IRENA
International Renewable Energy Agency

THE CHANGING ROLE OF HYDROPOWER

CHALLENGES AND OPPORTUNITIES

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About IRENA

The International Renewable Energy Agency (IRENA) is an intergovernmental organisation that supports countries in their transition to a sustainable energy future, and serves as the principal platform for international co-operation, a centre of excellence, and a repository of policy, technology, resource and financial knowledge on renewable energy. IRENA promotes the widespread adoption and sustainable use of all forms of renewable energy, including bioenergy, geothermal, hydropower, ocean, solar and wind energy in the pursuit of sustainable development, energy access, energy security and low-carbon economic growth and prosperity.

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CONTENTS

Figures

Tables

Boxes

Abbreviations

°C	degree Celsius
BEP	best efficiency point
GW	gigawatt
IDB	Inter-American Development Bank
IHA	International Hydropower Association
IFPSH	International Forum on Pumped Storage Hydropower
IRENA	International Renewable Energy Agency
KWh	kilowatt hour
LCOE	levelised cost of electricity
MW	megawatt
O&M	operations and maintenance
PSH	pumped storage hydropower
PWh	petawatt hour
TWh	terawatt hour
USD	US dollar
WETO	World Energy Transitions Outlook

KEY MESSAGES

- Hydropower is already the largest source of renewable electricity and an important part of energy systems worldwide. Whilst untapped hydropower potential is vast, **strict and transparent sustainability criteria will have to be followed to ensure that hydropower development is truly sustainable**.
- IRENA's 1.5°C Scenario suggests that if the world is to completely decarbonise and meet the climate goals set in the Paris Agreement, **hydropower installed capacity, including pumped storage hydropower, should more than double by 2050.**
- This will require **annual investments in hydropower to grow roughly fivefold**. However, as hydropower projects can struggle to attract investment, governments and decision makers need to create a suitable business environment that will attract investors.
- Most hydropower potential lies in developing countries. **Financing institutions need to work together with governments to overcome local risks and limitations**, find common ground and start funnelling much-needed investment into these regions and countries.
- **Hydropower has high value** based on its ability to provide flexible energy generation and other services, namely ancillary grid services, as well as water management and socio-economic benefits. **However, this value is not always recognised by existing markets**.
- **Regulatory frameworks and markets should take all hydropower services into account to reduce misalignment between compensation and infrastructure needs.** Attracting the nearly USD 100 billion needed in investments will require markets that support modern hydropower operations and value the wide range of hydro services appropriately.
- **Most hydropower assets were built several decades ago to operate under different conditions to those of today.** Changes and current trends in the power sector require both an acknowledgment of the value of hydropower,

and a rethinking of its future role. The increasing need to integrate variable generation resources, such as solar and wind, will lead to greater demand for grid flexibility and balancing services, and for a change in the way hydropower plants are operated and maintained.

- **The world's hydropower fleet is ageing and will need refurbishment.** This need presents an opportunity to introduce new technologies and to modernise plants to fit the requirements of today's power systems.
- **While hydropower is susceptible to climate risks, it can also be a source of resilience when projects are adequately planned.** Existing plants will have to be assessed and retrofitted where necessary to account for increased climate risks, and new projects will need to incorporate these risks in their design.
- Key actions policy makers can take to better recognise the value of hydropower and accelerate its deployment include the following:
    - Create an attractive business environment for hydropower.
        - Develop and implement policies and markets that recognise the value of the flexibility and ancillary services provided by hydropower.
        - Develop market frameworks that allow for broader participation of hydropower in energy and capacity markets (including sub-hourly markets) in countries that do not have them yet.
        - Develop incentives and financial support structures for the deployment and testing of new hydropower technologies – either for refurbishment or new development.
        - Implement a combination of closely co-ordinated incentives and regulatory streamlining that can accelerate the deployment of hydropower.
    - Create a pipeline of bankable and sustainable projects, backed with robust feasibility studies and following strict sustainability criteria.
    - Embed the concept of integrated planning in long-term energy strategies, not only focusing on the supply of energy, but also incorporating climate risks, storage needs and water management.
- IRENA's Collaborative Framework on Hydropower aims to raise awareness of current hydropower barriers, foster dialogue and the sharing of best practices among the Agency's stakeholders, and ultimately enable the deployment of the additional hydropower capacity required for the energy transition.

01 INTRODUCTION

For over a century, hydropower has contributed to global development by generating local jobs and providing affordable and reliable clean electricity. Hydropower is a very important component of power systems worldwide. It is the largest source of renewable electricity, and it enables a higher penetration of variable renewables such as solar and wind by providing balancing and flexibility services. Pumped storage hydropower (PSH) is the single-largest source of energy storage, accounting for 95% of the world's electricity storage capacity (DOE, 2020). Beyond electricity, hydropower also provides other services, including storage for drinking and irrigation water, increased resilience to flooding and droughts, and recreational opportunities.

However, despite being the most mature renewable technology, hydropower faces challenges. These include the need to ensure sustainability and climate resilience; address ageing fleets and the need for new investments; adaptation in terms of operation and maintenance (O&M) to meet modern power system requirements; and updated market structures and business models that recognise and reward all of the services provided by hydropower beyond power generation.

Modernisation, use of the latest technological advancements, along with guaranteeing social and environmental sustainability, are key to overcoming these challenges. Owing to the rising penetration of variable renewables, and as hydropower plants are increasingly called upon to operate outside conditions for which they were originally designed, markets and business models will have to adapt and appropriately reward the full suite of services provided by hydropower beyond just power generation.

This document, produced in the context of IRENA's Collaborative Framework on Hydropower, is aimed at policy makers and hydropower practitioners. It provides a snapshot of the current status of hydropower and lays out a vision of how to maximise and realise its potential. It does not aim to provide a comprehensive assessment of hydropower technologies.

02 HYDROPOWER TODAY

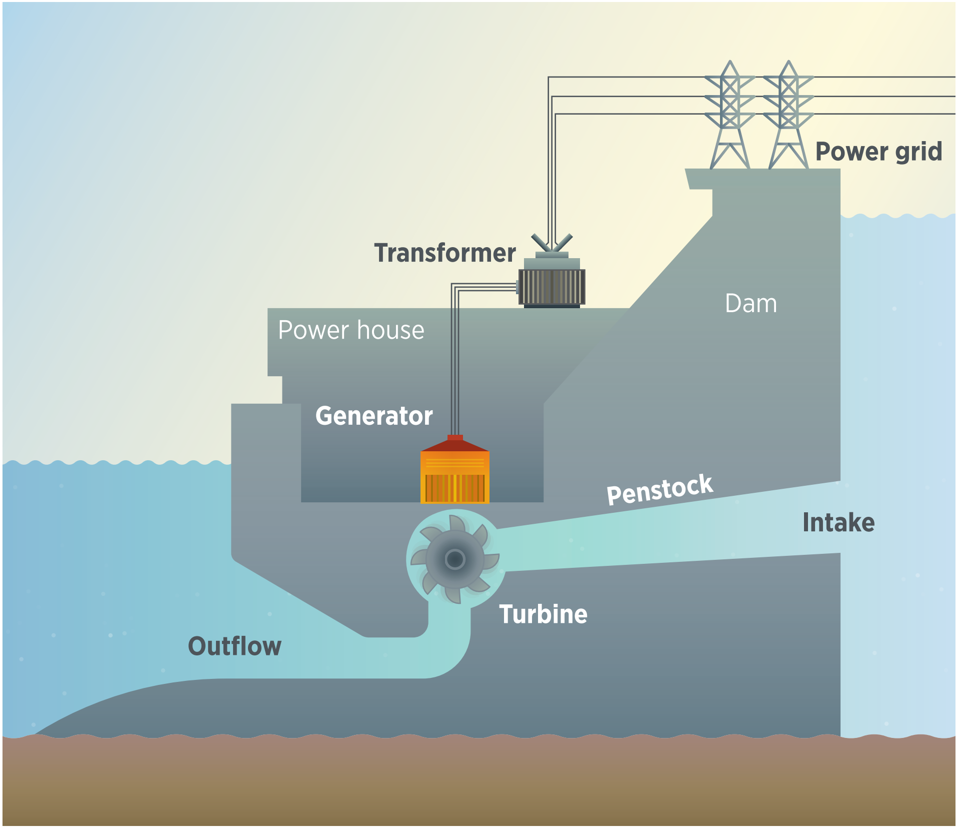
According to IRENA's latest *World energy transitions outlook*, hydropower will have to play a crucial role in keeping the rise in global temperatures to 1.5 degrees Celsius (°C), providing power, flexibility and reliable support for power systems (IRENA, 2022a). To achieve this, however, hydropower's deployment pace will need to increase substantially, especially considering the projected increase in clean electricity demand owing to the decarbonisation of end-use sectors and a rapidly ageing hydropower fleet (see section 3.1).

