ASIAN INFRASTRUCTURE
INVESTMENT BANK

Hydropower Modernization Needs in Asia

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Abstract

Hydropower has and continues to make an essential contribution to increasing energy access, boosting prosperity and meeting climate targets. In 2019, hydropower accounted for nearly half of the global renewable energy capacity with just over 1,300 gigawatts (GW) and approximately 16 percent of global electricity generation.

However, while much attention is given to new hydropower development, there is also an increasing need to modernize and optimize the existing assets to ensure hydropower's vital role in energy systems is sustained and enhanced. Hydropower has an aging fleet, with nearly half of its global capacity more than 30 years old (600 GW) and about one-third more than 40 years old (400 GW). In Asia, home to half of the world's hydropower capacity (nearly 650 GW), the need for modernization is ever-present. By 2030, over one-third of the existing capacity will have undergone, or be due for, modernization. This rises to 50% when excluding China.

The Asian Infrastructure Investment Bank (AIIB) commissioned the International Hydropower Association (IHA) to undertake a study to help identify hydropower stations in need of modernization in Asia. The study identified 21 hydropower stations with an installed capacity of over 6 GW in high need of modernization representing up to USD2.7 billion of estimated investment needs. These projects, located in seven countries across South Asia and Southeast Asia, range from opportunities to rehabilitate existing infrastructure to improve efficiency and dam safety to expanding a station's capacity to meet increasing electricity demand and support the integration of variable renewables. In addition, a further 45 stations, accounting for nearly 20 GW of installed capacity were assessed as being in medium need for modernization representing between USD7 to 11 billion of estimated investment needs. With 11 stations identified, India had the most stations assessed as being in high need.

Keywords: Hydropower, modernization, upgrade, power, renewable energy, Asia

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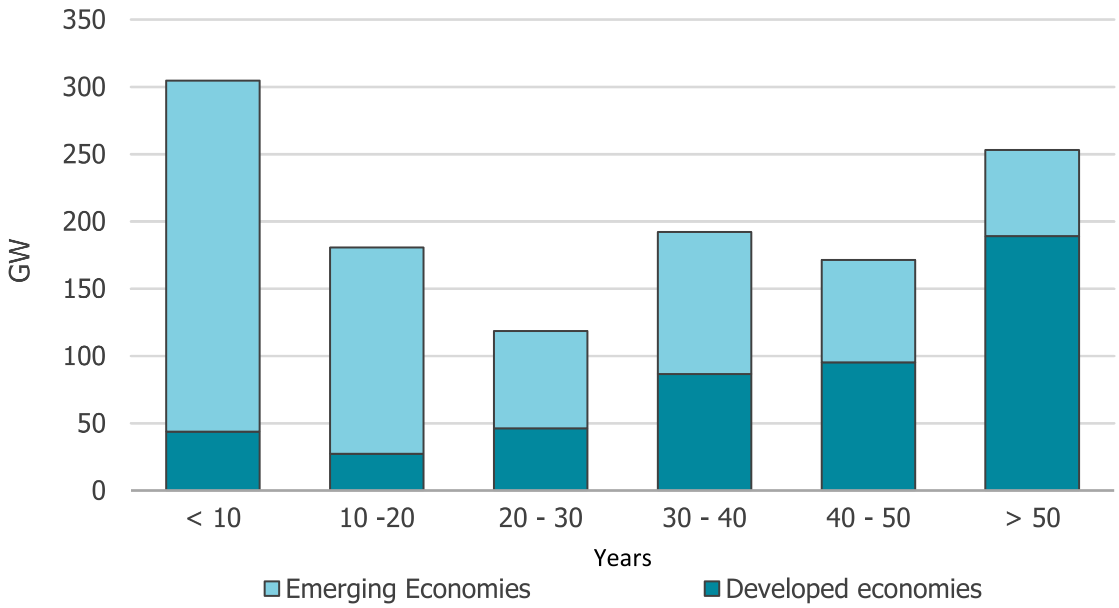
1 Introduction

Hydropower development has and continues to make an essential contribution to increasing energy access, boosting prosperity and meeting climate mitigation targets. It remains the single largest source of renewable electricity and accounted for 16 percent of all electricity generated across the globe in 2019—more than all other renewable sources combined (IHA, 2019a). However, while much attention is paid to scaling up new development, there is also an increasing need to modernize and optimize the current fleet of aging assets to ensure hydropower's vital role in energy systems is sustained and enhanced.

As the oldest renewable technology, hydropower has an aging fleet with nearly half (600 GW) of its global capacity more than 30 years old. Furthermore, one-third of its capacity is older than 40 years (see Figure 1) (Frankl P., 2019). The performance and reliability of components are reduced as stations age, impacting output, revenue and safety. Therefore, modernization programs—from repairing and replacing components to implementing innovative technologies—are needed to extend the lifespan of stations and maintain or even increase their output. Other factors such as changing market circumstances, including the requirement to deliver greater flexibility services to support higher penetrations of variable renewables, may also bring about the need for modernization.

Figure 1: Age of Global Hydropower Fleet



Source: Frankl, P., 2019. The need for modernizing hydro in rapidly changing power systems.

In Asia, home to half of the world's hydropower capacity (nearly 650 GW), the need for modernization is ever present (IHA, 2019a). By 2030 over one-third of the existing capacity will have undergone or be due for modernization. A figure which rises to 50 percent when excluding China as its 352 GW of installed capacity has an average age of less than 20 years (Frankl P., 2019).

With thousands of stations in operation having generated 1,990 TWh in 2018, or 14 percent of total generation, hydropower is a major contributor to the region's electricity mix. It is also the dominant source in Afghanistan, Bhutan, Cambodia, Georgia, the Kyrgyz Republic, Lao PDR, Myanmar, Nepal and Tajikistan, where it constitutes more than 50 percent of total annual generation.

Over the coming decade, as the region's population and economies expand, its need for reliable and sustainable electricity will become greater than ever. If properly managed and invested in strategically, hydropower's existing assets will form the backbone of this energy transition and be essential in meeting the objectives set out in both the Paris Agreement and the Sustainable Development Goals.

It is against this backdrop that the International Hydropower Association (IHA), on behalf of the Asian Infrastructure Investment Bank (AIIB), has undertaken this study to help identify the hydropower modernization needs in 20 of the Bank's regional members. These members include Azerbaijan, Cambodia, Georgia, India, Indonesia, Kazakhstan, the Kyrgyz Republic, Lao PDR, Malaysia, Myanmar, Nepal, Pakistan, Philippines, Russia, Sri Lanka, Tajikistan, Thailand, Turkey, Uzbekistan and Vietnam.

2 Categorization of High, Medium and Low Modernization Needs

For this study "modernization" is used as an overarching term which includes updating control systems and replacing, refurbishing or upgrading electromechanical equipment and civil infrastructure beyond routine operation and maintenance (O&M) practices. This also includes expansion projects (adding additional units).

