2024

August

Ebb and Flow: The Future of Hydropower

Energy Research Paper

The Al-Attiyah Foundation

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For over a century, hydropower has driven global development by generating affordable and reliable electricity. It accounts for 14% of global power generation and is the largest contributor to renewable energy (in 2023, wind generated 7.8% of global electricity and solar 5.5%). Hydropower generation supports the integration of non-dispatchable renewables like solar and wind by offering balancing and flexibility services. What are the key challenges faced by hydropower as a mature dispatchable renewable technology? What are the benefits of upgrading existing hydropower infrastructure compared to developing new facilities? How can ongoing technological innovation and material research improve hydropower generation? How will future capacity factors depend on a power system's hydropower and grid flexibility strategy

ENERGY RESEARCH PAPER

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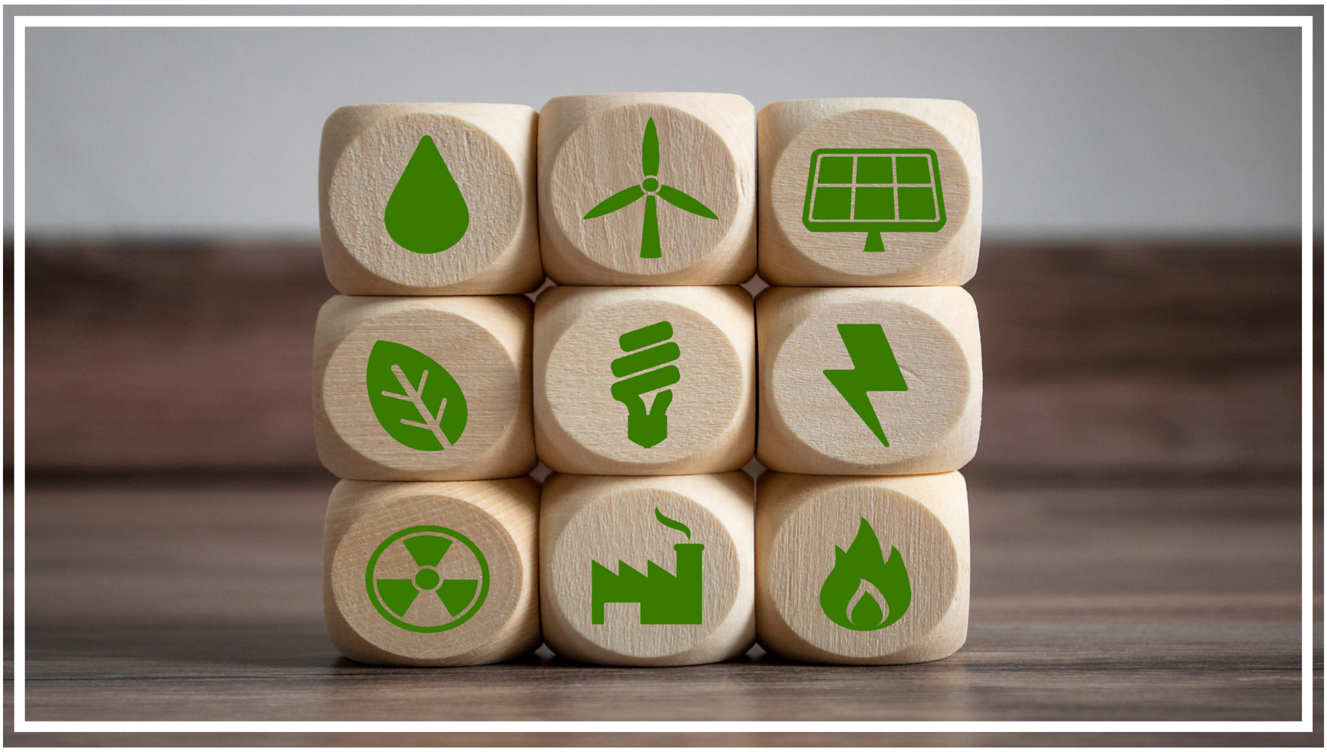


Introduction

- Hydropower, while the most mature renewable technology and having the advantage of being dispatchable, faces significant challenges, including inadequate management of environmental impacts, insufficient hydrological data, unexpected geological conditions, lack of comprehensive river basin planning, climate and hydrological cycle change, and limited financing.
- Many governments and international organisations distinctly define "small" (< 30 MW) and "large" (or utility-scale) hydropower capacities, to determine their eligibility for specific programmes. Some utility-scale (> 30 MW) projects are sources of regional environmental and/or geopolitical concerns (e.g. the Grand Ethiopian Renaissance Dam, the Pakul Dul Hydropower Project in India, and the Xe-Pian Xe-Namnoy Dam in Laos).

Hydropower Generation and Storage

- Hydropower is the only low-carbon dispatchable power source that offers system flexibility from sub-seconds to hours and can store power cost-effectively for days to months. As non-dispatchable renewable generation increases and thermal generation retires, the flexibility and storage of reservoir projects and pumped-storage hydropower, and the non-correlated output of run-of-river capacities, will be crucial for integrating solar and wind capacities.
- Captive hydropower could mitigate demand-supply imbalances and generate grid-independent decentralised power for energy-intensive industries such as steel, aluminium, cement, and deregulated power markets.

Existing Hydropower Projects

- Upgrading and modernising hydropower projects is the most cost-effective mode of enhancing hydropower generation efficiency. Replacing or repairing components such as turbine runners, generator windings, and excitation systems could improve operational efficiency, peak power generation, and availability.
- Global modernisation projects are projected to cost US$ 127 billion by 2030, with 43% needed to maintain the existing fleet's performance. By 2030, 20% of the global hydropower fleet will be ~50 years old, requiring major electromechanical equipment replacements.

Emerging Hydropower Technologies

- Ongoing technological innovations and material research will continue to lessen hydropower's environmental impact and lower operational costs. Development in new technologies such as variable-speed generation, efficient tunnelling, hydrokinetics, silt erosion-resistant materials, and aquaculture-friendly turbines will enhance future sustainable hydropower generation.

Cost of Hydropower Generation

- The levelised cost of electricity for hydropower generation largely depends on civil works such as dam and infrastructure construction, which accounts for ~45% of total costs, whilst electromechanical equipment procurement makes up ~33%[i]. In 2022, global installed costs increased by 25% y-o-y, averaging US$ 2,881 / kW, primarily due to challenging site conditions and supply chain inflation[ii].
- Pumped-storage hydropower is the most economical utility-scale electricity storage solution compared to other storage technologies such as batteries, compressed air, hydrogen, and flywheel energy storage. Whilst batteries are suitable for storing small quantities of energy for shorter durations, pumped-storage hydropower is much more cost-effective for storing and releasing larger amounts.

Future of Hydropower Generation

- In the long-term, hydropower capacity factors will depend on the power system's hydropower and grid flexibility strategy. With increasing renewable capacities, hydropower projects can provide balancing and flexibility services, leading to capacity factors that are below average.
- Hydropower generation will continue to be constrained by climate-related events and hydrological conditions, particularly water runoff patterns, which makes it sensitive to extreme climatic and hydrological events, with both heavy precipitation and droughts affecting operations.

For over a century, hydropower has driven global development by generating affordable and reliable electricity. It accounts for 14% of global power generation and is the largest contributor to renewable energy (in 2023, wind generated 7.8% of global electricity and solar 5.5%[iii]). Hydropower generation supports the integration of non-dispatchable renewables like solar and wind by offering balancing and flexibility services. Additionally, it provides essential services such as storage for drinking and irrigation water and enhances resilience to flooding and droughts.

Hydropower, whilst being the most mature dispatchable renewable technology, faces significant challenges, which include inadequate management of environmental impacts, insufficient hydrological data, unexpected geological conditions, climate and hydrological cycle change, lack of comprehensive river basin planning, and limited financing.

In order to address these challenges, public policies must create an appropriate environment for investment, a stable regulatory framework, and incentives for research and technological development. Beyond country-specific policies, several larger policy issues have been identified as crucial for hydropower development, such as carbon markets, financing, administration and licensing procedures, and size-based classification schemes.

Carbon credits can significantly benefit hydropower projects by providing additional funding and reducing project risks. Whilst the UNFCC – Clean Development Mechanism (CDM) is not exclusive to hydropower, these projects are among the largest contributors to both the CDM and Joint Implementation – Kyoto Protocol mechanisms, consequently playing a vital role in existing carbon credit markets.

This is largely because new hydropower capacities are mainly deployed in developing countries that require investment capital, and international carbon markets offer a viable source of that capital. Presently, hydropower projects account for 24% of the projects in the active CDM Pipeline, out of 9,658 projects. These registered hydropower projects are projected to abate ~292 MT CO_2-eq / year of emissions[iv].