2.1 HYDROPOWER TECHNOLOGIES

Hydropower is a mature renewable energy technology that has been used to produce low-carbon electricity for over one hundred years. It is generally classified into three main sub-types:

- Conventional hydropower
    - Impoundment or reservoir: This is the most common type of hydropower plant, which uses a dam to store water in a reservoir. The water can be stored for various purposes but is mostly fed into a turbine that runs a generator and produces electricity, as shown in Figure 1.
    - Run-of-river: This type of plant channels water directly from a river into a penstock to rotate the turbine. It usually has very little or no storage capabilities.

Figure 1 **Generic reservoir hydropower plant**



- Pumped storage hydropower (PSH): This plant stores water at different elevations in a lower and an upper reservoir. During periods of high demand, water is released from the upper into the lower reservoir through a reversible pump-turbine to generate electricity. This process is reversed during periods of low demand, when water is pumped back into the upper reservoir. PSH plants can be open- or closed-loop systems. Open-loop systems use a natural water source as their lower reservoir, while closed-loop systems do not. While both reservoirs are "off-river" or off-channel, closed-loop systems generally have fewer environmental impacts. PSH can play a critical role as a source of flexible power storage in future power systems, enabling higher penetration of variable renewable energy generation, such as wind and solar.

This report will consider both conventional and pumped storage hydropower.

2.2 HYDROPOWER SERVICES AND BENEFITS

Hydropower is a low-carbon, renewable electricity source. However, its advantages are not limited to power generation. In fact, many of its other services are becoming increasingly important in the context of the energy transition and climate change. As seen in Table 1, hydropower plants offer a broad range of services to the grid that include balancing and ancillary services, and enjoy a high capacity factor relative to some other renewable energy sources. Additionally, hydropower can provide water services such as flood control, irrigation control, water distribution and wastewater control. Finally, water storage areas can offer recreational value through facilities such as boat ramps, beaches, picnic areas and trail systems.

Table 1 **Power-related services of hydropower**

				Hydropower plant type		
				RoR	**Reservoir**	**PSH**
Power generation				🟢	🟢	🟢
Balancing			Positive	🔴	🟢	🟢
Balancing			Negative	🔴	🔴	🟢
Ancillary services	Frequency regulation	Primary	Positive	🔴	🟢	🟢
Ancillary services	Frequency regulation	Primary	Negative	🔴	🔴	🟢
Ancillary services	Frequency regulation	Secondary	Positive	🔴	🟢	🟢
Ancillary services	Frequency regulation	Secondary	Negative	🔴	🔴	🟢
Ancillary services	Frequency regulation	Tertiary	Positive	🟢	🟢	🟢
Ancillary services	Frequency regulation	Tertiary	Negative	🟢	🔴	🟢
Ancillary services	Non-frequency regulation	Voltage support		🟢	🟢	🟢
Ancillary services	Non-frequency regulation	Active power-loss compensation		🟢	🟢	🟢
Ancillary services	Non-frequency regulation	Black start		🟢	🟢	🟢

Note: The green circles indicate that a plant can provide this service while the red circles indicate it cannot. Positive balancing refers to the ability to supply the correct amount of electricity to the grid to meet fluctuations in demand. Negative balancing would imply consuming electricity to counter oversupply. Positive frequency regulation refers to the act of feeding energy to the grid in order to increase the system frequency and level out frequency deviations. Negative regulation requires consuming energy from the grid. PSH = pumped storage hydropower; RoR = run-of-river.

Adapted from: Gaudard and Romerio (2014).

2.3 POTENTIAL

Despite being the largest renewable power source in terms of both installed capacity and power generation, hydropower has yet to be fully exploited. As shown in Table 2, hydropower potential has been estimated in a number of studies with varying results, although all results confirm that considerable potential remains. This finding is particularly important when considering that hydropower is one of the cheapest forms of renewable electricity and has levelised cost of electricity (LCOE) values that are among the lowest of all power generation technologies (see section 2.5).

Table 2 **Global hydropower potential**

Hydropower potential	PWh/year
Theoretical	31-127
Technical	13-31
Economic	9-15

Note: PWh = petawatt hour.

Source: Lehner, Czisch and Vassolo (2005); Fekete *et al.* (2010); Pokhrel, Oki and Kanae (2008); Zhou *et al.* (2015); Hoes *et al.* (2017); Gernaat *et al.* (2017).

Gernaat *et al.* (2017) conducted a high-resolution assessment of global hydropower potential, concluding that total global hydropower potential is around 50 petawatt hours per year (PWh/year). They also estimate a potential of 5.7 PWh/year below USD 0.1/kilowatt hour (kWh)[1] and an ecological[2] potential of 3.3 PWh/year below USD 0.1/kWh. To put this into context, 3.3 PWh/year is equivalent to over three-quarters of the global hydropower generation in 2018 (4.2 PWh/year). Most of this potential lies in Asia, South America and Africa – regions where continued growth and economic development are expected.

[1] *The fossil-based LCOE range in 2019 was USD 0.05-0.18/kWh (IRENA, 2020).*

[2] *Ecological restrictions require hydropower plants to release at least 30% of the discharge to maintain natural river flow and a preference for small reservoirs.*

Glacier conservation should undoubtedly be a top priority. Using these areas for water storage could mitigate some of the impacts of ice retreat, such as diminishing water resources and changes in run-off. A study by Farinotti *et al.* (2019) investigates the hydropower potential offered by areas that are expected to become ice free during the course of this century due to the changing climate. In this study, they estimate a theoretical hydropower potential of 0.8-1.8 PWh/year, of which around 40% would be feasible for realisation (0.3-0.7 PWh/year). Three-quarters of the potential storage volume could be ice free as early as 2050. In this case, it is estimated that the predicted storage volume would be enough to retain about half of the annual run-off leaving these sites.

Hydropower can also provide long-term energy storage services through PSH configurations. As seen in Figure 2, the Australian National University, in their Global Pumped Hydro Atlas, identified 616 000 potentially feasible PSH sites globally with a storage potential of 23 terawatt hours (TWh) (RE100, 2019). Similarly, Hunt *et al.* (2020) estimate that the potential for seasonal PSH below a cost of USD 0.05/kWh is 17.3 PWh/year, justifying the very large potential with a lower land requirement of seasonal PSH compared to conventional hydropower dams. This potential is substantially larger than the storage required by the transition, which is roughly equivalent to 80% of the world's electricity generation and extremely important for the hydropower industry, given the growing value of its flexibility and balancing capabilities.

Finally, hydropower does not necessarily need to be considered in isolation. Some sites offer the possibility of developing hybrid projects (*e.g.* wind/hydro or floating photovoltaic [PV]/hydro), opening the possibility of deploying even more renewable capacity. According to one study, the technical potential for installing floating solar PV on existing reservoirs worldwide reaches 4.2-10.6 PWh/year (Lee *et al.*, 2020), equivalent to over a third of the world's electricity generation.