Below is a description of the key characteristics that informed the categorization of stations in terms of modernization need for this study, including for those stations where no information or limited information was available.

<u>LOW—no immediate need for modernization identified</u>

- Good operating performance over an extended period including high availability and low forced outage rates.
- Major modernization recently completed or underway, involving the replacement or refurbishment of electromechanical equipment (e.g., stators, rotors and other drivetrain components).
- Station owner advised that the station was not a priority for modernization or that they are not in need of finance from an International Financial Institution (IFI).
- If a modernization project was due to commence shortly (already financed and contracted) and was expected to address the main performance issues identified.
- In cases where there was insufficient data to confirm or identify the level of need, stations were marked as "Low" if < 25 years old. Below this age threshold, the equipment is still considered to perform well unless otherwise reported.

<u>MEDIUM—possible modernization need identified but not considered urgent</u>

- Generally displayed satisfactory operating performance over an extended period; experienced some years with low availability and high forced outage rates.
- Partial modernization may have recently been completed or is underway. For example, work may have been carried out on some components such as excitors or control systems, but rehabilitation of major electromechanical equipment will be required in the medium to long term.
- Planned modernization works may have been in place, but they were only minor (i.e., below USD5 million) or scheduled to commence in 2025 or beyond.
- In cases where there was insufficient data to confirm or identify the level of need, stations were marked as "Medium" if > 25 years old.

HIGH—urgent need for modernization identified but further investigation required

- Poor operating performance over an extended period including low availability and high forced outage rates, likely due to electromechanical equipment deficiencies.
- Major failings in the station's civil infrastructure have been identified, e.g., concrete issues, intake gates, hoists, spillway, etc.
- Station had not been significantly modernized over the life of the facility or was last completed > 30 years ago; in particular the electromechanical equipment has not been refurbished or replaced.
- Station owner or government (regional or national) had listed the station as a priority for modernization or expansion. This was due to poor performance and/or major systems approaching the end of their useable life.
- Station owner had modernization plans in place, sometimes pending a feasibility study.

3 Scope

The following three criteria was used to select stations for investigation in this study:

1. Must be located in 20 of AIIB's regional members.
2. Must be 20 years or older.
3. Must have installed capacity of 150 MW or greater. The only exception was Nepal, where stations with an installed capacity of 10 MW or greater were included.

Using these criteria and applying them to IHA's stations database, 155 stations were identified across 19 countries as shown in Figure 2 (no stations fitting the criteria were located in Cambodia). The combined capacity of these stations is 100 GW which represents over two-thirds of the total hydropower capacity found in these 19 countries. In terms of the types of hydropower station covered, the majority are conventional reservoir storage (112) followed by run-of-river (34), pumped storage (8) and one mixed storage and pumped storage.

Russia and India combined make up the lion's share of both the installed capacity covered (59.8 GW) and the number of stations (79) (Table 1). This reflects that they have among the largest and oldest hydropower fleets in the world. Meanwhile, with a regional average age of less than 30 years, only 13 percent (13.1 GW) of the installed capacity and 19 percent of the stations (29) are located in Southeast Asia.

Figure 2: Map Displaying Geographical Spread, Age Grouping and Size of the Stations Within the Scope of the Study

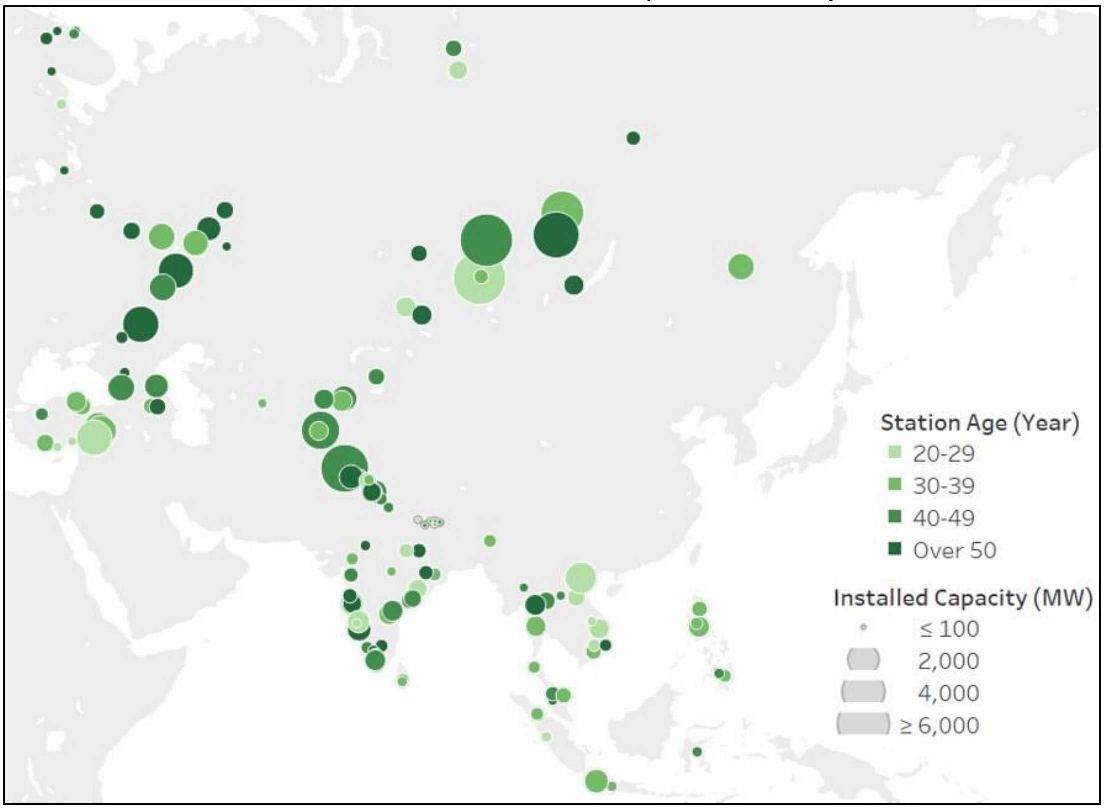


Table 1: Country Breakdown by Number of Stations and Their Age

	≥ 20 years old		> 40 years old	
	MW	**No. of stations**	**MW**	**No. of stations**
Russia	40,921	34	24,507	24
India	18,852	45	10,750	25
Turkey	8,328	11	438	2
Pakistan	6,131	3	6,131	3
Tajikistan	3,845	3	3,245	2
Vietnam	3,505	5	240	1
Indonesia	3,049	8	382	2
Kyrgyz Republic	2,870	5	1,380	2
Thailand	2,539	5	1,279	2
Philippines	2,158	7	380	2
Kazakhstan	2,150	4	1,448	3
Georgia	1,704	3	1,704	3
Uzbekistan	981	3	831	2
Malaysia	898	3	498	2
Lao PDR	827	3	155	1
Azerbaijan	804	2	424	1
Sri Lanka	411	2	0	0
Nepal	237	8	49	3
Myanmar	168	1	168	1
	100,379	**155**	**54,010**	**81**

The scope of this study contains 52 different station owners. While there are more individual station operators, only the parent companies of subsidiaries and the majority shareholders in special purpose entities were counted.