Hydropower projects can supply power at relatively low costs compared to existing market energy prices (see Future Hydropower Systems and Costs). However, many economically viable hydropower projects face high upfront costs. In addition, the long lead times for planning, permitting, and construction increase development risks whilst delaying commissioning.

Higher interest rates, a global feature since 2022, are negative for the economics of hydropower, and developing countries typically face much higher interest rates than established markets. A key challenge in emerging markets is to build sufficient private sector confidence in hydropower investments, particularly before project permitting.

In developing regions like Africa, hydropower power interconnections between countries, as well as the creation of larger energy markets, could enhance investor confidence by reducing the risk of a monopsony buyer.

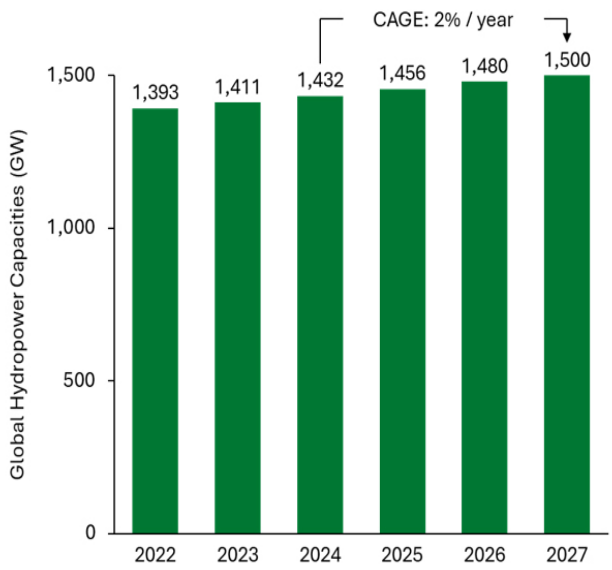
Angola (which is a non-operating member of the Southern African Power Pool) intends to connect its power grid with Namibia through the 600 MW Baynes Dam project, with each country sharing 300 MW, supported by Power Africa[v]. Angola is also considering a northern connection with the Democratic Republic of the Congo via the Grand Inga Dam, a proposed 40-70 GW facility to be built on the Congo River[vi].

Still, developing appropriate financing structures that address the uncertainties of long planning and regulatory processes and defining the optimal roles for the public and private sectors remain key challenges for hydropower development.

Hydropower is often viewed as a public resource, since reservoirs can operate for > 100 years. However, legal frameworks vary significantly across countries, affecting the award and structuring of concessions, including concession periods, royalties, and water rights.

As the private sector becomes more involved in areas previously managed by the public sector, the contractual arrangements surrounding hydropower have grown increasingly complex, involving more parties and greater regulatory accountability. Consequently, the policies and procedures established by regulators for granting licenses and concessions will significantly influence the development of hydropower projects.

Figure 1: Projected Global Hydropower Capacities[vii]



Many governments and international organisations distinctly define "small" (< 30 MW) and "large" (or utility-scale) hydropower capacities, to determine their eligibility for specific programmes. Some utility-scale (> 30 MW) projects are sources of regional concerns (e.g. the Grand Ethiopian Renaissance Dam1, the Pakul Dul Hydropower Project in India2, and the Xe-Pian Xe-Namnoy Dam in Laos3).

The environmental impact of a hydropower project cannot be solely inferred from its size. Although increasing physical size may amplify the overall impacts of a particular project, still capacity-based classifications (despite their limitations) have significant implications for policy and financing.

For example, in China, small hydropower projects are typically classified as projects with capacities < 50 MW[viii]. The government promotes such developments as part of its renewable energy strategy, offering financial incentives and support for projects within this capacity range. Projects > 50 MW are classified as large hydropower and face different regulatory requirements and support mechanisms[ix].

In the United States, small hydropower projects are generally defined as those with a capacity of < 20 MW[x]. However, many states, such as California, classify projects < 30 MW as small[xi]. The National Hydropower Association specifies a minimum limit of 5 MW for small hydro projects, while the Federal Energy Regulatory Commission also uses the 20 MW threshold to distinguish between small and large generators. This classification influences eligibility for renewable portfolio standards and various financial incentives.

1- The Grand Ethiopian Renaissance Dam is a major point of contention between Ethiopia and Egypt. Ethiopia sees the dam as crucial for its development and energy needs, whilst Egypt fears it will significantly reduce the Nile River's flow, vital for its water supply. Political tensions have escalated, with Egypt seeking international mediation to secure its water rights, while Ethiopia insists on its right to utilise its natural resources.

2- Located on the Marusudar River, which flows into Pakistan – the US$ 1.18 billion project has raised geopolitical tensions. India's increased investment in the facility is viewed as a strategy to enhance energy security whilst limiting Pakistan's ability to develop similar projects on its side of the border. The cross-border nature of this project underscores the political implications of hydropower development in South Asia.

3- The collapse of the Xe-Pian Xe-Namnoy Dam in 2018 resulted in at 40 deaths and the displacement of over ~6,600 people, raising serious political concerns regarding the management and oversight of hydropower projects. The Laotian government attributed the disaster to poor planning and faced public outcry for accountability, leading to a temporary suspension of all hydropower projects in the country.

Hydropower is the only low-carbon dispatchable power source that offers system flexibility from sub-seconds to hours and can store power cost-effectively for days to months. As non-dispatchable renewable generation increases and thermal generation retires, the flexibility and storage of reservoir projects and pumped-storage hydropower, and the non-correlated output of run-of-river capacities, will be crucial for integrating solar and wind capacities.

System integration challenges mainly depend on the portion of non-dispatchable renewable generation in the power mix, the type / amount of flexible renewable resources in the power system, and the correlation in time (over minutes, days or seasons) of the various renewable inputs.

Power systems can already handle the variability of solar and wind generation across different timescales, manage demand volatility, and recover from unexpected outages.

However, as the share of renewables increases, residual loads will become more volatile, gaps between peak and minimum net demand will widen, and ramp-up and ramp-down requirements to adjust to peak and off-peak demand will become steeper.

For example, solar and wind generation is expected to account for 25% of India's power mix by 2030, significantly transforming its power system and creating much higher ramping needs[xii]. Maximum hourly ramps could increase from 16 GW (7% of daily peak net load) to 68 GW (19% of daily peak net load), and maximum 3-hour ramps could rise from 40 GW (18% of daily peak net load) to 342 GW (40% of daily peak net load)[xiii]. Achieving these load changes will require conventional power projects to ramp generation up and down more quickly and intensively than before, and to start up and shut down more often. This puts more mechanical strain on systems, and requires them to run at lower efficiencies, increasing costs and emissions.

Moreover, as renewable capacity increases, the power system's technical, market, regulatory, and institutional frameworks must be updated to ensure sufficient flexibility to maintain consistent security of supply. Power system flexibility is required across various timescales, with different hardware and operational solutions offering timescale-specific flexibility, ranging from sub-seconds for system stability issues to months or years for seasonal and inter-annual demand—supply variability.

Hydropower is a key contributor to flexible generation and storage, but its flexibility varies based on turbine type, project design, and installation type (e.g. reservoir, run-of-river, or pumped storage).

Figure 2: Energy Capabilities and System Support Provided by Selected Hydropower Generation Systems

Energy Capabilities	Hydropower Systems		
	Reservoir	Pumped Storage	Run-of-River
Inertial Response	High	High	High
Voltage Support	High	High	High
System Strength	High	High	High
Black Start	High	Moderate	Moderate
Fast Start	High	High	High
Ramping	High	High	Moderate
Scheduling Adequacy	High	Moderate	Moderate
Intra-day Flexibility	High	High	Moderate
Inter-day Flexibility	High	High	Low
Demand-side Response	Low	High	Low
Baseload Power Generation	High	Moderate	Moderate
Daily Water Storage	High	High	Moderate
Seasonal Water Storage	High	Moderate	Low

Run-of-river projects are among the least flexible hydropower technologies. Their turbine output depends on seasonal river flows, and they have little or no storage capacity. They are also usually small, although they can be important for local grids. There are some larger examples, for instance the 600 MW Karuma plant in Uganda, which started operations in June 2024[xiv]. However, these projects provide relatively stable generation that varies only with seasonal water flow changes.

As synchronous generators, run-of-river projects offer essential system services like frequency response; however, their ability to provide intraday balancing, ramping, and reserve capabilities is limited.

In contrast to run-of-river, reservoir hydropower installations consist of one or more turbines connected to one or several reservoirs. They allow power generation through the synchronous inertia of rotating turbines, frequency control from sub-seconds to minutes, and system balancing capabilities. The long-term storage capabilities of these projects depend on the reservoir size and their installed capacity.

Reservoir installations offer inter-day and seasonal balancing by increasing generation during peak demand or lower renewable generation. They can also provide other important system services such as black-start, ramping, and regulation capabilities.