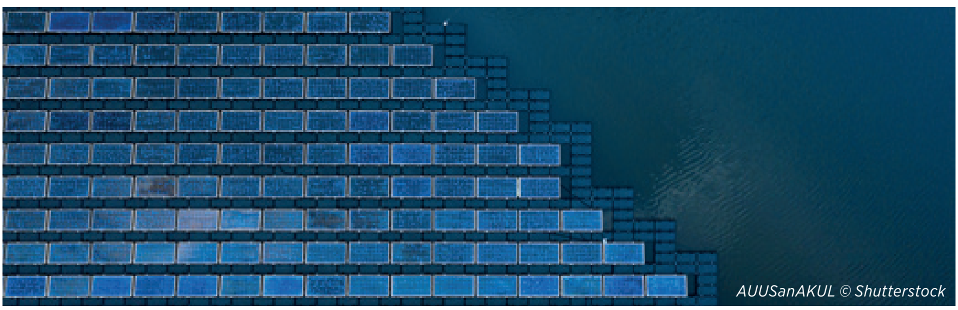


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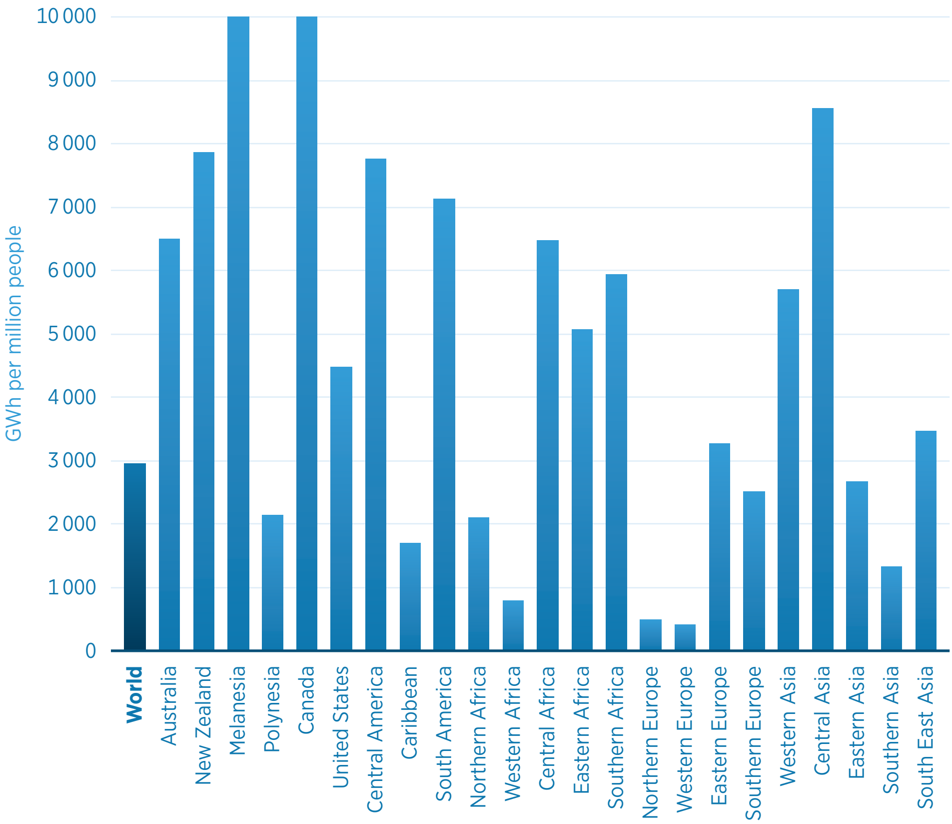
Figure 2 **Energy storage potential by region**



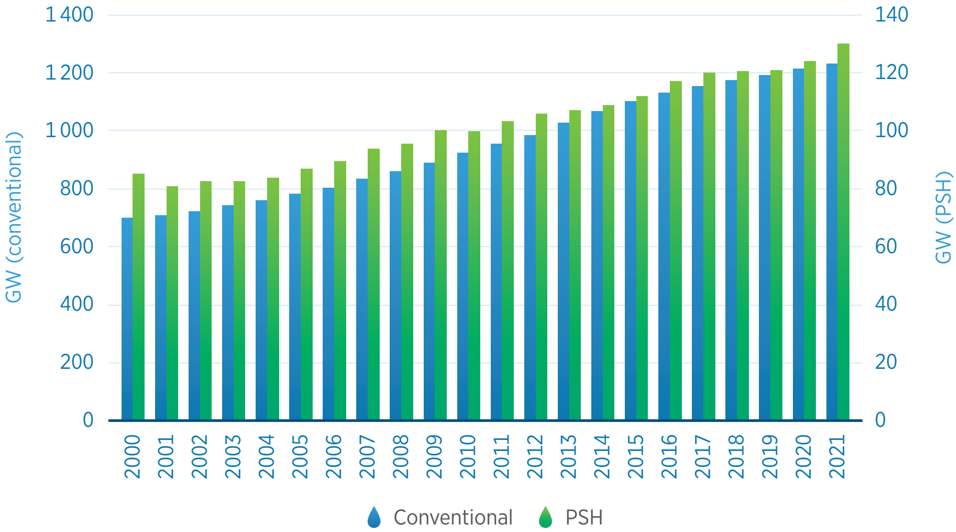
Note: GWh = gigawatt hour.

Source: RE100 (2019).

2.4 CURRENT DEPLOYMENT

Hydropower is the most mature renewable energy technology, with its first projects dating back to the late 1800s. Figure 3 shows that significant progress has been made, with conventional hydropower growing by more than 75% in 2000-2021, reaching an installed capacity of over 1230 gigawatts (GW). PSH capacity, on the other hand, grew by over 50% in the same period, reaching 130 GW in 2021. Together, they account for over 50% of global renewable installed capacity.

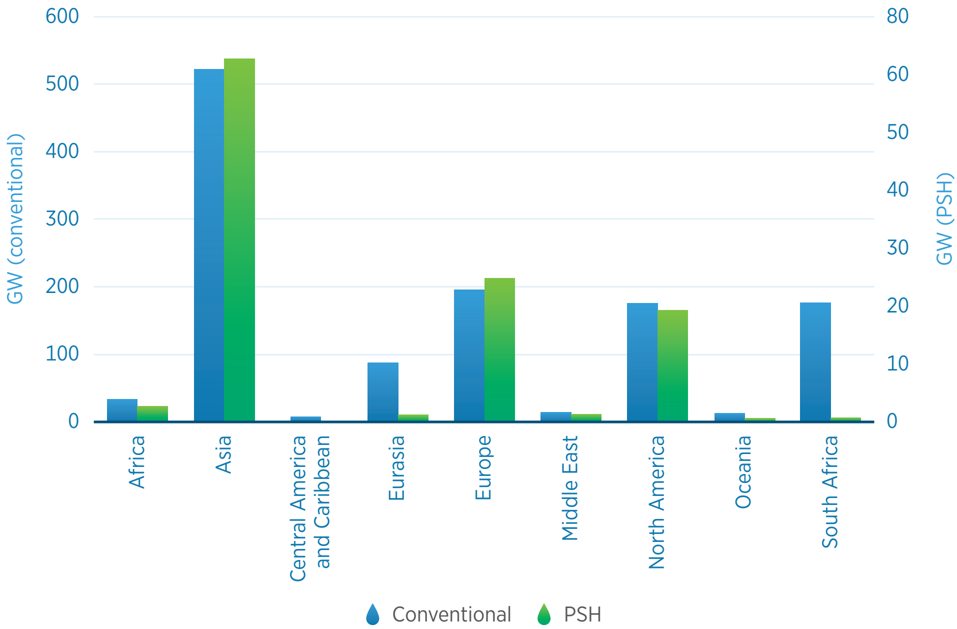
Figure 3 **Hydropower installed capacity by year, 2000-2021**



Note: GW = gigawatt; PSH = pumped storage hydropower.
Source: IRENA (2022b).

In terms of geographic distribution, Figure 4 shows that the majority of the world's hydropower capacity is in Asia (42%), followed by Europe (17%), North America (15%), South America (13%), Eurasia (7%) and the rest of the world (6%). It is noteworthy that for most regions, PSH represents 9-13% of total hydro installed capacity; however, it is almost completely absent in Latin America, apart from a few plants in South America (<1 GW).

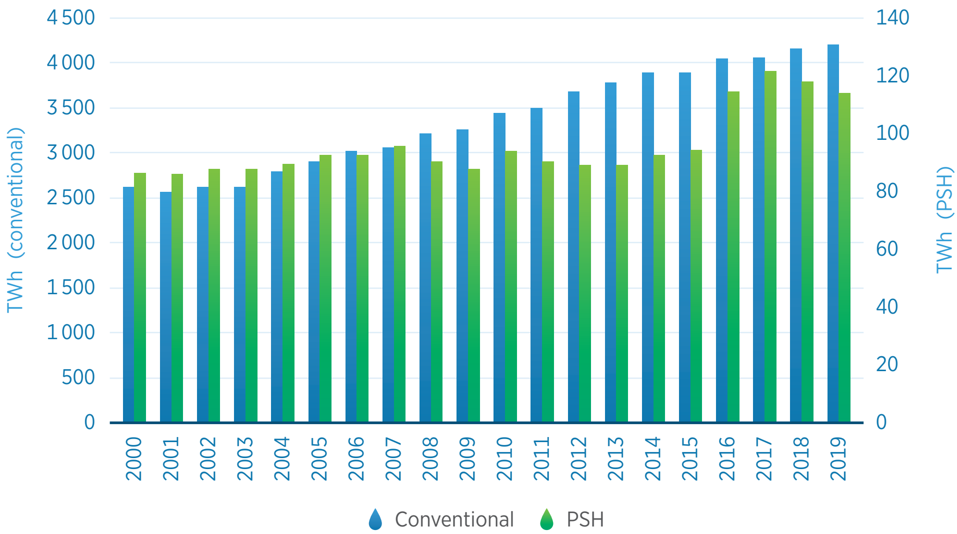
Figure 4 **Hydropower installed capacity by region, 2021**



Note: GW = gigawatt; PSH = pumped storage hydropower.
Source: IRENA (2022b).