Most stations are publicly owned (89 percent), either by central or state governments and they represent 81 percent of the total capacity (see Table 2). Publicly-owned companies with the largest fleets include RusHydro (22 GW), Elektrik Üretim A.Ş. (EÜAŞ) (7.2 GW), Water and Power Development Authority (WAPDA) (6.1 GW), Barqi Tojik (3.8 GW), the Electric Stations Open Joint Stock Company (2.9 GW), the Electricity Generating Authority of Thailand (EGAT) (2.5 GW) and the Maharashtra State Power Generation Company (1.9 GW).

Private sector companies account for only 11 percent of the stations but 19 percent of the total capacity. With 15 GW of capacity, Russia's EuroSibEnergo has the largest fleet of privately-owned companies in the study followed by Norilsk Nickel (1 GW).

Table 2: Station and Capacity Breakdown by Ownership

	No. of owners	No. of stations	Capacity (MW)
Central government	23	94	61,683
State/Provincial government	16	44	19,526
Private sector	13	17	19,170
	52	**155**	**100,379**

4 Drivers and Opportunities for Modernization

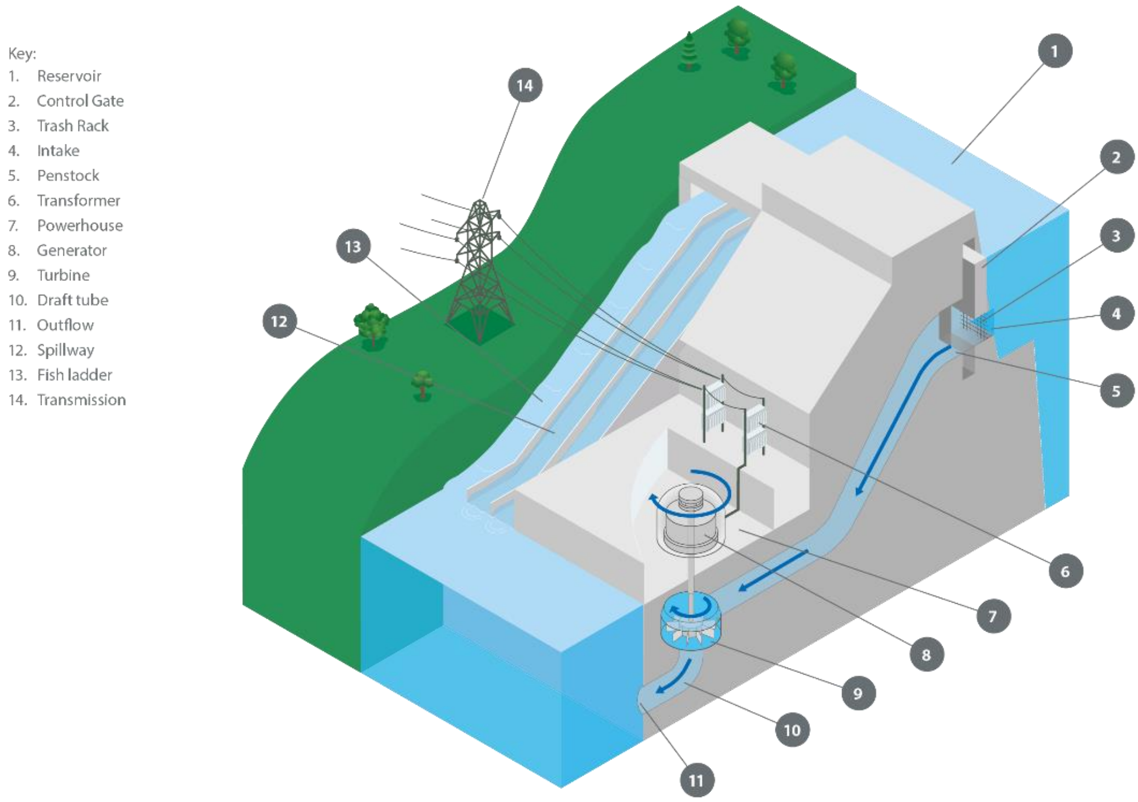
The modernization of hydropower stations is driven by numerous and often interrelated factors, from aging equipment to improving energy performance, operating strategies and environmental impacts. In all cases parts of a station will need to be replaced, refurbished or upgraded (Figure 3). Beyond extending the lifetime of these assets, modernization represents a key opportunity for existing hydropower infrastructure, providing benefits such as optimised power production, improved O&M and enhanced water services at multipurpose hydropower sites.

Projects to refurbish and modernize hydropower plants go further than business-as-usual O&M and involve a more significant reinvestment in an existing asset. Although the type of modernization will vary case-by-case depending on the needs and options available for a given site, strategies will generally fall into the following categories:

- **Life extension—**projects look to extend the life of the station, with repairs or replacements of existing key electromechanical components to restore and often improve performance.
- **Major upgrade/uprate—**projects often aim to improve services by increasing generating efficiency, uprating installed power capacity, redesigning the operating regime, or reequipping an existing site with new technologies, while also extending the life of the station.
- **Total redevelopment—**projects involve larger-scale station overhauls, rebuilds or plant expansion schemes, including significant civil works to modernize and often replace the existing station either in-situ or by adding a new powerhouse. Repurposing hydropower dams and reservoir sites with pumped storage capability is another example.

Digitalization can also play a central role and be integrated within any of the listed categories. Such projects focus on updating plant control, monitoring and communication systems, using state-of-the-art digital analytics to optimise operations and support preventative maintenance strategies.

