Hydropower modernization: Policy, technology and global implications for net zero transitions

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The global energy transition depends on rapidly integrating variable renewables such as solar and wind. These sources already account for record shares of generation in multiple regions, but their variability creates challenges of balancing and reliability. Hydropower is uniquely positioned to provide the flexibility, storage and stability required.

Pumped storage represents more than 90 per cent of global storage capacity, demonstrating the sector's systemic importance. Many hydro plants are ageing, with nearly 600 GW of global capacity exceeding 30 years of operation, and 400 GW older than 40 years. Ageing infrastructure undermines efficiency and increases risks of failure, just as demand for system services accelerates. Modernization is not simply maintenance, but a strategic necessity.

Modernization in China

China remains the global leader in hydropower expansion. In 2024, it commissioned 14.4 GW of new capacity, accounting for more than half of global additions. Pumped-storage has emerged as a cornerstone of the country's grid strategy. With 58.7 GW installed, and about 200 GW under construction, China is on track to exceed its 2030 target of 120 GW and reach about 130 GW.

However, expansion alone is insufficient. Much of China's conventional hydro base dates back to the mid-20th century and requires systematic refurbishment. Modernization programmes that upgrade turbines, generators, and control systems extend asset life, raise efficiency, and allow plants to provide more flexible services. Digitalization, including predictive maintenance and variable-speed turbine technology, improves performance and reduces operational stress from frequent cycling. Moreover, climate resilience is enhanced through dam safety retrofits and sediment management.

European experience

Europe's hydropower sector is largely mature, with limited scope for new development. Hydropower provides around 30 per cent of Europe's flexibility needs across all time scales and will remain indispensable as demand rises. By 2030, daily flexibility requirements are projected to have reached 288 TWh, with weekly and monthly needs increasing by 166 per cent and 300 per cent, respectively.

Modernization in Europe emphasizes technological innovations. Variable-speed turbines expand operating ranges, SCADA and unmanned operation systems improve efficiency, and predictive maintenance using machine learning mitigates fatigue from frequent cycling. Environmental performance is being increasingly integrated, with fish-friendly turbines, ecological flow regimes, and biodiversity monitoring through environmental DNA (eDNA).

Despite these advances, finance and policy remain barriers. Hydropower receives less than 1 per cent of EU renewable energy funding. Current investment frameworks undervalue hydropower's system services, creating weak incentives for refurbishment.

South America: Lessons from Colombia

South America is one of the most hydro-dependent regions, with more than half of its installed capacity more than 30 years old. Colombia exemplifies both the opportunities and challenges of modernization. Hydropower generates nearly 70 per cent of Colombia's electricity, making it central to energy security, but also exposing the system to climate risks such as droughts and low flows.

Recent refurbishment projects demonstrate strong returns. At the Chivor plant, generator rewinding raised breakdown voltage from 38.4 kV to 95.6 kV, improving reliability significantly. Modernization extended the plant's lifespan by 45 to 50 years, and avoided projected outage losses of US$ 14 to 28 million. At the Tunjita small hydro plant, digital control systems have been introduced, optimizing turbine efficiency and enabling more flexible operation. These measures increased reliability and aligned with Sustainable Development Goals 7 and 9, that target clean energy and resilient infrastructure.

Colombia's experience illustrates the benefits of combining technical upgrades with digitalization. However, it also reveals barriers common across South America: weak regulatory frameworks, the absence of tailored financing instruments, and under-valuation of system services.

Green infrastructure

Green infrastructure plays a transformative role in advancing net zero ambitions when combined with hydropower modernization. It represents a fundamental rethinking of how ageing hydro installed bases are maintained, upgraded, and integrated into energy systems that are increasingly dominated by variable electricity generation by renewables.

Benefits of modernization extend beyond system balancing. Technical refurbishments, such as turbine replacements, generator rewinding, and the deployment of digital control systems, have been shown to extend the operating life of hydro plants by decades while simultaneously increasing efficiency.

Equally important are the ecological and social dimensions. Europe's experience illustrates how modernization can be combined with environmental retrofits, such as fish-friendly turbines, biodiversity monitoring using environmental DNA, and ecological flow regimes that mimic natural river conditions. These measures ensure that hydropower retains public legitimacy while reducing its ecological footprint. The convergence of technological innovation and environmental safeguards turns hydropower from a contested source into a model of sustainable infrastructure.

Modernization is generally cheaper and faster than building new capacity, making it one of the most cost-effective pathways for sustaining low-carbon generation. However, financing and regulation remain chronic bottlenecks. Innovative financing tools, such as concessional loans from development banks, sustainability-linked bonds, and green credit lines tied to refurbishment, could close this gap. Regulatory frameworks that tie concession renewals to modernization and sustainability performance could create binding incentives to accelerate upgrades.