Hydropower is also the largest source of renewable electricity globally. As shown in Figure 5, hydropower generated approximately 4.3 PWh of electricity globally in 2019, which is equivalent to 65% of all renewable generation or over 16% of all electricity generation. This makes hydropower extremely important not only as a renewable generation source, but for power systems worldwide, particularly since hydropower is also able to offer clean flexibility and balancing services to power grids. China is the largest producer of hydropower globally (1.3 PWh/year), followed by Brazil (0.4 PWh/year), Canada (0.4 PWh/year) and the United States (0.3 PWh/year).

Figure 5 **Global hydropower electricity generation, 2000-2019**



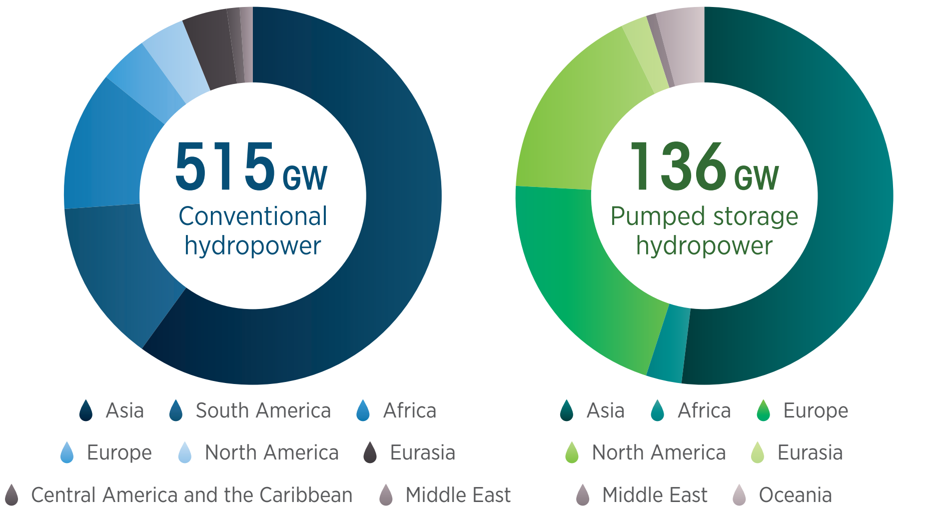
Note: TWh = terawatt hour; PSH = pumped storage hydropower.
Source: IRENA (2022c).

As Figure 6 shows, beyond these numbers, there are approximately 650 GW of hydropower already in the project pipeline with plans to come on line in the next 25 years, including 136 GW of PSH[3] (S&P Global, 2022). The vast majority of these projects will be deployed in Asia, which accounts for almost 60% of conventional capacity and over 50% of the total PSH capacity in the project pipeline.

[3] The Power Construction Corporation of China unofficially announced plans to start construction of 270 GW of PSH capacity by 2025 (Bloomberg, 2022). Figure 6 does not include this figure and contemplates only 40 GW of PSH in the pipeline for China.

In terms of conventional hydropower, South America and Africa follow with 14% and 12% of the capacity in the pipeline, respectively. In terms of PSH, Europe and North America follow Asia, with 21% and 17% of the pipeline, respectively. Similar to what was observed above, there are virtually no PSH projects in the pipeline in Latin America, except for the 300 megawatts (MW) in Chile.

Figure 6 **Hydropower project pipeline, 2022-2037**



Note: GW = gigawatt.
Based on: S&P Global (2022).

A regional overview of the numbers presented above can be found in Appendix B.

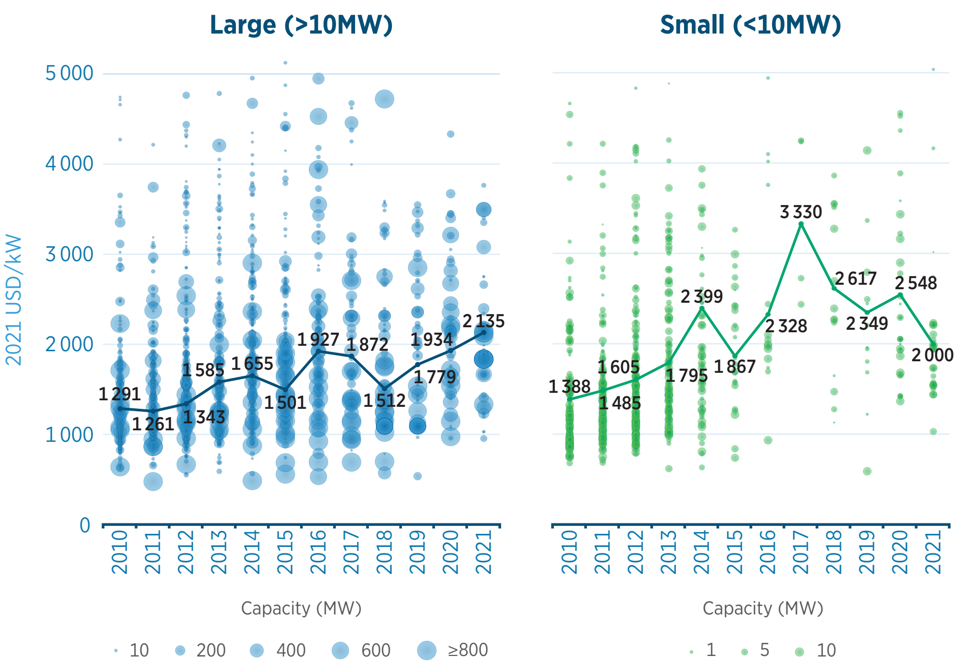
2.5 COSTS AND INVESTMENT TRENDS

Hydropower costs

Hydropower costs are site specific and depend on a project's size and specification, with the largest cost component being the civil works, which account for roughly 45% of the costs and include the construction of the dam, tunnels, canal and powerhouse, as well as any other infrastructure needed to access the site. This is followed by the procurement costs of the electromechanical equipment, which account for roughly 33% of the total costs (IRENA, 2022d).

Total installed costs for newly commissioned hydropower plants have risen over the past decade, as seen in Figure 7. The global weighted-average total installed cost of new hydropower in 2021 was USD 2 135/kW for large projects and USD 2 000/kW for small projects. The increase in total installed costs could be partly attributed to the fact that the best hydro sites have already been developed and countries are now trying to develop hydropower in less than ideal sites with higher than average installed costs. Another important component is the share of new deployments in each region, as they have different costs (*e.g.* total installed costs for large hydropower are highest in Oceania and Central America and the Caribbean, while the lowest are in China and India) (IRENA, 2022d).

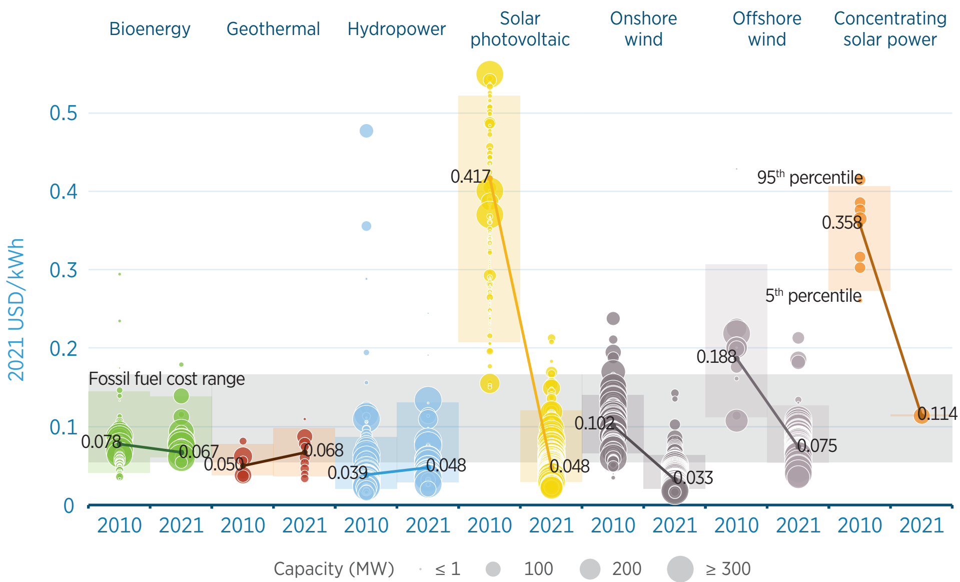
Figure 7 **Hydropower's total installed costs, global weighted average, 2010-2021**



Note: kW = kilowatt; MW = megawatt.
Source: IRENA (2022d).