Figure 3: Hydropower Plant Diagram With Main Components



Source: International Hydropower Association

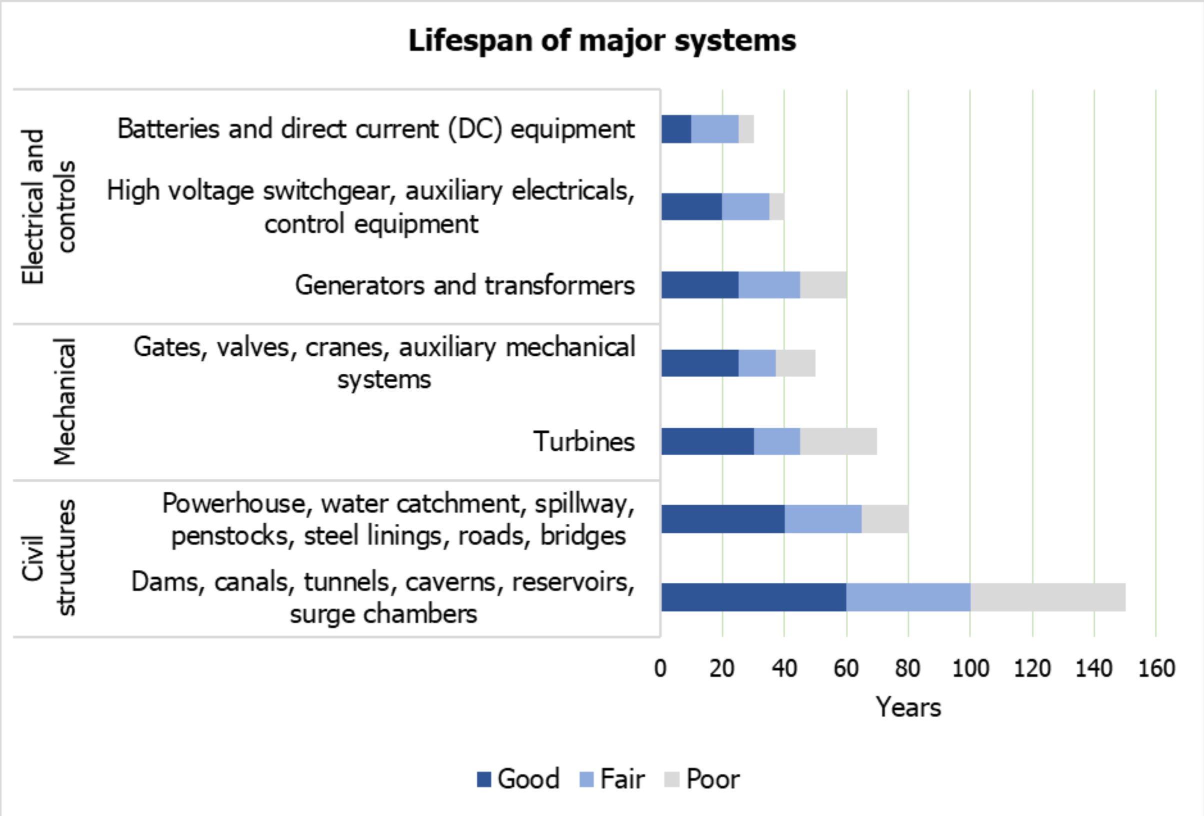
With different types and scale of projects, there can be many reasons for modernizing an existing hydropower station. This review looks to introduce the main drivers and opportunities for modernization projects.

Plant Aging

All hydropower stations age over time, causing a degradation in reliability and sometimes performance. For example, turbines undergo mechanical wear and tear, electrical generators slowly deteriorate from high thermal or mechanical stresses, and civil structures also degrade over longer timeframes, potentially reducing energy production as well as safety levels. Studies published by IFIs, original equipment manufacturers and research organizations describe the physical processes which lead to degradation as well as remedial measures taken in modernizations in more detail [(Goldberg J & Espeseth LO, 2011); (Matins NM & Alarcón A, 2019); (Kainberger M, 2012); (Woeber G, 2012); (IHA, 2019b); (Maryse François et al)].

Figure 4 presents the lifespans of the major systems of a hydropower station based on assessments applied in a World Bank study. The dark blue bars show the number of years each type of system is in good working condition after entering service; the light blue bars show subsequent years of fair performance; and above this threshold the systems are expected to be in poor condition shown in grey.

Figure 4: Indicative Average Lifespans of Major Systems in a Hydropower Station (Goldberg J., 2011)



As shown, the electrical ancillary and control systems are typically replaced or updated first, often due to obsolescence. The major electromechanical drivetrain components such as hydraulic turbines, generators and transformers are often modernized 30 to 45 years after the original commissioning date depending on a number of factors including the original materials used in manufacturing components and site conditions. Degradation rates can be accelerated for different reasons, for instance high sediment loads in river waters or a lack of proper equipment maintenance. Changes in modes of operation, when machines are more extensively used for peaking or provision of grid support services, can also cause higher stresses on rotating machinery and electrical systems, therefore reducing their lifetime.

Finally, the civil structures and associated features including the powerhouse, spillway gates, underground assets, dam and reservoir typically last longer, with overall plant lifetimes anywhere from 60 to 100 years and even higher in some cases. Condition assessments of the main structures are usually carried out periodically to assess structural integrity and any need for repairs.

Performance Recovery

Reduced performance over time can lead to longer and more frequent maintenance outages, increased incidence of forced outages and loss of efficiency, all of which can lead to losses in energy production. This can increase business risk and, depending on the owner's appetite for risk over time, determine when an intervention is required. Moreover, as hydropower is commonly the lowest marginal cost unit in a power pool in many markets, the consequences of failing to adequately modernize assets can have detrimental impacts. If the station is operating significantly below rated capacity for long periods, the shortfall in electricity supply is often replaced by more expensive and polluting thermal alternatives. Modernization addresses this risk by repairing and replacing old equipment to reduce outages, improve availability and increase power output. A study undertaken by an original equipment manufacturer showed that life extension projects where turbine runners are replaced can recover efficiency by 3 percent and potentially up to 6 percent or more; while larger projects involving upgrade of turbine-generator units can increase power capacity by 10 percent to 20 percent, and even up to 40 percent can be possible (GE, 2018).

For example, EuroSibEnergo is modernizing its hydropower fleet in Siberia with replacement turbine runners at its 4,500 MW Bratsk hydropower station and its other major stations. The program has successfully recovered generating unit efficiency by up to 5 percent in some cases and has resulted in overall energy gains. Upon completion, the overall program is expected to increase annual production by 1.9 TWh across the hydropower fleet and will in turn reduce the use of coal-fired power generation in the region, saving over 1.8 million tons of CO_2 emissions per year according to estimates [(IHA, Case Study a); (Harris M, 2016)].

Other projects, such as Mainstream Energy Solutions' Capacity Recovery Programme in Nigeria, have involved more extensive refurbishments of older plants. Mainstream took over the 760 MW Kainji and 578 MW Jebba hydropower stations in 2013 and needed to address generating units either left unavailable or running at derated capacity due to years of poor maintenance. To date, the owner has already rehabilitated three units at Kainji and restored available capacity to 922 MW across the two stations, with works progressing on remaining units (Mainstream, n.d). In the period from 2014 to 2018, the operator was able to reach over 99 percent availability for declared capacity and increasing the annual electricity output (IHA & World Bank, Case Study).

Capacity and Technology Upgrades

Opportunities can also be taken to upgrade or uprate the installed capacity and overall efficiency of existing stations (Matins NM & Alarcón A, 2019). In these cases, installed capacity (MW) may be increased by replacing turbine runners with larger units and optimized systems [(IHA, 2019b); (Andritz, 2018)]. In Russia for instance, RusHydro's modernization project at the 1,380 MW Saratov hydropower station will increase the installed capacity by 10 percent. With completion expected in 2025, the project will have upgraded the station's 21 Kaplan turbines, the largest of their kind in Russia, raising unit capacity from 60 MW to 68 MW and offering higher annual production [(IHA, Case Study b); (Rushydro, 2019); (Voith Hydro, 2018)] . Another example is the modernization of the 2,620 MW Chief Joseph, the third largest hydropower station in the United States. In 2011 and 2012, 10 of the plant's Francis turbines were refurbished and put back into service; this produced leading performance for existing designs, uprating each unit (under a net head of 50m) from 75 MW to 90 MW and raising turbine peak efficiency by more than 6.5 percent.