Green infrastructure enables hydro modernization to deliver systemic benefits across technical, ecological, and economic dimensions. It reinforces hydropower's capacity to provide stability and storage, raises efficiency and extends asset life, integrates environmental safeguards that protect ecosystems, and establishes financing and regulatory conditions that make refurbishment viable at scale. These outcomes converge on the central goal of net zero transitions: reliable, flexible, affordable, and sustainable electricity systems capable of integrating massive shares of wind and solar while maintaining resilience. In this sense, green infrastructure is integral to ensuring that hydro continues to anchor the decarbonized power systems of the future.

Policy implications

The global evidence points to several urgent policy directions.

First, markets must value hydropower's system services. Current energy-only remuneration models do not account for the flexibility, inertia, and seasonal storage that hydropower provides. Without explicit compensation, operators face weak incentives to invest in refurbishment. Policy reforms should expand ancillary service markets and remunerate system stability functions directly.

Second, financing must be scaled and diversified. Hydropower refurbishment requires substantial upfront capital. More than US$ 10 billion is needed for medium-priority modernization in Asia alone.

Third, regulatory frameworks should link modernization to licensing. In both China and South America, many plants operate under long-term concessions without refurbishment obligations. Tying concession renewals to modernization and sustainability performance would create enforceable incentives for refurbishment.

Fourth, environmental safeguards must remain integral. Europe's example offers transferable practices that can mitigate impacts and secure public acceptance.

Finally, international cooperation can accelerate progress. China's experience with scale and pumped-storage, Europe's leadership in digitalization and ecological retrofits, and Colombia's evidence of strong returns from refurbishment all provide valuable lessons.

These policy reforms highlight that hydro modernization is not a peripheral technical activity but a central component of global net zero strategies.

Policy pathways

Evidence shows that technological solutions are already proven and available. The main obstacles are institutional, financial, and regulatory. Therefore, the design of effective policy frameworks will determine whether hydropower modernization can scale quickly enough to sustain its role in the energy transition.

The first pathway concerns the valuation of system services. Current energy markets generally remunerate electricity generation without recognising the broader suite of services that hydropower provides, including inertia, and seasonal storage. This undervaluation weakens incentives for operators to invest in refurbishment, even though modernization yields measurable efficiency and reliability gains.

The second pathway is financing. Modernization requires substantial upfront capital. Evidence indicates that the resources mobilized remain insufficient. Policy responses could include the use of concessional finance from development banks, the creation of sustainability-linked loans that reward efficiency and ecological retrofits, and the issuance of green bonds tied specifically to refurbishment projects.

A third pathway lies in regulation and licensing. Many hydropower concessions, particularly in China and South America, allow long-term operation without requiring refurbishment or sustainability upgrades. This creates a structural disincentive to modernize, as operators can legally continue running ageing and less efficient assets. Tying concession renewals to demonstrated modernization efforts and ecological safeguards would change this dynamic by embedding refurbishment obligations into legal and regulatory frameworks.

Finally, there is the dimension of international cooperation. Different regions are advancing along distinct trajectories: China demonstrates the scale of investment in pumped-storage, Europe shows how digitalization and ecological retrofits can be mainstreamed, and Colombia provides evidence of strong technical and economic returns from refurbishment.

Policy frameworks that encourage systematic knowledge exchange can accelerate the dissemination of the lessons learnt.

Looking to the future

The future of hydropower modernization will be defined by the convergence of three global trends: the rise of variable renewables, the ageing of the global installed base, and the evolution of policy frameworks.

By 2030, solar and wind will dominate new capacity additions worldwide, driving unprecedented demand for balancing and storage. Hydropower will remain the only renewable capable of providing inertia, seasonal storage, and black-start capability at scale.

China is set to shape the trajectory of global hydropower. Modernization of its vast conventional installed base will determine whether its hydropower sector remains efficient, reliable, and climate-resilient through mid-century. If China successfully aligns modernization with its net zero 2060 target, it could provide a model for other hydro-dependent economies.

Europe's future role lies in demonstrating how modernization can be made environmentally and socially sustainable. Digitalization, predictive maintenance, fish-friendly turbines, and biodiversity monitoring using environmental DNA are likely to become global standards.

For South America, the future depends on whether financing and regulation evolve to match the urgency of modernization.

Looking ahead, the central challenge is no longer technical feasibility. The tools (turbine upgrades, digitalization and ecological retrofits) are well established. The question is whether policy frameworks and financial systems will evolve quickly enough to modernize nearly 600 GW of ageing capacity before it becomes a liability.

If this challenge is met, hydropower will not only retain, but expand its role as the backbone of renewable electricity systems through 2050 and beyond. If neglected, ageing installed bases risk undermining global decarbonization just as the pace of the energy transition accelerates.