Despite being highly capital intensive, hydropower is one of the cheapest sources of electricity. As seen in Figure 8, the global weighted average LCOE of utility-scale hydropower projects was USD 0.048/kWh in 2010-2021 – lower than any fossil-fuel-based alternative and only bettered by the LCOE of onshore wind power. LCOE values can vary substantially, first because of the investment costs, which are site dependent, but also depending on how the plant is designed to operate (to provide base or peak load, ancillary services, *etc.*) and the capacity factors achieved (IRENA, 2022d).

Figure 8 **Levelised cost of electricity for utility-scale renewable power generation, global weighted average, 2010-2021**



Note: kWh = kilowatt hour; MW = megawatt.

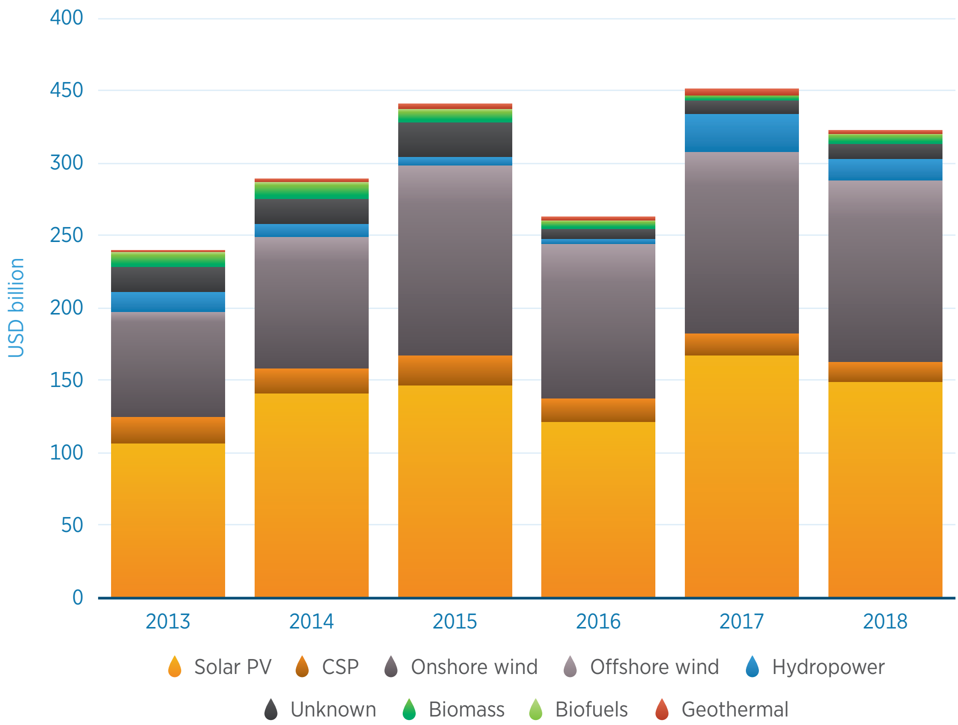
Source: IRENA (2022d).

For a more comprehensive analysis of hydropower costs, please refer to IRENA's latest *Renewable power generation costs* report (IRENA 2022d).

Investment trends

Renewable energy deployment is growing at a considerable pace, attracting USD 1.8 trillion in investment between 2013 and 2018 (IRENA and CPI, 2020). However, despite being one of the cheapest sources of renewable electricity, over the last decade, investments in hydropower have been dwarfed by investments in solar PV and wind technologies, as shown in Figure 9. Over that same period, approximately USD 72 billion were invested in hydropower. This amount is equivalent to roughly 4% of all investments in renewable energy – a relatively small amount, especially when considering that it is a mature technology that generates around 65% of all renewable electricity.

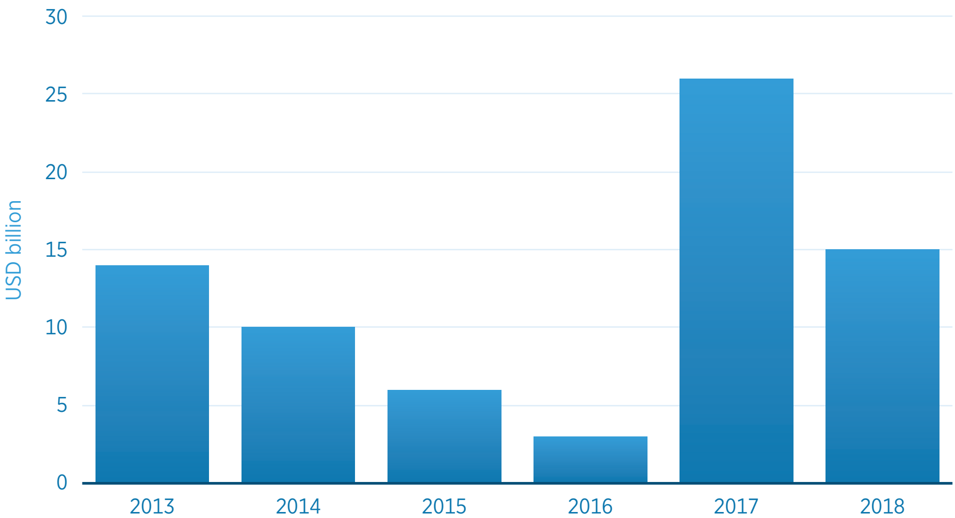
Figure 9 **Annual financial commitments in renewable energy by technology, 2013-2018**



Note: CSP = concentrated solar power; PV = photovoltaic.
Source: IRENA and CPI (2020).

Figure 10 provides an overview of the financial commitments in hydropower between 2013 and 2018. As can be seen, hydropower investments decreased gradually from 2013 to 2016 before increasing substantially in 2017. Together, hydropower investments in 2017 and 2018 totalled USD 26 billion and USD 15 billion, respectively, and were larger than the combined investments in the previous four years. Finally, in terms of sourcing, 75% of the USD 72 billion invested between 2013 and 2018 corresponded to public investment, leaving the private sector with only one-quarter of the total investment during that period (IRENA and CPI, 2020).

Figure 10 **Annual financial commitments in hydropower, 2013-2018**



Source: IRENA and CPI (2020).

03 PRESENT CHALLENGES AND OPPORTUNITIES

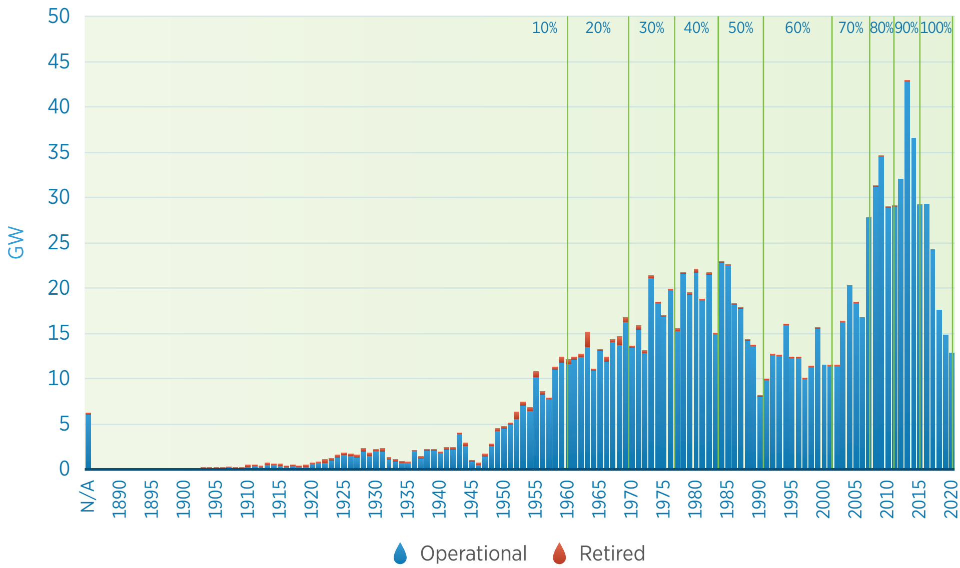
Despite being the most mature renewable technology, hydropower is not without its challenges. These include changing water flows due to climate change, social and environmental impacts, an ageing fleet and changing power system requirements that increasingly require hydropower plants to operate in ways they were not originally designed to. These challenges call for additional investments in hydropower in the form of modernisation, including refurbishment, and new capacity to cope with present and future power system requirements. Attracting finance is a challenge due to the nature of hydropower development and its timelines, an issue that will be addressed in this chapter. Also important is the need for new business models and market structures that appropriately reward the services, other than power generation, that hydropower can provide and that are increasingly more valuable, like flexibility and balancing services.