Technology developments are a key factor in hydropower modernizations. Old systems can be replaced with state-of-the-art equipment, bringing benefits for operators. From turbine-generators to spillway gates, equipment installed over 30 to 40 years ago can be retrofitted with new parts optimized for improved efficiency and reduced ecological impact, thanks to advanced manufacturing and materials. Technology upgrades can also bring forward the decision to modernize a project.

There are further examples around the world of utilities investing in their existing hydropower fleet, making use of innovations. Southern Company has a Capex plan totaling USD1.8 billion for its station fleet across the southeast United States, which includes new spillway gate designs and modern digitalized controls in addition to electromechanical components (Johnson H., 2019). In France EDF invests annually in modernization, such as at La Coche pumped storage station where a 240 MW Pelton turbine was recently added and is expected to increase production by 100 GWh annually. Moreover, at Grand Maison, the largest pumped storage station in Europe, new Pelton turbines will be installed with optimized efficiency based on modern runner designs alongside new static excitation systems which will improve startup rates [(Mattei J.D., 2019); (Andritz, a)].

Policy and Markets

The decision to extend the life and potentially upgrade a hydropower station will typically be influenced strongly by electricity prices and market design. At the national level, where there is a risk of having to decommission old hydropower stations and losing reliable, renewable generation capacity, governments may also develop enabling policies to encourage reinvestment by the private sector.

In Switzerland, for instance, there is a significant amount of hydropower capacity coming up for renewal over the next 10 to 20 years as existing concessions come to an end. The Swiss Federal Office of Energy has therefore developed measures under Energy Strategy 2050 to support modernizations that go beyond standard refurbishments, for example increasing electricity production from existing sites. Creating stable tax and regulatory conditions can also support the investment case (Dupraz C., 2019).

Electricity markets can therefore act as a key driver for modernization decisions, with hydropower often having to adapt to new supply and demand patterns. Ongoing reforms in many markets will have to better recognize and remunerate the role hydropower plays in supporting grids and offering balancing services to the system. In parts of both North and South America, Europe, and Australia, hydropower units are already moving away from traditional baseload generation to modes of operation which accommodate and support a changing energy mix [(Marx P., 2019); (Electric Power Research Institute, 2017)]. This continues to make use of hydropower's unique characteristics as a dispatchable power source, but it can also lead to higher operating costs and the need to reinvest in plants. This is expected to become a key trend in countries with ambitious 2050 climate targets, as integrating variable wind and solar power will increase demand for the low cost, clean and flexible supply associated with hydropower (Frankl P., 2019).

Power Flexibility

As markets evolve, power flexibility and energy storage are becoming increasingly essential and strongly support the need for hydropower modernization. Many generators are looking for ways to improve frequency control and other ancillary services to stabilize the grid; this can require hydropower units to operate over an extended range, requiring quicker response ramping, part-load and stop/start capabilities among other improvements. If existing stations were not originally designed for these services, components may need to be reengineered and replaced.

A useful case study of a national system growing its supply of variable renewable sources including wind and solar power is Australia, with supporting plans to expand and modernize hydropower capacity. For example, modernization of the hydropower fleet in the Snowy Mountains includes projects like the 60 MW Guthega station, where generator upgrades will improve both the operating reserve and peaking capability (Harris M., 2017). Another initiative is 'Battery of the Nation', which aims to unlock the potential of new and existing hydropower capacity and pumped storage on the island of Tasmania, as a source of low carbon and flexible supply for the National Electricity Market (NEM) (Harby A. & Schaffer L.E., 2019). This ties in with the proposed interconnection from Tasmania to mainland Australia, which will complement significant amounts of proposed wind generation in Tasmania and across the NEM (Hydro Tasmania, 2018).

Innovative generating systems are also making an impact in hydropower. Variable speed hydroelectric technologies can increase the power flexibility and efficiency of pumped storage stations, especially in markets where network stability is influenced by asynchronous wind, solar and battery technologies. Variable speed turbines, such as those installed at the 780 MW Frades II and 1000 MW Linthal pumped storage projects in Portugal and Switzerland, can add a degree of flexibility for plant and system operators. Although fixed-speed units can also provide benefits through natural inertia, variable speed allows power to be adjusted in pumping mode; further, when in turbine mode it can offer greater partial load efficiency, higher outputs at low heads and quicker electrical response [(Voith, a); (XFLEX Hydro, 2019); (Voith, b); (EDP, 2018a); (GE Renewable Energy, n.d.)].

Digitalization of Systems

Digitalization of hydropower technologies and O&M practices can be central to modernization programs. Projects may install new digital controls, intelligent condition monitoring systems, remotely operated systems, and supervisory control and data acquisition systems. For example, modernization of the 108 MW Batang Ai hydropower station in Sarawak, Malaysia, includes automation of out-of-date controls, a major overhaul of four Francis units, and dynamic water and dispatch management through forecasting river inflows and optimizing power dispatch. This will enable the operator, Sarawak Energy, to manage the reservoir levels safely and run the power units at optimum range. After completion, estimates suggest an additional 16 percent of energy will be produced on an annual basis. Flood warning stations at upstream and downstream flood vulnerable areas have already been installed to mitigate flood risk (GE Renewable Energy, n.d.).

Updates to plant controls, communication and computer systems are also being applied in larger scale projects and across entire fleets. Itaipu Binacional, for example, is starting a modernization program of the 14,000 MW hydropower complex on the border of Brazil and Paraguay, with digital upgrades planned for the turbine-generators. In Europe, Energias de Portugal (EDP) has already established remote operation centers and will update asset management platforms at a multitude of stations across Portugal and Spain (Salto Grande, 2018). After the decision to create a Monitoring and Diagnostics Centre for its conventional generation across Iberia, EDP partnered with GE to develop a Digital Asset Management project, accelerating the move toward a global fleet optimization strategy based on data and intelligence analytics as opposed to a more traditional approach on targeted generating units (EDP, 2018b).

Renewable Hybrids

Another option which is gaining interest is hybrid technologies where different renewable technologies work together to complement each other and work more efficiently. One example is floating solar photovoltaics (PV) installed on existing reservoirs, providing additional renewable generation that is also low carbon. Solar-hydro hybrids can make use of existing infrastructure at the hydropower site, saving on land and grid connection costs otherwise incurred in greenfield solar projects.

In 2017, EDP successfully completed a pilot floating solar PV project at its Alto Rabagão pumped storage station in Portugal, and calculated a 10-percent solar PV efficiency gain compared to on-land systems. Hydropower units can provide operating reserves to backup solar output fluctuations during daytime and feed a more stable power profile into the grid network. One such project is the 1,280 MW Longyangxia hydropower dam in China, which has a transmission connection to the nearby Gonge solar PV farm (Rogner M., 2015).