Pumped-storage hydropower technologies store energy by using the power grid to pump water from lower to higher altitude reservoirs during low-demand periods. When demand is high, the water is used for power generation.

A pumped-storage project's techno-economic viability is mainly determined by the site's topology, which determines its configuration, reservoir size, and achievable reservoir-level variation, versus the spread of power prices or the capacity payments it can achieve.

Pumped-storage hydropower has traditionally compensated for inflexible thermal and nuclear generation by pumping water at night and on weekends to generate power during peak periods. However, their cycling frequency increases as renewable generation increases, with multiple pumping / generating switches during the day.

Like reservoir installations, pumped-storage hydropower projects provide critical services such as power system inertia, frequency response, and grid regulation to reinforce system stability. Depending on their design, they can also have black-start capability.

Newer solutions like battery storage, demand-side response, increased sectoral coupling, power-to-X pathways, and interconnected and innovative power grids can also complement hydropower generation in expanding renewable capacity deployment.

However, many of these are still in early-to-growth development stages and are relatively costly. Whilst many technologies compete to provide short-term flexibility from seconds to hours, only a few can meet longer-term needs. Besides hydropower, only fuels like hydrogen or hydrogen-based fuels produced with power-to-X technologies (e.g. electrolysers) can provide seasonal storage, and this comes at a higher cost and lower efficiency.

Captive hydropower could mitigate demand-supply imbalances and generate grid-independent decentralised power for energy-intensive industries such as steel, aluminium, cement, and deregulated power markets.

In emerging markets such as India, captive hydropower offers a solution to unreliable power supplies and high industrial tariffs by promoting decentralised generation and private participation[xv]. In remote locations with excellent hydropower resources but without a large local electricity market, such as Siberia and Iceland, hydropower can be used to power aluminium smelters, since aluminium is cheaper to export over long distances than electricity.

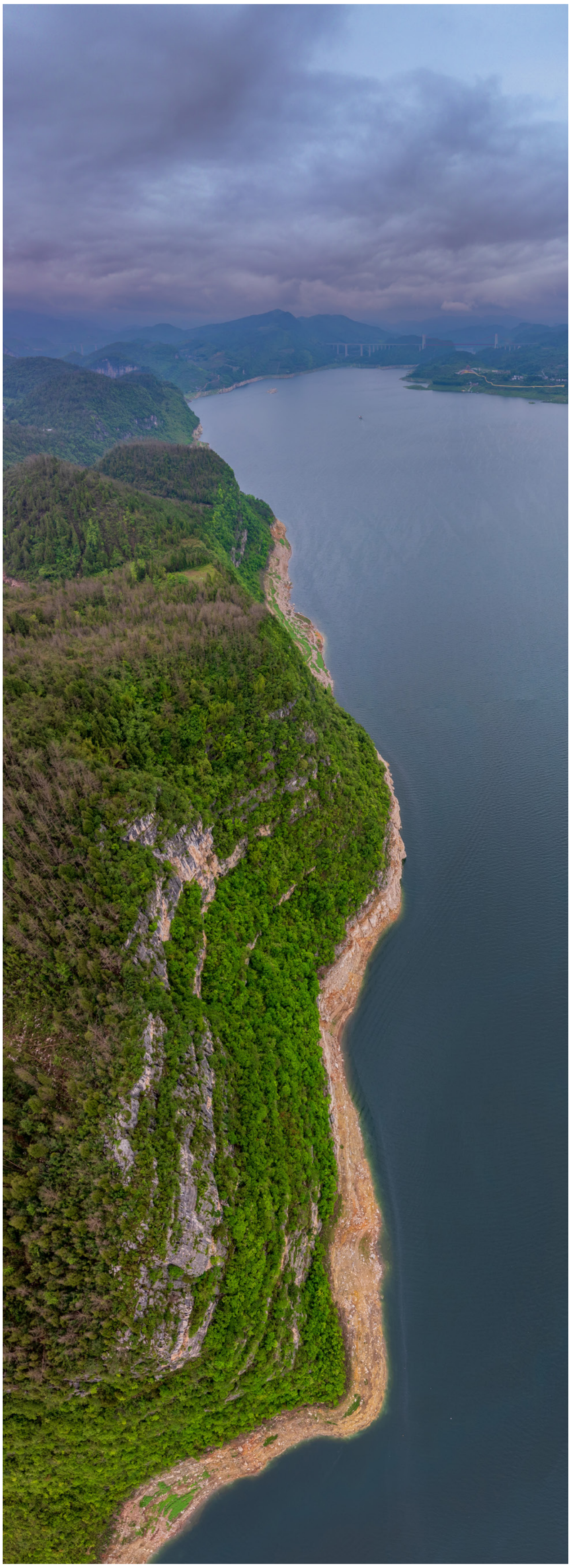
Figure 3: Flexibility of Thermal and Hydropower Projects

	Hydropower	OCGT	CCGT	Coal
Start – up Time (Cold Start for Thermal)	< 5 – 20 minutes	5 – 10 minutes	120 – 140 minutes	200 – 600 minutes
Minimum Load	35% - 45%	40% - 50%	40% - 50%	25% - 40%
Average Ramp Rate	80% - 100%	8% - 12%	2% - 4%	1% - 4%

China's small-scale hydropower-based rural electrification has been a remarkable success. With a total small hydropower capacity of 60 GW generating 170 TWh / year, many of these projects are integrated into centralised regional power grids. Small hydropower constitutes one-third of China's total hydropower capacity[xvi].

Small hydropower can be deployed across isolated grids, off-grid settings, and central-grid configurations. However, with 75% of costs being site-specific, effective site selection is crucial. In isolated grid systems, seasonal flow variations may require combining hydropower with other generation sources to ensure continuous supply during dry periods and manage excess production during wet seasons.

Small hydropower projects often, but not always, use run-of-river schemes, which can utilise existing infrastructure like dams or irrigation channels, and are located close to villages to minimise expensive high-voltage distribution equipment. They can also employ pumps such as turbines and motors as generators, whilst having a high level of local content in terms of materials and workforce during construction and civil works. Small hydropower has also proven to be a viable solution for remote communities, replacing diesel generation.



Upgrading and modernising hydropower projects is the most cost-effective mode of enhancing hydropower generation efficiency. Replacing or repairing components such as turbine runners, generator windings, and excitation systems could improve operational efficiency, peak power generation, and availability.

Several regional and national programmes support modernisation and upgrade efforts. For example, the Africa Hydropower Modernisation Programme, introduced by the African Development Bank in 2021, aims to rehabilitate and modernise low-performing and non-operational hydropower infrastructure across Africa[xviii].

The XFLEX HYDRO Research and Innovation Project, introduced by the European Union through the Horizon 2020 programme, focuses on upgrading and enhancing existing hydropower operation flexibility and their contribution to grid stability across the European Union[xix].

The 2020 Hydropower Modernisation Needs Programme, undertaken by the Asian Infrastructure Investment Bank, assesses and ranks the low-to-high modernisation needs of hydropower projects across the Asia-Pacific region. It focuses on identifying investment requirements and prioritising projects that can enhance the performance of existing facilities[xx].

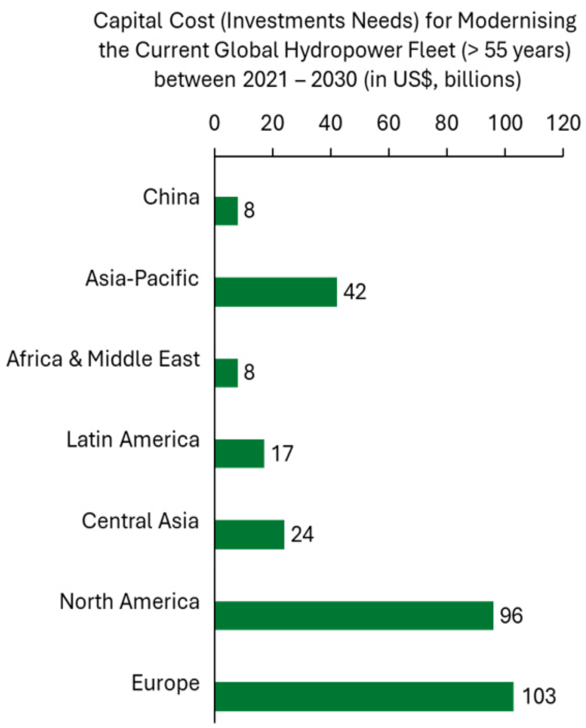
Hydropower projects typically last 50 – 100 years, with their electromechanical components requiring upgrades or replacement after 25 years. Civil structures such as dams and tunnels often last longer before needing renovation[xxi]. With proper maintenance, hydropower projects can exceed 100 years of operation.