3.1 AGEING FLEET

Hydropower has been providing renewable electricity around the world for over a century. Inevitably, this also means that a large number of power plants are quite old, given their extremely long lifetimes. Historically, hydropower plant lifetimes have varied substantially from plant to plant, ranging from less than 10 to over 100 years. An analysis of the global hydropower fleet shows that the average age of hydropower plants in operation is close to 40 years, while the average lifetime of already retired hydropower plants was around 60 years (S&P Global, 2022).

Figure 11 provides a breakdown of the global hydropower capacity by year of commissioning. The data support the points raised above, showing that hydropower plants are indeed aged. However, they also indicate that over 50% of the world's hydropower installed capacity (roughly 620 GW) is over 30 years old and approximately 25% (roughly 275 GW) is over 50 years old. These values are only indicative since some of these plants have already been refurbished. A detailed and accurate overview of the remaining useful life of the global hydropower fleet would necessitate a plant-by-plant assessment. However, it is clear that ageing fleets already present a real challenge in several countries and could eventually become a challenge for others. Andritz (2019) estimates that 50% of the primary and secondary equipment installed worldwide is more than 40 years old.

Figure 11 **Global hydropower capacity by year of commissioning**

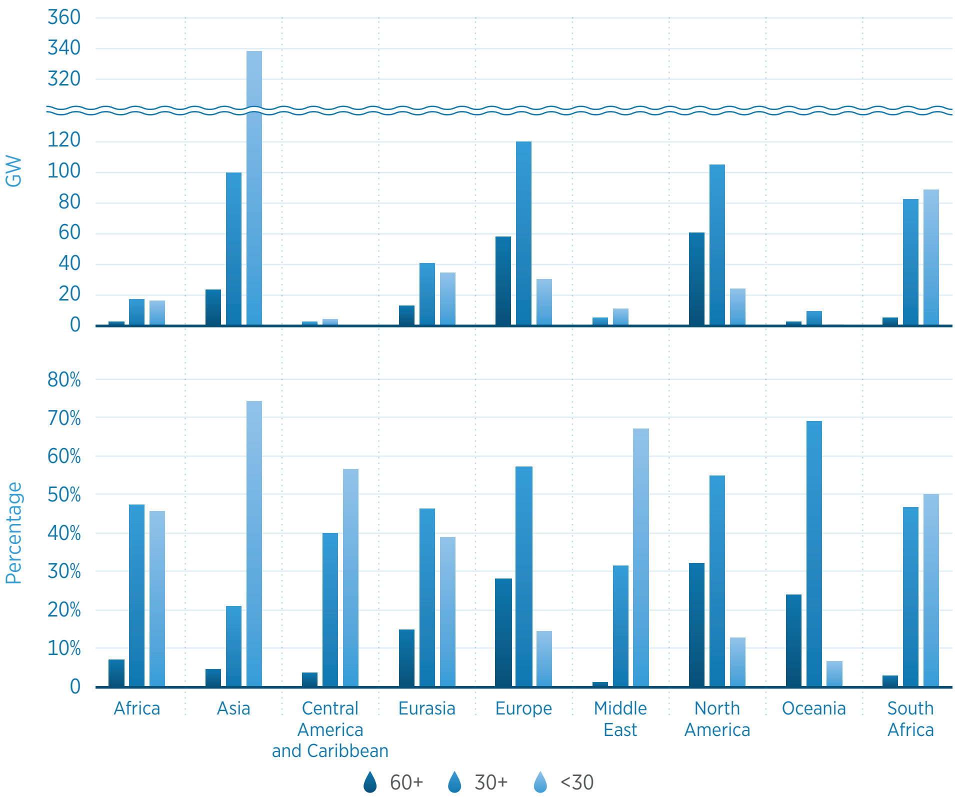


Note: Data include pumped hydropower storage. Data points with no commissioning date are grouped under N/A. The green vertical lines with percentages indicate the share of the total operational hydropower capacity commissioned by a certain year, *e.g.* 10% of the global capacity was commissioned before 1960. GW = gigawatt; N/A= not available.

Based on: S&P Global (2022).

As Figure 12 demonstrates, this issue does not currently affect all regions equally. Regions like Europe, North America and Oceania have considerably older fleets than others such as Africa, Asia, the Middle East and South America, where most of the hydropower assets were commissioned in the last 30 years. In this regard, there appears to be a clear distinction between developed and developing economies, as developed economies began exploiting their hydropower resources earlier and therefore have more urgent refurbishment needs. However, the issue of an ageing fleet and refurbishment needs will eventually become relevant for all regions. This highlights the need for countries with older plants to act urgently and modernise their fleets. Even countries with relatively new fleets can already start planning and making provisions for the eventual modernisation of their plants, as it may take some time to deploy the necessary resources.

Figure 12 **Breakdown of hydropower fleet age by region**



Note: Data include pumped hydropower storage. GW = gigawatt.

Based on: S&P Global (2022).

The global hydropower fleet is reaching a tipping point, where a large share of the installed capacity will soon require upgrades, refurbishment or possibly retirement. All options will require considerable investments in the form of capacity additions or maintenance costs if capacity is to be maintained on line. It is important to highlight that different components have different lifetimes, as shown in Table 3.

Table 3 **Lifetimes of selected hydropower plant components**

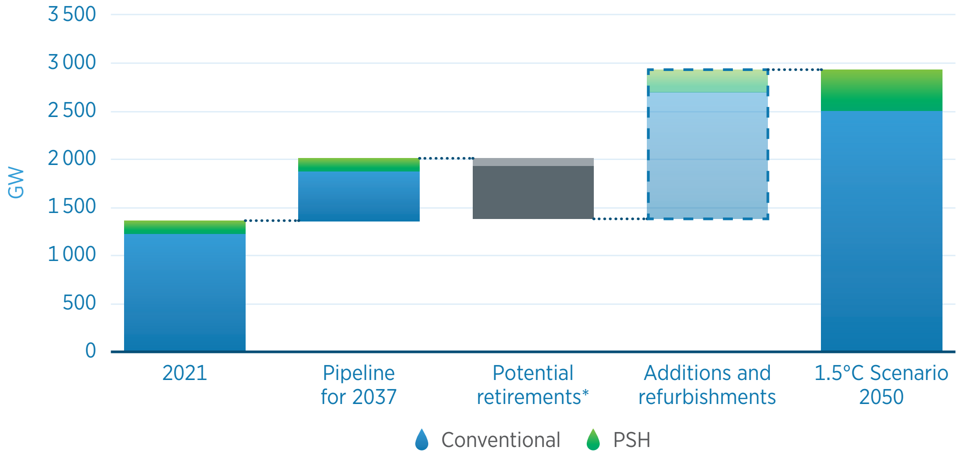
	Economic lifetime (years)	Technical lifetime (years)
Electrical installations		
Generators, transformers	25-40	30-60
High-voltage switchgear, auxiliary electrical equipment, control equipment	20-25	30-40
Batteries, direct current equipment	10-20	20-30
Mechanical installations		
Turbines		
Kaplan and Francis turbines	30-40	30-60
Pelton turbine	40-50	40-70
Pump turbine and storage pumps	25-33	25-50
Gates, butterfly valves, special valves, cranes, auxiliary mechanical	25-40	25-50
Civil works		
Dams, canals, tunnels, caverns, reservoirs, surge chambers	60-80	80-150
Powerhouse structures, water catchment, spillway, sand traps, penstocks, steel linings, roads, bridges	40-50	50-80

Source: Goldberg and Espeseth Lier (2011).

IRENA's 1.5°C Scenario suggests that if the world is to completely decarbonise and meet the climate goals outlined in the Paris Agreement by 2050, hydropower installed capacity should reach roughly 3 000 GW, including 420 GW of PSH (IRENA, 2022a). As shown in Figure 13, when considering the present installed capacity (1 360 GW), the current pipeline (652 GW) and the potential plant retirements by 2050[4] (630 GW), capacity additions and/or refurbishments amounting to 1 545 GW will be needed.

[4] *Assuming an average lifetime of 60 years for a hydropower plant.*

Figure 13 **Necessary hydropower capacity additions by 2050**



Note: *Dark grey represents potential retirements of conventional hydropower capacity. Light grey represents potential retirements of PSH capacity. This was calculated assuming a 60-year average lifetime for a hydropower plant. GW = gigawatt; PSH = pumped storage hydropower.