Battery hybrids are an added opportunity whereby a battery system is colocated with an existing hydropower station. Such combined systems can improve energy storage services, using the battery to provide fast frequency response over short timescales and in turn using the hydro-generators for network regulation over the longer term. Using battery electronics for frequency control can also relieve control requirements and mechanical wear and tear on hydroelectric machinery. Examples are Engie's installation of a 12.5 MW battery at the Kraftwerksgruppe Pfreimd hydropower complex in Germany and EDF's plan to hybridize a small battery at its 142 MW Vogelgrün run-of-river hydropower station in France [(XFLEX Hydro, 2019); (Colthorne A., 2018)].

Socioenvironmental Impact

Sustainability and environmental and social impact can be a key driver for modernization, particularly in large-scale redevelopments. New environmental technologies are also being increasingly adopted to improve natural habitats, water quality, fish management and reduce detrimental impacts on ecology upstream and downstream of hydropower sites [(Andritz, b); (IHA, 2017)]. For example, EDF's Romanche-Gavet modernization project in France involves a complete redesign of the existing hydropower scheme. The project involves decommissioning six hydropower stations that have been operating along the Romanche river since the early 1900s and building a new underground powerhouse. As well as raising power production from the site, replacing the above-ground stations will reduce the visual impact in the Romanche valley area. This will benefit communities and also improve the ecological impact along the river stretch (IHA, 2017). The project has benefited from being assessed by the Hydropower Sustainability Assessment Protocol (HSAP), part of a suite of tools developed by IHA through a multistakeholder process to promote and advance the sustainability of hydropower projects (see below for further information on the tools).

Hydropower Sustainability Tools

Through a multi-stakeholder process, IHA has developed Hydropower Sustainability Tools to define international good and best practice in sustainable hydropower development. The tools provide a common language for governments, civil society, financial institutions and the hydropower sector to discuss and evaluate sustainability issues in hydropower projects. The Hydropower Sustainability Guidelines on Good International Industry Practice (HGIIP) define processes and outcomes that constitute good international industry practice for topics relevant to preparing, implementing and operating hydropower projects.

Performance against the Hydropower Sustainability Guidelines can be measured through two complementary tools:

The Hydropower Sustainability Assessment Protocol, which takes into account all the 26 guideline topics and measures performance above and below defined good practice; this enables projects to benchmark their performance in a comprehensive way.

The Hydropower Sustainability Environmental, Social and Governance Gap Analysis Tool (HESG Tool), which can be used to check for gaps against good practice on targeted topics and includes a gap management plan to improve processes and outcomes.

For further information on the Hydropower Sustainability Tools, please see here: https://www.hydrosustainability.org/

For multipurpose hydropower, water services can be improved as a result of modernization by increasing reservoir capacity or by adding or improving existing irrigation services and flood management. Hydropower sites and their operations can also impact a region's public water resources, meaning changes expected from modernization projects must be considered at the planning stage and in collaboration with the water authority (Dupraz C., 2019).

Climate Resilience

Climate resilience is a growing concern, with hydrological variability now being considered in hydropower modernization projects. Greater weather extremes will affect hydropower infrastructure in climate-sensitive regions and may require investment in adaptive measures. These could range from better flood defenses to sediment management strategies, improved dam safety measures including early warning systems, and structural improvements to river and reservoir areas (IHA, 2019c). Modernization of the 126 MW Qairokkum hydropower station in Tajikistan is a good example as the project includes various upgrades and local skills training to improve resilience (EBRD, 2016). The project has benefited from the Hydropower Sector Climate Resilience Guide being tested on it during the guide's pilot phase (see below for further information).

Hydropower Sector Climate Resilience Guide

To facilitate the development of hydropower infrastructure that can withstand the risks of variable climatic conditions, the Hydropower Sector Climate Resilience Guide was developed and launched in May 2019. It is the first sector specific climate resilience guide providing a practical and useful approach for identifying, assessing and managing climate risks to enhance the climate change resilience of new and existing hydropower projects.

The six-phase methodology can be applied to projects of all types, scales and geographies and looks at climate risk screening, data analysis, climate stress testing, climate risk management, and monitoring, evaluation and reporting. The guide responds to the need for clarity on good international industry practice for project owners, financial institutions, governments and private developers when considering climate risks in hydropower development and operations.

The guide also complements the Climate Change Mitigation and Resilience topic of the Hydropower Sustainability Tools. The guide can help ensure that the evaluations conducted through the HSAP or the HESG Tool can adequately assess the resilience of a hydropower project.

In addition to Qairokkum, the guide was applied in the modernization of the Nenskra hydropower project in Georgia and Kabeli A hydropower project in Nepal during its pilot phases.

For further information, please see here: https://www.hydropower.org/publications/hydropower-sector-climate-resilience-guide

More generally, the magnitude and variability of river inflows affect the availability of water for electricity production, sometimes requiring remedial measures to be taken. Long-term changes in hydrology may justify more extensive redesign at an existing site for both reservoir storage and run-of-river hydropower projects. For example, if the long-term average river flow is declining, station modernization may be required to optimize the use of water by changing the turbine design to adapt to lower minimum flows, or potentially to decommission older units. Conversely, if flows are increasing, plant modernization would consider returbining to increase unit capacity where possible or in some cases add additional units. In other cases, dam, reservoir and spillway upgrades may be required if average river flows have changed significantly over the decades, and if there is greater risk of extreme climate or flood events in the future.

Contractual Limits and Regulations

Many large-scale hydropower stations operate under long-term concession agreements held with a local authority or power off-taker. Expiry of an existing concession or power purchase agreement (PPA) can be a key driver for reinvesting in an existing asset. For a station nearing the end of its life, renewal of the concession agreement may be necessary before a modernization can proceed (Dupraz C., 2019).

Other regulatory risks may also affect decisions around modernization projects. Environmental legislation can come into force, requiring owners to refurbish existing hydropower sites to meet stricter limits, while power operations may be impacted by grid rules and network codes if for example the transmission operator updates grid connection requirements or charging regimes for ancillary services. National policy can also support and guide reinvestments in existing hydropower stations, particularly when electricity production is increased as is the case in Switzerland and Norway [(Dupraz C., 2019); (IHA, 2019c)].

Case Studies

There are a variety of drivers and potential improvements provided by modernization and these are usually determined by the conditions and options available for an individual site. Investment projects provide an opportunity to address legacy issues of older stations while also offering a window to implement up-to-date energy technologies, capacity upgrades as well as environmental measures at existing sites. A number of case studies illustrated the type of benefits achieved, which in addition to environmental and operational improvements, showed the range of energy gains that can be achieved from projects as indicated in Table 3.