Upgrading hydropower projects requires a systematic approach since hydraulic, mechanical, electrical, and economic factors significantly influence the techno-economic profile of a hydropower asset. Their techno-economic profile could also be enhanced by increasing the size of the turbine capacity, rehabilitation, modernisation, and life extension initiatives. New and improved performance components could also be retrofitted to meet peak demand through flexible generation.

The structural components of a hydropower project account for ~70% of the capital cost for utility-scale projects, which can last for > 100 years[xxii]. Technological advancements often justify replacing key components or even entire generating sets. Typically, operators can upgrade or replace generating equipment with more advanced electromechanical systems twice or thrice during the project's lifespan, allowing for more effective use of the same water flow.

Global hydropower modernisation projects are projected to cost US$ 127 billion by 2030, with 43% needed to maintain the existing fleet's performance[xxiii]. By 2030, 20% of the global hydropower fleet will be ~50 years old, requiring major electromechanical equipment replacements[xxiv].

Figure 4: Capital Cost (Investments Needs) for Modernising the Current Global Hydropower Fleet (> 55 years) between 2021 – 2030



~US$ 300 billion will be needed to replace turbines reaching the end of their lifespan, which is essential for maintaining plant availability and restoring performance[xxv]. Costs could be higher if additional investments are made to upgrade civil works, other electromechanical equipment (e.g. gates, penstocks, valves, etc.), and auxiliary machinery.

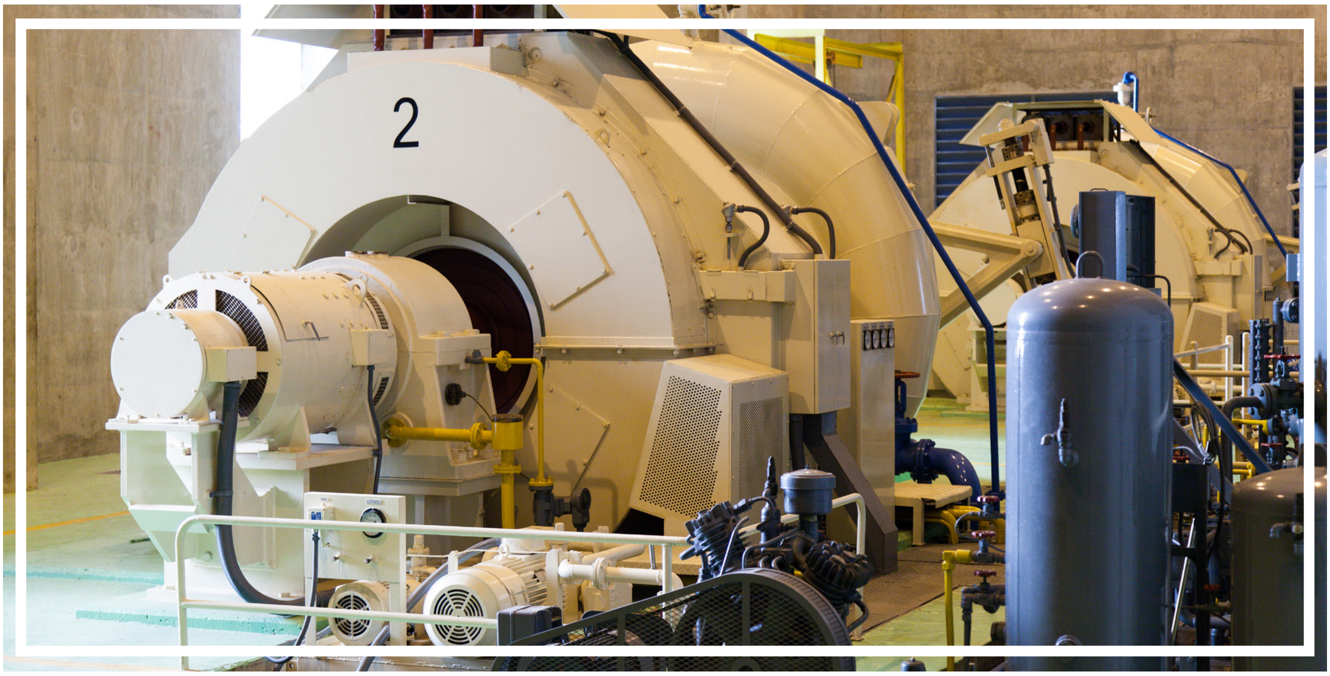
Further modernisation investments may involve automating controls, introducing remote monitoring, and predictive maintenance.

Refurbishment needs are also being driven by increased operational flexibility, changing hydrological patterns, and new safety regulations.

Two-thirds of the US$ 127 billion modernisation cost will be needed for ageing projects in Europe (with an average age of 50 years) and North America (with an average age of 58 years)[xxvi].

Declining wholesale prices in some markets and uncertainty over concessional renewal procedures reduce the long-term visibility needed to incentivise high capital costs. Other challenges include obtaining permits under new environmental, water, and dam safety regulations introduced after commissioning dates.

In emerging markets, investment needs may be even more significant due to poor operations and maintenance practices, which can cause projects to require replacement parts in < 50 years.



Technological innovations and material research will continue to lessen hydropower's environmental impact and lower operational costs. Development in new technologies such as variable-speed generation, efficient tunnelling, hydrokinetics, silt erosion-resistant materials, and aquaculture-friendly turbines will enhance future sustainable hydropower generation.

Hydropower turbines are typically optimised for a specific operating point (i.e. speed, head, and discharge). However, fixed-speed turbines lead to decreased efficiency when head or discharge levels deviate from nominal values. Variable-speed turbines offer significant advantages such as increased flexibility of turbine operation when flow or head substantially deviates from nominal conditions[xxvii]. In addition to improved efficiency, variable-speed generation also reduces abrasion from silt in the water[xxviii]. Simulation studies have found that variable-speed projects can substantially increase power generation compared to fixed-speed projects[xxix].

Hydropower developers could also install several small, identical power turbine and generator units through a matrix-shaped frame, adjusting the number of units to match the available flow. During operations, operators can start and stop any number of these units, allowing those in operation to run under optimal flow conditions consistently[xxx]. Matrix-shaped frame systems can be implemented at structures such as irrigation dams, low-head weirs, and ship locks, where water flow is released at low heads.

Norway-based Norhad AS uses oil-drilling technology to excavate small tunnels with diameters ranging from 0.7 to 1.3 metres for hydropower tunnelling systems[xxxi]. These systems allow directional drilling of penstocks for small hydropower systems directly from power projects to intakes up to 1 km or more away. By facilitating this method, costs can decrease whilst minimising the environmental and visual impacts associated with above-ground penstocks, thereby expanding the potential sites for small hydropower development[xxxii].

Hydropower project developers often conduct seismic hazard assessments during the planning and design phases, which include assessing dams / associated structures and their ability to withstand reservoir-induced seismicity, landslides, and earthquakes. The weight of water accumulated in the reservoir can trigger earthquakes in seismically active regions, for example the magnitude 6.1 tremor triggered by the Xinfengjiang dam in 1962.

Traditional technologies struggle to make projects viable when the head is under 1.5 – 2 metres. However, hydrokinetic turbines are emerging to harness these small water elevation changes by focusing on the stream flow's kinetic energy rather than the hydraulic head's potential energy. Hydrokinetic turbines capture energy from tides and currents and can also be deployed inland in free-flowing rivers and engineered waterways like canals, conduits, cooling water discharge pipes, or tailraces of existing dams.

Corrosion, cavitation, and abrasion pose a significant challenge to hydropower projects. However, stainless steel and aluminium materials have helped limit wear and extend asset lifespan. Ongoing improvements in materials have been made for almost every project component, including fibreglass penstocks, better corrosion protection through cold spray and friction stir processing for hydro-mechanical equipment, and plastic slide rails for waste rack systems.

Sediment-laden rivers, especially during floods, can create high abrasive erosion on guide vanes, runners, and other structural parts of hydropower projects, reducing turbine efficiency. Erosive wear largely depends on particle size, density, hardness, concentration, water velocity, and base material properties. Traditional solutions like de-silting chambers have struggled to trap all particles, especially fine sediments. Still, new solutions, such as coating steel surfaces with hard ceramics, are being developed to combat erosion.

Modern turbine design employs three-dimensional flow simulation to enhance energy conversion efficiency through improved shapes of turbine runners and guide / stay vanes. This reduces cavitation damage in high-head power projects and minimises abrasion effects caused by sediment-laden water[xxxix].

Aquaculture-friendly turbines are an emerging solution that ensures safe passage for fish, given their low-head hydraulic turbines, significantly reducing aquaculture fatality.

Moreover, higher temperatures / heatwaves increase evaporation levels in hydropower projects, reducing the amount of water available for power generation, which can be mitigated by solutions / technologies such as floating balls, shade structure, chemical covers, floating solar panels, and windbreakers.