Based on: IRENA (2022a, 2022b); S&P Global (2022).

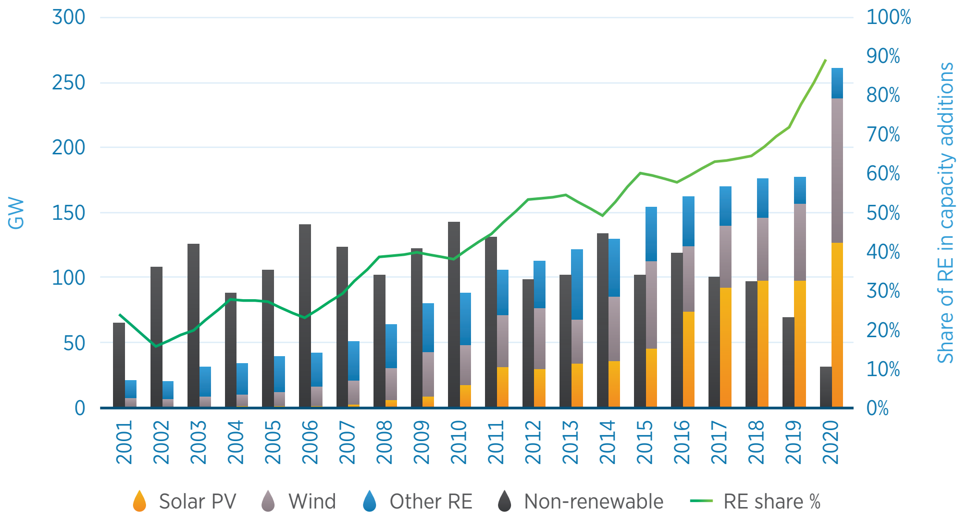
To put this number into perspective, the average capacity of hydropower projects in the pipeline is 160 MW (S&P Global, 2022), which means that in the coming decades thousands of new hydropower plants would need to be deployed globally at a rate of 53 GW/year until 2050. Given the long planning and construction time that hydropower projects require, countries need to start making considerable investments and developing additional hydropower capacity in the short term if the Paris Agreement's climate goals are to be met. That being said, not all of the capacity has to come from greenfield projects; for example, existing facilities can benefit from capacity increases, and non-powered dams can be retrofitted to generate electricity. Research estimates that roughly 78 GW could be added through these two options (Garrett, McManamay and Wang, 2021).

The advanced age of a large share of the global hydropower fleet is indeed a pressing challenge. However, it is also the perfect opportunity to modernise using the latest technological advancements, including cutting-edge components that can increase plants' efficiency, flexibility and sustainability. Also, digitalisation, artificial intelligence and big data can improve operations and facilitate decision making. This will enable hydropower to adapt to the increasingly complex requirements of present and future power systems with high shares of variable renewables and continue to provide valuable energy services reliably in the future.

3.2 CHANGING POWER SYSTEMS

In recent decades, renewable capacity additions have increased substantially. As seen in Figure 14, by 2012, renewable generation capacity additions had already exceeded those of non-renewables, and in 2020 nearly 90% of net capacity additions were renewable, with solar PV and wind technologies accounting for almost 90% of these additions. While this trend undoubtedly signifies great progress towards the decarbonisation of the power sector, it also implies the need for significant changes in power systems and the way they are managed. As the share of variable renewables in power grids increases, they require more flexible resource capabilities to ensure grid reliability.

Figure 14 **Comparison of renewable and non-renewable net capacity additions, 2001-2020**

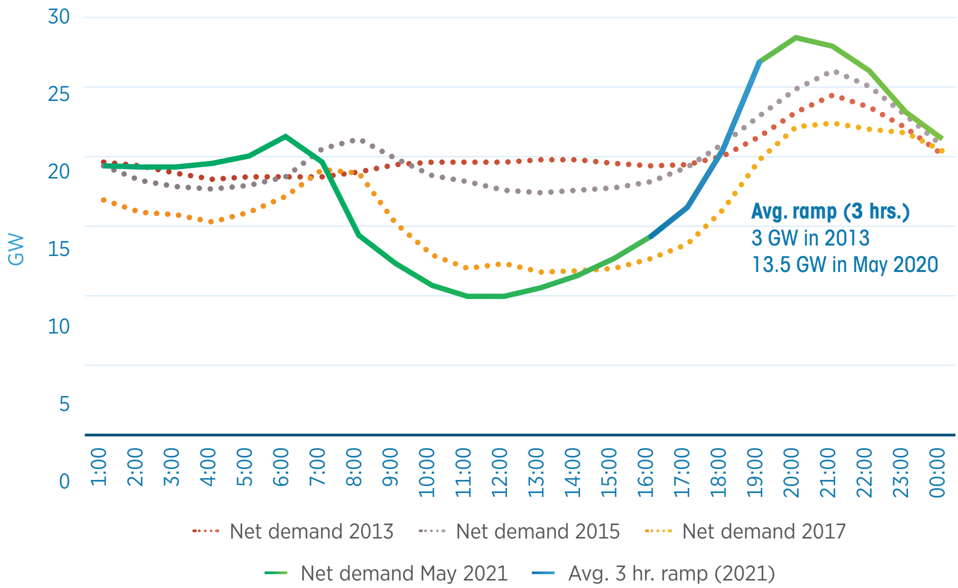


Note: GW = gigawatt; PV = photovoltaic; RE = renewable energy.
Sources: IRENA (2019, 2022b); IEA (2021a).

Since variable renewable energy (VRE) sources are non-dispatchable, their availability might not necessarily match the times at which the energy is actually needed most; for example, solar electricity production is at its peak at mid-day when electricity demand may not be at its highest. For this reason, system operators increasingly need to rely on dispatchable electricity sources like hydropower for frequency control, energy storage and peak load supply.

As more variable renewables are added to the grid, the ramping requirements increase, and so does the risk of oversupply and possibly curtailment during periods of low demand. To illustrate what is known as the "duck curve", Figure 15 shows the evolution of net demand (total demand minus the demand met by VRE sources) in California, a state with a high share of variable renewables which have at times covered over 75% of electricity demand. An increase in ramping requirements is evident here: the three-hour ramping requirement in 2013 was close to 3 GW, compared to over 13.5 GW on a spring day in 2020.

Figure 15 **Net demand curve for a spring day in California in 2020**



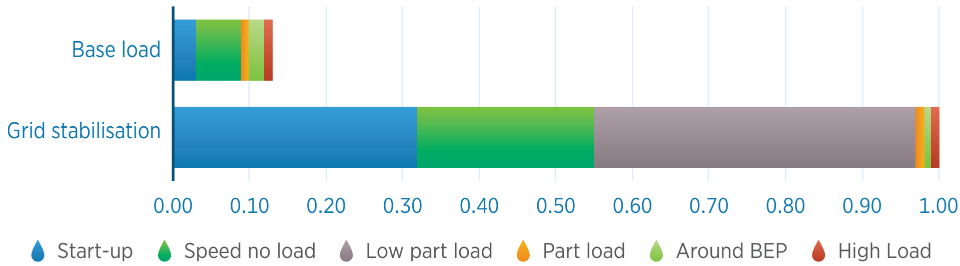
Note: Net demand is the demand not met by solar or wind generation. GW = gigawatt.
Source: CAISO (2022).

Operational consequences

Most hydropower plants were planned, designed and built to operate under different conditions to those of today, and therefore they are not unaffected by the changing power system. Historically, hydropower has been a source of base load generation. However, it is increasingly used as peaking capacity and as a source of ancillary services. This results in plants having to operate at partial loads more frequently, with a substantial increase in their number of start-stop cycles.

This change in hydropower operation modes introduces additional wear and tear, shortening the lifespan of important plant components like the turbine, increasing downtime and O&M costs. To exemplify this, Seidel *et al.* (2020) compared a base load and a grid stabilisation scenario for a Francis turbine (see Figure 16) and found that the latter scenario shortened the fatigue life of the turbine by approximately one order of magnitude.

Figure 16 **Relative operational damage contributions to a Francis turbine**



Operational mode	Start-up [cycles/ day]	Speed no load [%]	Low part load [%]	Part load [%]	Around BEP [%]	High load [%]
Base load	1	1	0	25	49	25
Grid stabilisation	10	4	24	24	24	24

Note: The baseload scenario considers one start-up cycle per day. BEP = best efficiency point (*i.e.* is the flow at which the turbine operates at its highest efficiency).
Source: Seidel *et al.* (2020).