Table 3: Examples of Energy and Efficiency Gains From Modernization Projects

Project	Date in service	Type of modernization	Power, energy and efficiency gains
Bratsk 4,500 MW, Russia	1963	Life extension	Replaced 12 turbine runners, with efficiency gains of up to 5 percent per unit in some cases.
Batang Ai 108 MW, Malaysia	1985	Life extension	Optimised energy and water services, with annual energy production gains of 16 percent
Kainji 760 MW and Jebba 578 MW, Nigeria	1968 and 1985	Life extension (plus expansion)	Restoring unavailable units, with 922 MW total capacity declared with high availability in 2017.
Saratov 1,380 MW, Russia	1967	Major upgrade	Upgrading 21 Kaplan turbines from 60 to 68 MW each and total plant power capacity increase of 10 percent.
Chief Joseph 2,620 MW, US	1958	Major upgrade	Upgraded 10 turbines in 2012 increasing power from 75 MW to 90 MW and peak efficiency > 6.5 percent per unit.
Nedre Røssåga 350 MW, Norway	1954	Redevelopment	Refurbished 3 of 6 units; expanding power capacity by 40 percent from 250 MW to 350 MW with new powerhouse and raising annual energy production (GWh) by 10 percent.
Romanche-Gavet 94 MW, France	1905	Redevelopment	Rebuilt a new underground powerhouse, replacing 6 old plants, raising installed power capacity by 15 percent and annual production increase of 155 GWh.

Moreover, the need for modernization has never been more important. With an aging global fleet, investing in today's capacity secures reliable and proven electricity supply for decades to come. In countries with ambitious plans to decarbonize the energy system, modernizing hydropower including new technologies to enhance flexibility services will help support growth in variable renewables coming onto the system.

5 Modernization Cost Benchmarking Exercise

Estimating the cost of a modernization project is notoriously difficult. Much like a greenfield hydropower project, modernization projects vary from site to site in complexity and scope and therefore costs. Furthermore, there is limited literature on the subject.

Consequently, a high-level benchmarking exercise was undertaken in order to help inform our understanding of investment cost ranges. The exercise covered 95 data points across 64 stations in 28 countries[1] focusing on projects greater than 10 MW in installed capacity and undertaken after the year 2000.[2] The cost information was drawn from both publicly available sources (e.g., company, government and IFI reports) and cost data supplied directly from station owners or operators. Publicly available information did present some problems as for several projects cost breakdowns were not reported. In such instances, discretion was used to determine how costs were apportioned but where sources were deemed unreliable, these projects were discarded.

First, Capex costs were collected, recorded in USD and divided into three main subsystems of a station:

- **Electrical installation costs**: including transformers, high voltage switchgear, electrical equipment, auxiliary electrical services and electrical control systems.
- **Electromechanical installation costs**: including key drivetrain components (i.e., generator, turbines, stators and rotors) and control structures (i.e., gates, valves and cranes).
- **Civil works costs**: including the civil infrastructure of a project such as the dam, intakes, powerhouse, penstocks, tunnels, spillways, roads and bridges.

These three categories are purposely broad due to the lack of detailed information available at a project level. This is why electrical installation costs have been combined with mechanical installation costs to create electromechanical installation costs. While generators are part of the electrical subsystem of a station, the costs associated with turbine-generator sets are typically reported together rather than separately.

Other costs which may be associated with modernization projects but were not quantified as part of this exercise included resettlement and transmission costs.

If required, costs were converted into USD and then escalated to obtain actualized costs (2020 USD), in order to make them comparable. The following formula was used:

$CAPEXn = CAPEX_0 \times (1+i)^n$

- $CAPEX_n$ = the actualized capital expenditure at year n.
- $CAPEX_0$ = the base capital expenditure at year 0.
- i = the escalation rate.
- n = the difference between year n and year 0.

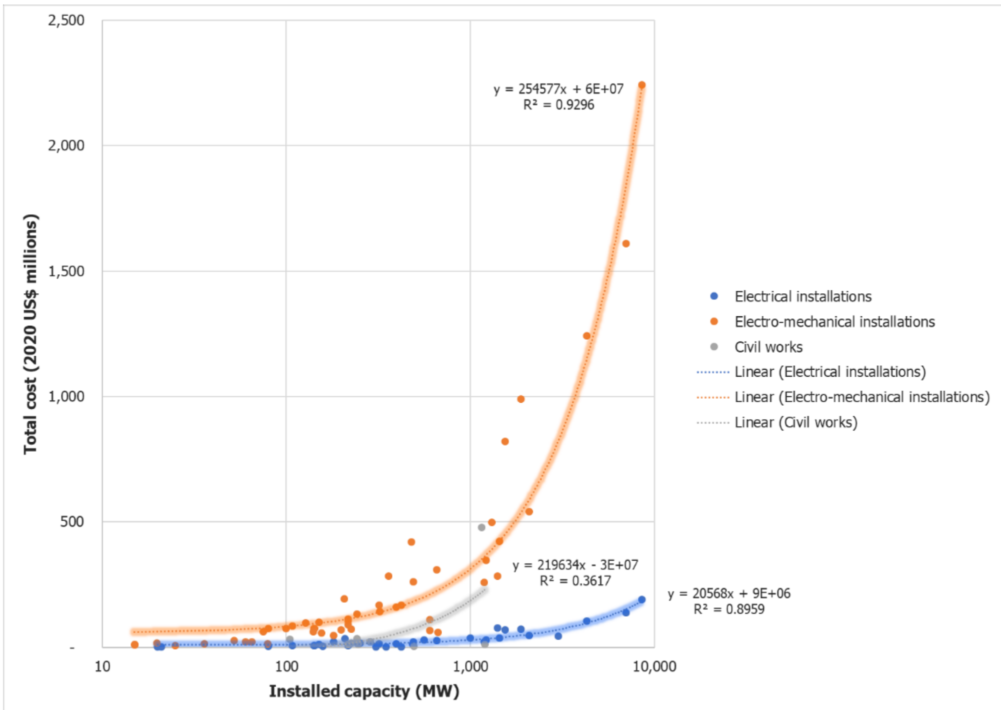
[1] Afghanistan, Argentina, Australia, Benin, Brazil, Canada, Colombia, Costa Rica, Dominican Republic, El Salvador, France, India, Kyrgyz Republic, Lao PDR, Mexico, Nepal, New Zealand, Nicaragua, Pakistan, Paraguay, Peru, Philippines, Russia, Tajikistan, United States of America, Uruguay, Ukraine, Uzbekistan, Vietnam

[2] Note that for several projects, two or even three data points were available as the information was sufficiently granular. For example, a project could have cost information on electrical installations and civil works.

In line with a recent study which focused on estimating the costs of greenfield projects across the world, an escalation rate (i) of 3 percent was adopted (Davitti A., 2018). The escalation rate refers to annual increases in prices associated with modernization projects due to inflation.

Figure 5 shows the total cost values actualized to 2020, broken down by subsystem and their distribution according to the station's total installed capacity or the capacity linked the units being impacted.[3] It is evident that both electrical and electromechanical costs, with 39 and 50 data points, respectively, were strongly correlated with capacity, allowing for a more accurate estimation.