Floating balls cover the water surface, reducing exposure to air and sunlight. Shade structures, such as shade cloths or other coverings over reservoirs, block sunlight and reduce water temperature. Chemical covers involve applying a thin layer of biodegradable chemical on the water surface, which creates a barrier to evaporation. Floating solar panels not only reduce evaporation by shading the water, but also generate electricity in hybrid-hydropower units. Windbreaks, such as planting trees or installing barriers around reservoirs, reduces wind speed over the water surface and so curb evaporation.

The levelised cost of electricity (LCOE) for hydropower generation mainly depends on civil works such as dam and infrastructure construction, which accounts for ~45% of total costs, whilst electromechanical equipment procurement makes up ~33%[xl]. In 2022, global installed costs increased by 25% y-o-y, averaging US$ 2,881 / kW, primarily due to challenging site conditions and supply chain inflation[xli].

Hydropower capital costs vary based on local hydrological conditions, terrain, geology, ecosystems, infrastructure, and the project's purpose and performance goals. Civil works (e.g., dam and infrastructure construction) are the main capital cost components in utility-scale hydropower projects. However, these projects benefit from economies of scale, resulting in lower costs per unit of installed capacity. In smaller run-of-river projects, electromechanical equipment is the largest capital cost component[xlii].

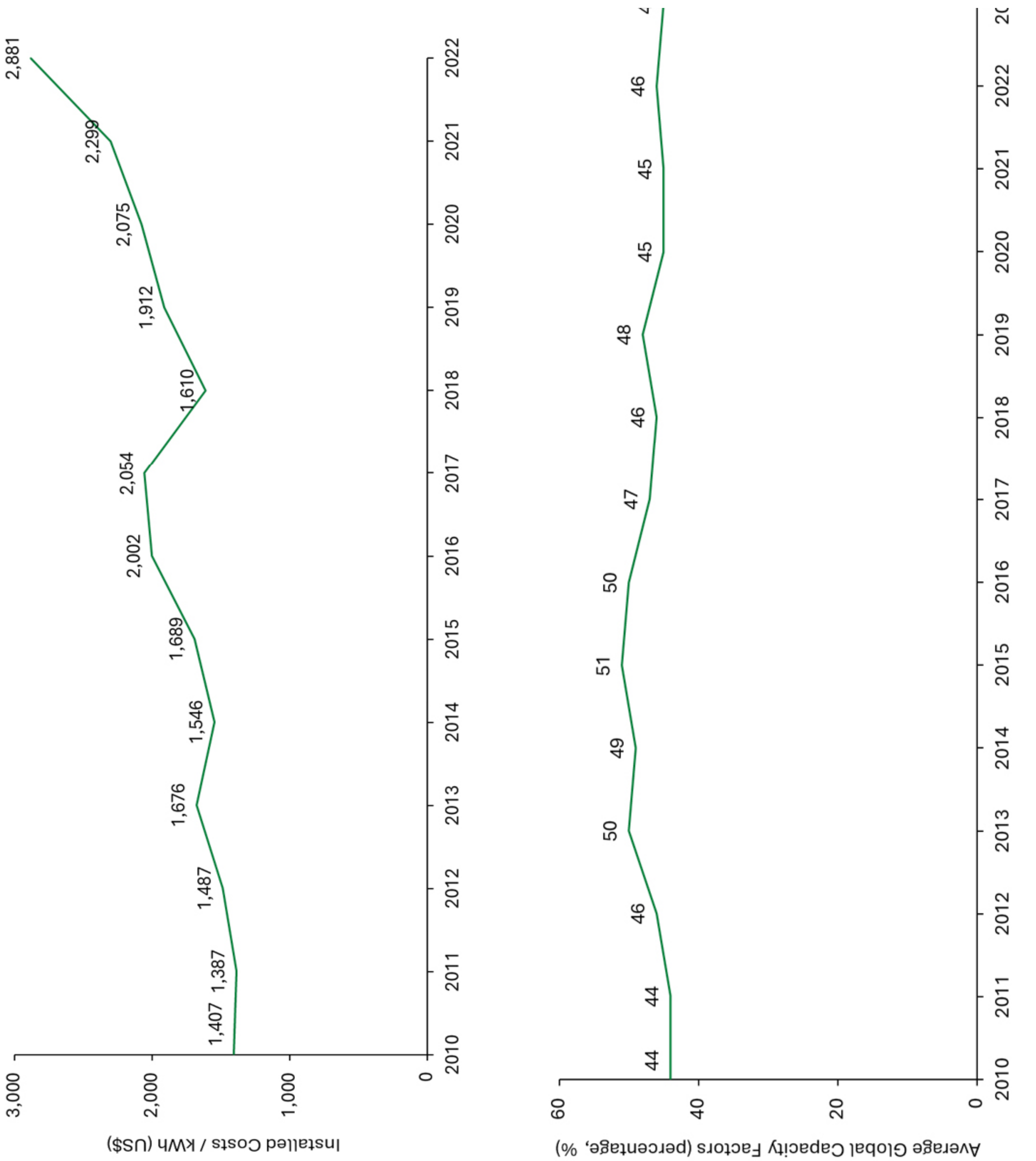
Hydropower capital costs also include the cost of utilising existing water management infrastructure (e.g. reservoirs, non-powered dams, and conduits), in contrast to brownfield projects, which involve expanding or upgrading operational capacity, typically costing ~70% less than new projects, since the primary cost component is replacing or adding electromechanical equipment).

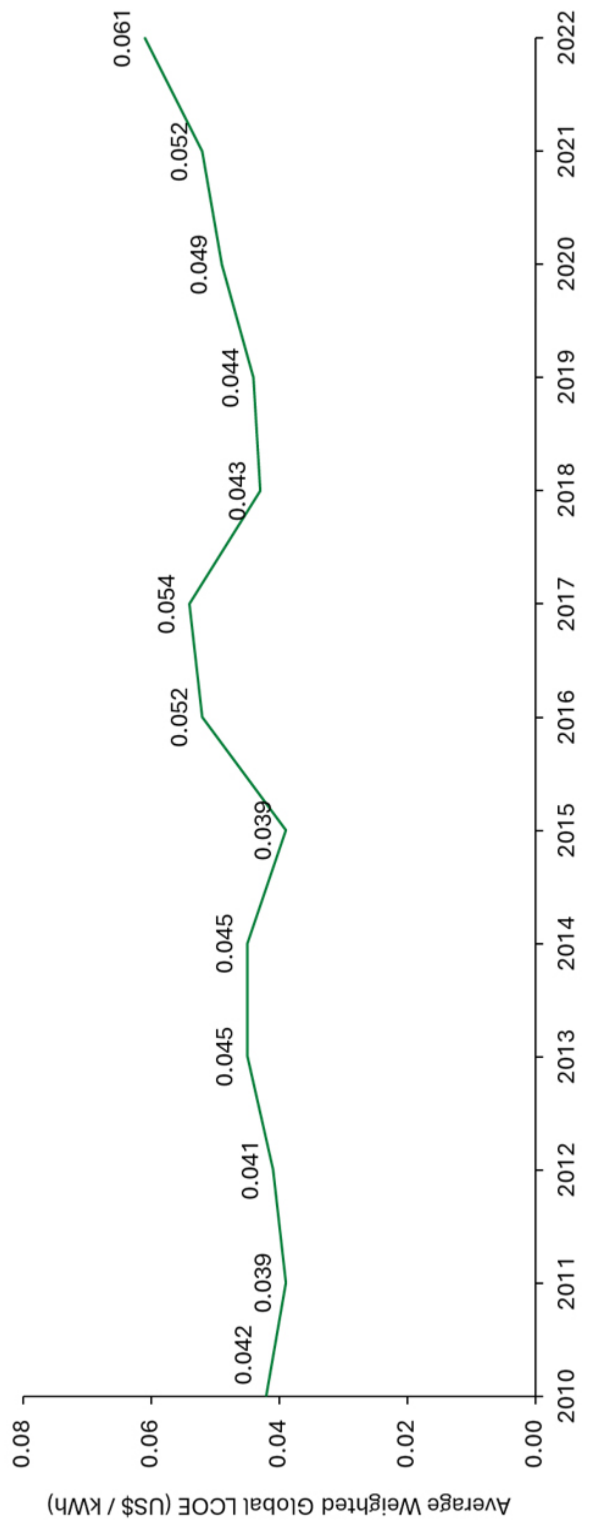
Capital costs for greenfield hydropower projects typically range between US$ 1,200 – US$ 4,500 / kW but can vary from US$ 1,000 / kW for very large utility-scale projects to US$ 10,000 / kW for small-scale projects[xliii]. Recently, hydropower investment requirements in the Asia-Pacific region, particularly China, have increased due to rising supply chain inflation and permitting costs.

