Safety standards for dam and hydropower infrastructure are typically governed by national regulations and international guidelines (e.g., ICOLD standards), which should be integrated into modernisation planning.

New opportunities regarding adaptation

Revisiting traditional methods such as dam height adjustments in the context of climate adaptation opens new avenues for enhancing water storage and resilience and coping with intensifying seasonal variability. Traditional dam raising techniques, strategically reframed in the context of climate resilience, are regaining importance.

In high-mountain regions, accelerated glacial melt is increasing river flows, which can be exploited by hydropower. While retreating glaciers are certainly detrimental to the environment, they will temporarily increase river flow and create new opportunities for dam sites and reservoir sites, potentially increasing the climate resilience of downstream river systems and water users. Some of these new opportunities include building new reservoirs in glacier forelands (e.g. plans to build a new reservoir hydropower beneath the retreating Trift Glacier in Switzerland [12]).

New opportunities regarding mitigation

Hydropower also contributes to the resilience of power systems by offering flexibility, grid services and black start capacity.

Hybrid renewable energy systems combining variable renewables with PSH offer enhanced grid flexibility and reliability. Studies show these systems can mitigate VRE intermittency and support decarbonisation. Financial viability of PSH depends on market signals, prompting a shift toward integrated energy hubs [13]. The "Superhybrid" model exemplifies this approach, merging PSH, renewables, and grid optimisation to improve system stability and investment appeal [14].

Closed-loop PSH plants, with their proven reliability and site-specific adaptability, are gaining renewed attention as key enablers of low-impact energy storage. Applications of PSHs like hydraulic short-circuit offer effective solutions by minimising freshwater withdrawal while delivering grid services. Besides, by integrating VRE sources with PSHs, generation from individual renewable sources can evolve into comprehensive energy hub management, optimising the 24/7 supply of continuous clean electricity and significantly increasing revenue.

Hydropower can also drive decarbonisation in other water-related sectors, such as inland waterway transport and carbon capture through land use and wetland restoration [15, 16].

Innovations in project planning and carbon footprint assessment are also gaining traction. Whether for new hydropower assets or the rehabilitation of existing ones, the use of life cycle assessment (LCA) methods and Building Information Modelling (BIM) can strengthen early-stage decision-making and improve sustainability outcomes. A streamlined LCA, tailored to hydropower assets in general and PSH in particular, would benefit from further research and innovation (R&I) to ensure practical applicability and consistency across projects [17, 18]. Reservoirs are also sources of net GHG emissions compared to pre-impoundment situation. However, these emissions are in most European situations a very low contributor to the global carbon footprint of Hydropower, considering the European climatic and land-use conditions. Recent developments in remote sensing offer new opportunities to better assess these emissions.

Cooperation through water-energy co-optimization

Regional cooperation, such as cross-border data sharing and joint management of transboundary rivers, can optimise hydropower benefits, mitigate risks, and promote balanced water resource management to reduce competition.

Digital innovations—in the fields of real-time monitoring and flow forecasting—will continue supporting water-energy nexus and improving the efficiency and environmental sustainability of hydropower operations, particularly for RoR plants.

Finally, eco-friendly innovations can enhance ecosystem services and support biodiversity conservation. They should be considered as part of all the previously proposed innovations. This topic is further explored by the ETIP HYDROPOWER's working group on Hydropower and Biodiversity. [19, 20]

Hydropower as an essential driver of Europe's clean energy transition

Hydropower plays a fundamental role in supporting Europe's transition to a sustainable, secure, and carbon-neutral energy system. As a mature renewable energy source, it provides more than electricity generation—it offers critical flexibility, dispatchability, and large-scale energy storage capabilities essential for balancing increasingly variable renewable sources such as wind and solar.

In the face of climate change, hydropower stands at a strategic crossroads. It is not only a source of clean energy but also a vital water management tool, offering unmatched multi-sectoral benefits. Its ability to mitigate floods and droughts, support ecosystem services, and ensure water availability across sectors underscores its unique value. To fully realise this potential, Europe must invest in modernisation, climate adaptation, and hybrid integration with other renewables.

While changing hydrological regimes, extreme weather events, and rising water demand present challenges, they also unlock opportunities for innovation, collaboration, and strategic investment. Hydropower's long service life, proven reliability, and capacity for innovation position it as a cornerstone of Europe's energy resilience. Modernising existing infrastructure and expanding pumped storage capacity will enhance hydropower's operational flexibility and climate resilience. Additionally, its ability to integrate variable renewable energy sources further strengthens Europe's grid reliability and supports the broader clean energy transition.

Coordinated policy support, regional cooperation, and continued research and innovation are essential to unlock hydropower's full contribution to the energy transition. Recognising hydropower as a strategic enabler—not merely a legacy technology—is imperative. Hydropower operators are fully aware of the investment needs; however, a clear and stable regulatory framework is crucial to unlock these investments. By addressing this, Europe can harness hydropower's full potential to deliver clean energy, system stability, and climate resilience for generations to come.

Key Takeaways

- **Modernisation and climate-resilient infrastructure upgrades:** Modernisation of hydropower infrastructure—regardless of scale—is essential to enhance climate resilience, operational flexibility, and long-term reliability. Investments should prioritise both structural safety (flood risk management, sediment handling) and operational optimisation (digitalisation, flow forecasting). Selective increases in reservoir capacities, where technically and environmentally justified, can further improve adaptive capacity.

- **Hydropower as a strategic provider of flexibility and storage:** Hydropower plays a pivotal role in supporting the integration of VRE sources. Its inherent flexibility, dispatchability, and long-duration energy storage capacity—especially through pumped storage hydropower—are critical to future energy systems. These system services will gain even greater importance as climate variability increases.

- **Digitalisation and adaptive water management:** Real-time monitoring, advanced hydrological forecasting, and digital operation tools must be integrated into hydropower management to address climate-induced variability in water availability. Digitalisation enhances both energy generation optimisation and multipurpose water use coordination.

- **Multipurpose water storage and cross-sectoral coordination:** Reservoir hydropower assets provide essential multipurpose services beyond electricity generation, including irrigation, flood control, and drought mitigation. Strategic operation of reservoirs under climate change must balance energy production with water management objectives, fostering cooperation between the energy and water sectors.

- **Cross-border collaboration and data sharing:** Given transboundary river basins and shared hydrological resources, cross-border data sharing and collaborative water management frameworks are critical to maximizing hydropower benefits and mitigating climate-related risks across regions.

- **Stable regulatory frameworks to enable investment:** While ETIP HYDROPOWER does not advocate for specific policy instruments, it underscores the need for clear, stable, and coherent regulatory frameworks to support investment in hydropower modernisation and adaptation measures.

- **Adopting a systems approach to hydropower modernisation and climate resilience**: A holistic, systems-based perspective is essential to ensure that infrastructure upgrades, flexibility services, digitalisation, multipurpose water use, ecosystems services, cross-border coordination, and regulatory frameworks are addressed in an integrated manner. This approach recognises the interdependencies between technical, environmental, and governance dimensions of hydropower, enabling coherent planning, investment prioritisation, and adaptive management across sectors and scales.

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