Figure 5: Distribution of Total Modernization Cost Values Broken Down by Subsystem According to Installed Capacity (Logarithmic Scale Used)



Meanwhile, civil costs bear little relationship with the capacity of a station, reflecting that the scope of civil works can vary widely and is more dependent on the size and conditions of the structure. For example, civil works can range from raising a dam's height to rehabilitating its spillway gates which have significantly different cost implications and are not directly linked to a station's generating capacity. Civil costs can also be greatly influenced by local material and labor costs which makes estimating costs on this scale difficult.

Figure 6 shows costs as unit values per installed capacity (USD/MW) for electrical installations and electromechanical installations. Civil costs were removed due to the low correlation recorded.

The methodology used for calculating each unit value on a USD/MW basis was:

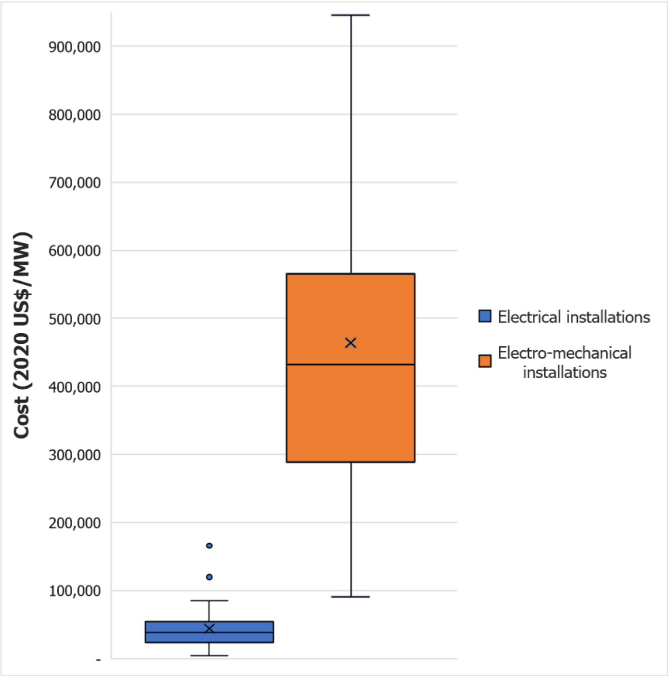
- Electrical installation cost (USD)/Total capacity of the station.

[3] Note that for electromechanical costs, the installed capacity is not the capacity for the whole station but rather the capacity directly linked to the units being impacted. For example, if only two of four 25 MW units were replaced or refurbished at a 100 MW station, 50 MW is the "installed capacity". For electrical installation costs, the total capacity of the station was used as information was not provided on a unit basis.

- Electromechanical installation cost (USD)/Capacity associated with the number of units impacted.

For electromechanical costs, the capacity of the units impacted was used as the denominator. To use the capacity of the entire station would significantly deflate the cost on a USD/MW basis and not reflect reality.

Figure 6: Distribution of Modernization Cost Values for both Electrical Installations and Electromechanical Installations on a USD/MW Basis



Note: The figure illustrates the range containing the minimum, Quartile 1 (Q1), the median, Quartile 3 (Q3), and to the maximum. The mean is marked by 'x'

With an average of USD43,630/MW, electrical installation costs represent a small percentage of the overall cost associated with modernization projects (see table 4). This closely aligns with figures provided for greenfield projects where electrical installations can typically range between 5 and 10 percent of the overall cost (O'Connor, et al).

Table 4: Range of Modernization Costs on a USD/MW Basis (2020)

	Electrical installations	Electromechanical installations
Minimum	3,491	90,988
Q1	24,020	290,923
Median	38,730	431,852
Q3	53,455	542,175
Maximum	166,027	945,427
Mean	43,630	463,815

Electromechanical costs varied by a range of over USD250,000/MW between Q1 and Q3. This can, in large part, be explained by the scope of work. Costs at the lower end of this range were generally associated with unit rehabilitation, whereas costs attributed to the replacement of the main drivetrain components (stators, rotors, turbines etc.) within the unit were at the higher end. Modernization projects that involved the rehabilitation of units tended to record average costs of below USD400,000/MW, while projects which replaced turbines and associated components incurred costs in excess of USD600,000/MW.

Moreover, even modernization projects similar in scope can vary due to the various other factors that influence costs including: access to units within the powerhouse, availability of replacement parts for non-typical unit designs, variable labor costs by country, upgrades required to undersized overhead cranes, etc. Unfortunately for much of the data gathered, detailed costs of the varying components were not provided so a deeper analysis could not be carried out. Considering the type of turbine and net head would also lead to more accurate cost estimates but this information was not available.

6 Conclusion

The study identified 21 stations (or 17 when combining stations part of a larger complex) with an installed capacity of over 6 GW in high need of modernization representing up to USD2.7 billion of estimated investment needs (see Table 5).[4] These projects, located in seven countries across South Asia and Southeast Asia, range from opportunities to rehabilitate existing infrastructure to improve efficiency and dam safety to expanding a station's capacity to meet increasing electricity demand and support the integration of variable renewables. With 11 stations identified, India had the most stations assessed as being in high need.

In addition, a further 45 stations, accounting for nearly 20 GW of installed capacity were assessed as being in medium need for modernization representing between USD7 to 11 billion of estimated investment needs. Located across 13 countries, with the benefit of further investigation and information a number of these stations could become strong and immediate candidates for modernization. This is particularly the case in Turkey, where several stations assessed as being in medium need are currently undergoing feasibility studies, the results of which are due in 2021.

Table 5: Country Overview of Modernization Needs by Number of Stations and Capacity

	Low		**Medium**		**High**	
	No. of stations	Capacity (MW)	No. of stations	Capacity (MW)	No. of stations	Capacity (MW)
Russia	28	38,439	6	2,482	0	0
India	20	10,149	14	4,945	11	3,758
Turkey	2	1,969	9	6,359	0	0
Pakistan	3	6,131	0	0	0	0
Tajikistan	2	3,245	1	600	0	0
Vietnam	4	3,105	0	0	1	400
Indonesia	4	1,664	4	1,385	0	0
Kyrgyz Rep.	5	2,870	0	0	0	0
Thailand	2	1,079	1	500	2	960
Philippines	2	626	1	739	4	793
Kazakhstan	2	1,014	2	1,136	0	0
Georgia	2	1,520	1	184	0	0
Uzbekistan	3	981	0	0	0	0
Malaysia	0	0	3	898	0	0
Lao PDR	2	672	0	0	1	155
Azerbaijan	1	424	1	380	0	0
Sri Lanka	0	0	1	201	1	210
Nepal	6	162	1	60	1	15
Myanmar	1	168	0	0	0	0
	89	**74,219**	**45**	**19,869**	**21**	**6,291**

[4] For those project costs which were estimated based on the findings of the cost benchmarking study (not the owner), the estimates only included electromechanical installation costs and therefore, are likely to be an underestimate for those stations which involve or may involve civil works.

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