Building access infrastructure and reinforcing transmission lines can significantly increase a hydropower project's capital costs, especially in remote areas[xliv]. Additionally, most countries require rigorous and lengthy permitting processes for hydropower projects, which often take several years. Large areas of land are flooded, and settlements, agricultural land and sites of cultural or historic interest may be inundated. Filling and emptying dams can lead to decomposing vegetation releasing methane, a powerful greenhouse gas, especially in tropical climates. The carbon footprint of the concrete and steel required for dam construction should also be considered in lifecycle greenhouse gas assessments, even though hydropower projects are still much lower-carbon than fossil-fuelled generation.

The carbon footprint is very site-specific, and may vary between 6-147 gCO_2equivalent per kWh, compared to about 950 gCO_2e/kWh for coal, 450 gCO_2e/kWh for natural gas combined cycle, 5-6 gCO_2e/kWh for nuclear, 8-23 gCO_2e/kWh for wind, and 8-80 gCO_2e/kWh for solar PV[xlv].

Figure 5: Global Weighted Average Installed Costs, Capacity Factors, and LCOE for Hydropower Generation[xlviii]





Conducting detailed environmental impact assessments and implementing compensatory measures also adds to the capital costs[xlvi]. The construction process, which can last 5 – 10 years, is often subject to delays, leading to extra maintenance, construction management, and capital engagement costs, similar to other large energy infrastructure projects[xlvii].

Capital costs typically account for 80% - 90% of the LCOE for hydropower generation. Similar to most other renewables, hydropower does not require an input fuel source. Operations and maintenance make up the remaining costs, averaging ~2% of the initial investment annually, though this can vary by country and project. Project development costs and required returns on investment (expressed as the weighted average cost of capital (WACC)) are critical factors in determining hydropower LCOEs[xlix].

For example, a percentage increase in WACC can raise hydropower generation costs by 7% - 14% for an average greenfield project, depending on the investor risk–return expectations and other factors such as macroeconomic and technology-specific conditions. For hydropower projects, risks related to institutional policy and regulatory structure, payment schemes, the financial health of off-takers, and the availability of future water flows can all influence WACC rates[l].

Project risks could be reduced through government policies such as state guarantees, long-term contracts, and measures, can lower project risks. Reducing financing costs through policy measures will be crucial for ensuring the competitiveness of hydropower LCOE, especially in developing countries where high macroeconomic risks lead to elevated financing costs.

Over the last decade, the global weighted average LCOE for utility-scale hydropower generation was US$ 0.048 / kWh. In 2022, it was US$ 0.061 / kWh, up 56% from US$ 0.039 / kWh recorded in 2011[li]. Despite rising costs, 96% of hydropower projects commissioned in 2022 had an LCOE within or lower than the newly commissioned fossil fuel capacity range[lii].

Pumped-storage hydropower is the most economical utility-scale electricity storage solution compared to other battery storage technologies, such as compressed air, hydrogen, and flywheel energy storage. Whilst batteries are suitable for storing small quantities of energy for shorter durations – pumped-storage hydropower is much more cost-effective for storing and releasing larger amounts.

Despite their low capacity factors, pumped-storage hydropower projects, in contrast to batteries, replace the use of expensive and emissions-intensive gas and oil turbines during peak demand periods and enable efficient nuclear and / or coal generation[liii].

Historically, pumped-storage hydropower projects pumped water at night and generated electricity during the day when prices were higher. However, the price differential between peak and off-peak hours has significantly narrowed in recent years, particularly in open / liberalised power markets, partly due to the growing share of solar and wind affecting pumped-storage hydropower operations.

As a mature technology, pumped-storage hydropower's levelised storage cost is expected to remain stable over the next decade, whereas battery costs are expected to decline, partly due to the increasing deployment of electric vehicles.

Future power systems will require both pumped-storage hydropower and battery storage, with the former providing longer-term storage (> 4 hours), particularly considering the growing solar supply to meet daytime demand.

Despite their similar functions and contributions to non-dispatchable integration, the financial factors influencing the decision to build pumped-storage hydropower or battery installations vary significantly. Pumped-storage hydropower projects have an economic lifetime of 40 years. They can operate longer with proper maintenance, in contrast to batteries that have a relatively short economic lifetime of 10 – 15 years, promising a faster return on investments[liv]. However, battery systems need to be replaced more frequently to maintain their contribution to the system.

The 2 GW Snowy 2.0 Project in New South Wales, Australia is expected to contribute 350 GWh of utility-scale storage to the Australian national power system, which is increasingly dominated by solar and wind energy. The project will pump water to the highest reservoir in a linked system during periods of low-power prices and release it during peak demand periods. However, the project is 2 years behind commissioning due to supply chain disruptions from the COVID-19 pandemic, complex engineering design, and challenging geological conditions, which have ultimately increased project costs from US$ 2 billion to US$ 5.1 billion.

In the long-term, hydropower capacity factors will depend on the power system's hydropower and grid flexibility strategy. With increasing renewable capacities, hydropower projects will be used for balancing and flexibility services, resulting in below-average capacity factors.

Hydropower projects used for baseload generation (e.g. run-of-river projects) have the highest capacity factors. In contrast, installations for peak generation can have capacity factors as low as 10% - 15%. Financially optimised schemes generally achieve above-average capacity factors, whereas pumped-storage projects, increasingly used for flexibility services and frequency response, have particularly low capacity factors. Pumped hydro projects can be large; the biggest in the world, Fengning in Hebei province, China, has a generation capacity of 3.6 GW, storage capacity of 40 GWh, and was fully completed in August 2024[lv].

The 250 MW Hatta Hydropower Project in the United Arab Emirates has pumped-storage capacity of 1,500 MWh and a lifespan of > 80 years. The project will use water from the Hatta Dam and an upper reservoir. During off-peak demand, turbines will use solar energy to pump water from the dam to the upper reservoir, which will be used to power the turbines during peak demand periods. The project is expected to achieve 79% efficiency and a 90-second response time to power demand. Similar projects, the Magna and Baysh pumped storage plants, are being developed in western Saudi Arabia.

Older pumped-storage hydropower projects often experience higher round-trip losses. They need a larger electricity price gap between pumping and generation to remain economically profitable, which limits their operation opportunities.

The multipurpose nature of some dams and reservoirs can also restrict hydropower capacity factors, as power generation is often given lower priority than other uses like flood control, irrigation, recreation, or navigation. In these cases, generation patterns follow the water-release schedules for their primary purpose, such as seasonal irrigation or stable water supply releases.

Hydrological fluctuations can also lead to seasonal variations in output, especially for run-of-river projects. In contrast, reservoir projects with seasonal storage capability can operate independently of hydrological cycles, either partially or totally, particularly when storage capacity exceeds 30% - 50% of annual water flow.

As a result, hydropower generation aligns more closely with seasonal runoff patterns in countries with large run-of-river shares, such as France (68% of hydropower generation), Austria (74%), and Italy (75%), compared to countries such as Norway and Switzerland, where reservoir and pumped-storage hydropower for > 50% of hydropower output / year[lvi].

In regions where pumped-storage hydropower and reservoir installations dominate, seasonality can also be influenced by electricity demand patterns. For example, in Norway, the capacity factor is highest during winter when widespread electric heating in buildings increases electricity demand[lvii].

Hydropower generation will continue to be constrained by climate-related events and hydrological conditions, particularly water runoff patterns, which makes it sensitive to extreme climatic and hydrological events, with both heavy precipitation and droughts affecting operations.

Hydropower generation relies on runoff patterns, making it sensitive to extreme climatic and hydrological events. While heavy precipitation can boost output, flood control priorities may limit generation flexibility. Excessive river flows can overload storage facilities, flood small projects, or compromise operations.

Prolonged droughts can also significantly reduce hydropower generation, though sensitivity varies by project.

The United States reported a 6% y-o-y decline, mainly attributed to "above-normal temperatures" rapidly melting snow in the northwest, where most hydropower is generated[lviii]. However, improved drought conditions in California have led to more rain and higher hydropower output, partially offsetting the decline[lix].

China's hydropower generation has remained flat over the last three years, despite several utility-scale projects coming online.

Since 2022, a prolonged drought has sharply reduced river flows in the southwestern part of the country requiring coal to make up the difference, in addition to wind and solar meeting some of the demand. China's hydropower capacity increased to 422 GW at the end of 2023, from 358 GW at the end of 2019, but hydropower generation fell to 1,141 TWh in 2023 from 1,153 TWh four years earlier[lx]. But heavy spring rains in 2024 allowed hydropower to set a new summer record of 166 TWh in July, up from 121 TWh in the same month in 2023[lxi].

Soil moisture in Brazil's main hydropower river basins has dropped to nearly two-decade lows, threatening prolonged drought impacts even after rains return. Tropical rains-driven hydropower projects generate about two-thirds of Brazil's electricity. However, years of weak rainfall have curtailed hydropower generation, increasing costs, prompting regulators to predict new interest rate hikes.

The current drought has also affected run-of-the-river generators, including the partial shutdown of the Santo Antonio project in northern Brazil (one of the largest hydropower projects in the country), which relies on the Madeira River. The Brazilian grid operator, Operador Nacional do Sistema Elétrico has struggled to manage the system during peak demand, leading to the activation of costly thermal generation.

The Himalayan range contains ~54,252 glaciers, covering 60,054 km^2, with ice reserves estimated at 6,127 km^3. The range spans about 3,500 km across eight countries: Afghanistan, Bhutan, Bangladesh, China, India, Myanmar, Nepal, and Pakistan; and is the primary water source for ten major Asian river systems, including the Indus, Ganges, and Brahmaputra. Currently, the region faces significant climate warming and altered precipitation patterns, impacting its ecosystem.

Ongoing climate warming will continue to exacerbate hydrological regimes across the Himalayan range due to changes in seasonal extremes, increased evapotranspiration, and glacier volume variations; and poses a risk of lower ana variable hydropower output across the region in the long-term.

The hydropower impact of climate change differs across the Indus, Ganges and Brahmaputra: with the Indus experiencing a marked effect on meltwater, the Ganges experiencing an increased runoff, and the Brahmaputra incurring an enhanced flood risk.

In 2023, few new projects were commissioned in South Asia, but many are nearing completion, including major ones in Bhutan and Pakistan. Much of the increased capacity is driven by modernising projects built in the 1960s and 1970s, which remain crucial for maintaining the region's electricity systems and water supply.

Hence, harmonised water flow, flooding, and drought management systems will be crucial for coordinated action among operators in the same river basin. Expanding storage capacity and investing in specific equipment, like wide-head turbines, can improve resilience and optimise hydropower operations during extreme hydrological events. Additionally, regulators and utilities can use risk-mitigation instruments, such as insurance schemes, to protect against the financial risks of hydrological deficits.

CONCLUSION

Hydropower will continue to drive the global energy system's expansion, supplying affordable and reliable clean power. As the largest renewable resource, it will continue to play a crucial role across global power systems.

Hydropower will also continue to support the deployment of non-dispatchable renewable capacities by offering balancing and flexibility services. Currently, pumped storage is the largest energy storage method, accounting for 95% of global power storage capacity. In addition to power generation, hydropower provides drinking and irrigation water storage, leisure opportunities, and enhances resilience to floods and droughts.

Despite being the most mature renewable technology, hydropower faces various techno-economic challenges, which include ensuring sustainability and climate resilience, addressing ageing infrastructure, dealing with greater climatic variability and higher evaporation rates, securing new capital investments, and adapting operations and maintenance to meet modern power systems.

Upgrading existing hydropower capacities with the latest technological advances will be key to overcoming these challenges and ensuring the environmental sustainability of hydropower generation. Hydropower units must adapt to changes in original design conditions by incorporating new system designs, technological innovations, and material research, which will further improve generation costs.

i. Renewable power generation costs in 2022, International Renewable Energy Agency (https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2023/Aug/IRENA_Renewable_power_generation_costs_in_2022.pdf)
ii. Renewable power generation costs in 2022, International Renewable Energy Agency (https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2023/Aug/IRENA_Renewable_power_generation_costs_in_2022.pdf)
iii. Statistical Review of World Energy 2024, Energy Institute (https://www.energyinst.org/statistical-review)
iv. Clean Development Mechanism, UN Environment Programme (https://unepccc.org/cdm-ji-pipeline/)
v. Multinational - Baynes Hydro Power Project between Angola and Namibia 600 MW Advisory, African Development Bank (https://mapafrica.afdb.org/en/projects/46002-P-Z1-FAB-025)
vi. Africa, International Hydropower Association (https://www.hydropower.org/region-profiles/africa)
vii. Hydroelectricity, International Energy Agency (https://www.iea.org/energy-system/renewables/hydroelectricity)
viii. Guide to Chinese Climate Policy 2022, Oxford Institute of Energy Studies (https://chineseclimatepolicy.oxfordenergy.org)Small hydropower in China: The survey and sustainable future, 2015, Renewable and Sustainable Energy Review (https://www.sciencedirect.com/science/article/abs/pii/S1364032115003068)
ix. Small hydropower in China: The survey and sustainable future, 2015, Renewable and Sustainable Energy Review (https://www.sciencedirect.com/science/article/abs/pii/S1364032115003068); Guide to Chinese Climate Policy 2022, Oxford Institute of Energy Studies (https://chineseclimatepolicy.oxfordenergy.org/)
x. Types of Hydropower Plants, Office of Energy Efficiency and Renewable Energy, United States (https://www.energy.gov/eere/water/types-hydropower-plants)
xi. Types of Hydropower Plants, Office of Energy Efficiency and Renewable Energy, United States (https://www.energy.gov/eere/water/types-hydropower-plants)
xii. Achieving India's Renewable Energy Target by 2030, 2024, JMK Research and Analytics (https://jmkresearch.com/renewable-sector-published-reports/achieving-indias-renewable-energy-target-by-2030/)
xiii. Pumped Storage Hydropower Capabilities and Costs, 2021, Pumped Storage Hydropower International Forum (https://assets-global.website-files.com/5f749e4b9399c80b5e421384/61432796645661f940f277a8_IFPSH%20-%20PSH%20Capabilities%20and%20Costs_15%20Sept.pdf)
xiv. Karuma Hydropower Plant, 2024, Power Technology (https://www.power-technology.com/projects/karuma-hydropower-plant/)
xv. More Power to India: The Challenge of Electricity Distribution, The World Bank (https://documents1.worldbank.org/curated/en/815021468042283537/pdf/More-power-to-India-the-challenge-of-electricity-distribution.pdf)
xvi. Statistics Data, International Renewable Energy Agency (https://www.irena.org/Data)
xvii. The changing role of hydropower: Challenges and opportunities, 2023, International Renewable Energy Agency (https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2023/Feb/IRENA_Changing_role_of_hydropower_2023.pdf)
xviii. Africa Hydropower Modernisation Programme (AHMP), Sustainable Energy Fund for Africa (https://www.ahmpafrica.org/)
xix. Making flexible hydropower a reality, XFLEX HYDRO (https://www.xflexhydro.com/)
xx. Hydropower Modernization Needs in Asia, Asian Infrastructure Investment Bank (https://www.aiib.org/en/news-events/media-center/working-papers/pdf/AIIB-Working-Paper-Hydropower-Modernization_7September2020.pdf)
xxi. Hydropower, MarineBIo (https://www.marinebio.org/conservation/hydropower/); How long do hydropower installations last, Renewable First (https://renewablesfirst.co.uk/renewable-energy-technologies/hydropower/hydropower-learning-centreold/how-long-will-hydropower-systems-last/)
xxii. Renewable Power Generation Costs in 2022, International Renewable Energy Agency (https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2023/Aug/IRENA_Renewable_power_generation_costs_in_2022.pdf)
xxiii. Hydropower Special Market Report, 2021, International Energy Agency (https://iea.blob.core.windows.net/assets/4d2d4365-08c6-4171-9ea2-8549fabd1c8d/HydropowerSpecialMarketReport_corr.pdf)
xxiv. Hydropower Special Market Report, 2021, International Energy Agency (https://iea.blob.core.windows.net/assets/4d2d4365-08c6-4171-9ea2-8549fabd1c8d/HydropowerSpecialMarketReport_corr.pdf)
xxv. Hydropower Special Market Report, 2021, International Energy Agency (https://iea.blob.core.windows.net/assets/4d2d4365-08c6-4171-9ea2-8549fabd1c8d/HydropowerSpecialMarketReport_corr.pdf)
xxvi. Hydropower Special Market Report, 2021, Inter-

national Energy Agency (https://iea.blob.core.windows.net/assets/4d2d4365-08c6-4171-9ea2-8549fabd1c8d/HydropowerSpecialMarketReport_corr.pdf)

xxvii. The Benefits of Variable Speed Operation in Hydropower Plants Driven by Francis Turbines, 2019, ResearchGate (https://www.researchgate.net/publication/336126729_The_Benefits_of_Variable_Speed_Operation_in_Hydropower_Plants_Driven_by_Francis_Turbines)

xxviii. The Benefits of Variable Speed Operation in Hydropower Plants Driven by Francis Turbines, 2019, ResearchGate (https://www.researchgate.net/publication/336126729_The_Benefits_of_Variable_Speed_Operation_in_Hydropower_Plants_Driven_by_Francis_Turbines)

xxix. Variable speed pumped hydro storage: A review of converters, controls and energy management strategies, 2021, Renewable and Sustainable Energy Reviews https://www.sciencedirect.com/science/article/abs/pii/S1364032120304470)

xxx. HYDROMATRIX: Innovative Hydropower Solutions, Andritz Hydro (https://www.andritz.com/resource/blob/31692/f484084e0869b431e2362b1e82bef5b2/hy-hydromatrix-en-data.pdf)

xxxi. Sustainable hydropower drilling with Norhard AS, 2018, Innovation News Network (https://www.innovationnewsnetwork.com/sustainable-hydropower-drilling/524/)

xxxii. Hydropower Tunnels, ScienceDirect (https://www.sciencedirect.com/topics/engineering/hydropower-tunnels)

xxxiii. Chinese dam triggers earthquake, rattles Hong Kong (https://journal.probeinternational.org/2012/02/16/chinese-dam-triggers-earthquake-rattles-hong-kong/)

xxxiv. Hydrokinetic Turbine, ScienceDirect (https://www.sciencedirect.com/topics/engineering/hydrokinetic-turbine)

xxxv. Hydrokinetic Turbine, ScienceDirect (https://www.sciencedirect.com/topics/engineering/hydrokinetic-turbine)

xxxvi. Advanced Manufacturing and Materials for Hydropower: Challenges and Opportunities, 2023, Oak Ridge National Laboratory (https://info.ornl.gov/sites/publications/Files/Pub190558.pdf)

xxxvii. Materials Science for Hydropower, Pacific Northwest National Laboratory (https://www.pnnl.gov/materials-science-hydropower)

xxxviii. Sediment erosion in hydro turbines and its effect on the flow around guide vanes of Francis turbine, 2015, ScienceDirect (https://www.sciencedirect.com/science/article/abs/pii/S1364032115004517)

xxxix. Sediment erosion in hydro turbines and its effect on the flow around guide vanes of Francis turbine, 2015, ScienceDirect (https://www.sciencedirect.com/science/article/abs/pii/S1364032115004517)

xl. Renewable power generation costs in 2022, International Renewable Energy Agency (https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2023/Aug/IRENA_Renewable_power_generation_costs_in_2022.pdf)

xli. Renewable power generation costs in 2022, International Renewable Energy Agency (https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2023/Aug/IRENA_Renewable_power_generation_costs_in_2022.pdf)

xlii. Renewable power generation costs in 2022, International Renewable Energy Agency (https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2023/Aug/IRENA_Renewable_power_generation_costs_in_2022.pdf); The changing role of hydropower: Challenges and opportunities, 2023, International Renewable Energy Agency (https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2023/Feb/IRENA_Changing_role_of_hydropower_2023.pdf)

xliii. Renewable power generation costs in 2022, International Renewable Energy Agency (https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2023/Aug/IRENA_Renewable_power_generation_costs_in_2022.pdf)

xliv. Hydroelectric Power, International Financial Corporation (https://documents1.worldbank.org/curated/en/917841468188335073/pdf/99392-WP-Box393199B-PUBLIC-Hydropower-Report.pdf)

xlv. Life Cycle Assessment of Electricity Generation Options, 2021, United Nations Economic Commission for Europe (https://unece.org/sites/default/files/2021-11/LCA_final.pdf)

xlvi. Hydroelectric Power, International Financial Corporation (https://documents1.worldbank.org/curated/en/917841468188335073/pdf/99392-WP-Box393199B-PUBLIC-Hydropower-Report.pdf)

xlvii. Hydroelectric Power, International Financial Corporation (https://documents1.worldbank.org/curated/en/917841468188335073/pdf/99392-WP-Box393199B-PUBLIC-Hydropower-Report.pdf)

xlviii. Renewable power generation costs in 2022,

International Renewable Energy Agency (https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2023/Aug/IRENA_Renewable_power_generation_costs_in_2022.pdf)
xlix. Hydroelectric Power, International Financial Corporation (https://documents1.worldbank.org/curated/en/917841468188335073/pdf/99392-WP-Box393199B-PUBLIC-Hydropower-Report.pdf)
l. Hydroelectric Power, International Financial Corporation (https://documents1.worldbank.org/curated/en/917841468188335073/pdf/99392-WP-Box393199B-PUBLIC-Hydropower-Report.pdf)
li. Renewable power generation costs in 2022, International Renewable Energy Agency (https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2023/Aug/IRENA_Renewable_power_generation_costs_in_2022.pdf)
lii. Renewable power generation costs in 2022, International Renewable Energy Agency (https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2023/Aug/IRENA_Renewable_power_generation_costs_in_2022.pdf)
liii. Pumped-Storage Hydroelectricity, 2021, ScienceDirect (https://www.sciencedirect.com/topics/engineering/pumped-storage-hydroelectricity)
liv. Pumped-Storage Hydroelectricity, 2021, ScienceDirect (https://www.sciencedirect.com/topics/engineering/pumped-storage-hydroelectricity)
lv. China completes world's largest pumped storage hydropower plant, 2024, International Water Power (https://www.waterpowermagazine.com/news/china-completes-worlds-largest-pumped-storage-hydropower-plant/?cf-view)
lvi. ENTSOE (https://transparency.entsoe.eu/)
lvii. ENTSOE (https://transparency.entsoe.eu/)
lviii. Hydropower: How droughts are affecting the world's biggest renewable energy source, 2023, World Economic Forum (https://www.weforum.org/agenda/2023/11/hydroelectricity-generation-falls-droughts-climate-change/)
lix. Hydropower: How droughts are affecting the world's biggest renewable energy source, 2023, World Economic Forum (https://www.weforum.org/agenda/2023/11/hydroelectricity-generation-falls-droughts-climate-change/)
lx. China's hydro generators wait for the rains to come, 2024, Reuters (https://www.reuters.com/markets/commodities/chinas-hydro-generators-wait-rains-come-2024-03-22/)
lxi. China's record hydro and solar cut coal power during heatwave, 2024, Reuters (https://www.reuters.com/business/energy/chinas-record-hydro-solar-cut-coal-power-during-heatwave-kemp-2024-08-20/)
lxii. Brazil's hydropower faces risk from drying river basins, 2024, Reuters (https://www.reuters.com/business/energy/brazils-hydropower-faces-risk-drying-river-basins-2024-09-11/)

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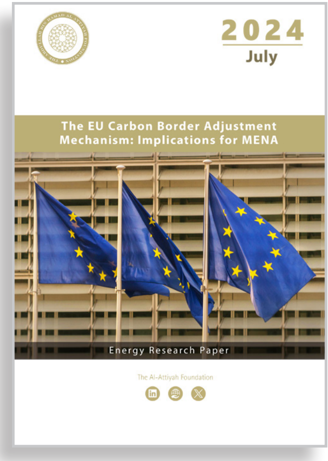
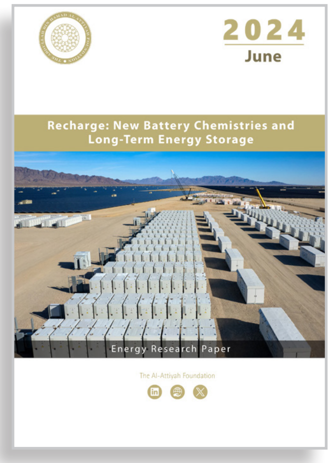


July - 2024

The EU Carbon Border Adjustment Mechanism: Implications for MENA

The European Union's (EU) Carbon Border Adjustment Mechanism (CBAM) imposes a reporting obligation, and a carbon tax on EU imports of certain goods in order to reduce carbon emissions.



June - 2024

Recharge: New Battery Chemistries and Long-Term Energy Storage

Battery technologies are receiving intense attention and innovation, with new chemistries emerging that offer benefits over the conventional lithium-ion designs. These benefits span various aspects, including cost-effectiveness, reduced charging time, increased energy capacity, enhanced safety, and minimised use of scarce battery raw materials.

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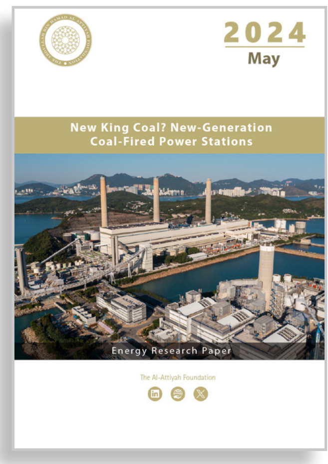

May - 2023

New King Coal? New-Generation Coal-Fired Power Stations

The prevailing belief is that the use of coal must cease to achieve net-zero emissions. However, new coal power plants, equipped with advanced ultra-supercritical, fuel cells, small supercritical, co-combustion, combined heat and power, and carbon capture, use and storage (CCUS) technologies offer enhanced thermal efficiency, reduced emissions, and increased flexibility in power generation.

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