Financial consequences

The other consequences of this change in operations are financial. The outdated design of many hydropower projects can affect their revenue streams and their ability to be profitable. Increased downtime, higher O&M costs and reduced power generation volumes are factors at play.

In the case of PSH, most plants were built decades ago around day-night arbitrage business models to compete with oil- and gas-based peaking capacity. However, when fuel prices are low, and as combustion efficiencies improve, day-night arbitrage may be insufficient to justify the investment in a PSH plant (ANL, 2014). PSH can offer benefits to the grid that fossil-fuel-based power plants cannot, such as storage and flexibility capabilities that enable higher variable renewable shares.

However, the value of these services is hard to define with precision and, therefore, hard to reward appropriately. This is a crucial topic that is the focus of substantial research and where policy interventions are needed. One thing is certain though, as variable renewable shares in power systems grow, the value of storage and ancillary services provided by hydropower increases as well, and so does the importance of adequately rewarding the provision of these services and maintaining the profitability of hydropower projects.

3.3 INVESTMENT NEEDS

As detailed in sub-section 3.1, substantial hydropower capacity additions will be needed if the clean energy transition is to materialise. However, this cannot happen without substantial investments to finance the construction and refurbishment of all these hydropower projects. IRENA's *World energy transitions outlook* estimated that if the climate goals are to be achieved by 2050, the necessary investments in conventional hydropower and PSH amount to USD 85 billion/year and USD 8.8 billion/year, respectively (IRENA, 2022a). This is more than three times the investment in hydropower seen in 2017, and more than five times the investment in 2018. This highlights the urgency for governments to put in place policies that boost hydropower project bankability and incentivise investment in the technology, especially when considering its long development timeframes.

Reaching the necessary level of investment is not an easy task, particularly because investing in hydropower can be more challenging than investing in other renewable energy technologies for a number of social, technical, regulatory and market-related reasons, including:

- **Capital intensity and site specificity:** Hydropower, like some other renewable technologies, is capital intensive. However, it is also highly site specific. This results in the need to have multiple components individually designed for a specific project, unlike solar or wind projects that rely on standardised panels or turbines, a fact that impacts time and cost. Furthermore, due to the difficulty in precisely predicting geotechnical conditions before construction starts, unexpected costs and delays can occur (Markkanen and Plummer Braeckman, 2019).

- **Limited sources of financing:** Hydropower financing requires long-tenor loans, making it more unattractive for private investors than other shorter-term projects. Furthermore, hydropower usually has high construction risks. Higher-risk projects are less attractive to private finance and thus may need public finance, although they can be developed and financed as public-private partnerships (IFC, 2015).

- **Social and environmental concerns:** Despite having made great progress in terms of sustainability over the last few decades, hydropower still has a reputation for being less sustainable than many other renewable energy technologies. This is mostly caused by the fact that when hydropower projects are not adequately planned or managed, the consequences can be catastrophic, something that has unfortunately happened in the past and which highlights the need for significant regulatory oversight to ensure safety and environmental support. That being said, adequately planned and managed hydropower projects can minimise environmental impacts while offering substantial socio-economic benefits, some of which are mentioned in section 2.2. To further clarify this last point, an assessment carried out by the World Bank's Independent Evaluation Group found that over 90% of the Bank's evaluated hydropower investments complied with the applicable environmental and social safeguards and performance standards (World Bank, 2020).

- **Regulatory uncertainty:** The process of granting a concession for a hydropower project is much longer and more complex than that of other renewable energy technologies, such as solar and wind power. Hydropower makes use of hydrologic resources, therefore, it is not as simple as making a plot of land available. This complexity can cause delays and uncertainty in the development of projects (Markkanen and Plummer Braeckman, 2019). Furthermore, environmental complexity, unclear information, lack of expertise and limited human capacity in licensing authorities can cause delays (Levine, 2021).

- **Inadequate valuation:** Not all of the value of a hydropower plant can be quantified in monetary terms, which causes a disparity between financial and economic viability. Hydropower projects tend to be valued on their capacity to generate electricity while overlooking other benefits like increased grid flexibility and reliability, increased resilience to floods and droughts, and multiple other socio-economic benefits that are difficult to quantify (more on this can be read in section 4.1). Furthermore, ancillary services provided by hydro plants are not always rewarded appropriately by grid operators, an issue that is especially challenging for PSH plants.

- **Lack of bankable projects:** The number of fully studied projects available is limited and many of the most promising are located in developing economies. Some of these developing economies might not have the necessary credit ratings, which makes projects in these economies more difficult to finance, even when capital is available (Markkanen and Plummer Braeckman, 2019).

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04 HYDROPOWER FOR THE FUTURE

Hydropower will be essential for the decarbonisation of the energy sector. However, for hydropower to have a bright future, it needs to keep up with the changing times, which means that some aspects need to be improved and some adjustments need to be made. This applies across the hydropower sector, relevant markets, and regulators and other stakeholders. This chapter will describe the changes necessary.

4.1 SUSTAINABILITY

Renewable energy projects must be sustainable and resilient. Hydropower is no exception since poor planning and management can have considerable and unfortunate impacts on society and the environment. Examples include forced resettlement, the alteration of river flow regimes, the fragmentation of ecosystems and the changing of habitats. To avoid this, new hydropower projects need to be planned and implemented, prioritising the minimisation of the negative social and environmental impacts without compromising their ability to generate electricity and provide ancillary and water services. This can be achieved by ensuring that adequate measures that protect communities, water flows, water quality and local species are embedded throughout the development and operation of hydropower projects.

Like any other infrastructure project, the environmental impacts of hydropower projects cannot be completely avoided. However, impacts can be minimised or offset. For example, when it comes to PSH, closed-loop schemes generally have lower environmental impacts than open-loop schemes, mainly due to their higher siting flexibility and the fact that they are located offstream (PNNL, 2020). In this sense, countries considering new PSH systems might want to prioritise the deployment of closed-loop systems. The impacts can further be reduced if projects make use of pre-existing infrastructure, such as mines and quarries. Furthermore, environmental impacts can be offset by the benefits offered by multipurpose hydro projects. For example, research has shown that the water storage capacity provided by dams can supply additional water for irrigation, drinking and industrial use, as well as flood regulation, which all translate to economic benefits. Some of these benefits can be funnelled into efforts such as afforestation, which can offset some of the environmental costs of submerged areas due to dam construction (Amjath-Babu *et al.*, 2019).

Hydropower technology has made considerable progress toward sustainability over the last couple of decades. For example, fish-friendly turbines, now in operation, and the increasingly common inclusion of fish ladders in dams to prevent the fragmentation of migration routes. Other relevant innovations include the standard modular hydropower[5] being researched by the US Department of Energy, and the restoration hydro[6] being developed by the American company Natel Energy.

Other notable efforts to increase the sustainability of hydropower projects have been made by the International Hydropower Association (IHA), which together with a multi-stakeholder council, has developed *Hydropower Sustainability Tools*, which include guidelines for good practices and a sustainability assessment protocol. In addition, in September 2021, the IHA launched the *Hydropower Sustainability Standard*, under which projects can be rated and certified based on their sustainability compliance.[7]

Despite significant progress, more efforts need to be made to minimise the impact of hydropower projects. Additional research and best practices are needed to understand and address certain phenomena, such as methane emissions from submerged vegetation in impoundment areas and exposure to methylmercury water contamination. Addressing environmental impacts at the planning stage is easier, cheaper and more effective than doing so after a project has been constructed.

[5] *Standard modular hydropower can be conceptualised by deconstructing a small hydropower plant into discrete functional units each with a dedicated purpose and a common interface (Witt et al., 2017).*

[6] *Restoration hydro consists of the restoration of degraded water basins through the use of biomimicry in the form of low-head structures paired with a small turbine (Natel Energy, 2020).*

[7] *For more information on the Hydropower Sustainability Standard and Tools, see: www.hydrosustainability.org/.*

A key support of future hydropower developments is the concept of integrated planning, which allows for (EC, 2018):

- the integration of water, nature and energy policy objectives;
- the involvement of all interested stakeholders, which can reduce subsequent impacts and conflicts;
- the prioritisation of energy, nature and water management considerations;
- increased transparency and the streamlining of authorisation processes;
- the management of risks of the cumulative effects of hydropower plants; and
- the integration of a strategic planning approach through river basin management.

The last point is particularly important. The planning of hydropower projects should not be done exclusively at the plant scale. Instead, new projects need to be planned at a system scale that can potentially include other interconnected assets, an entire river basin or even a region. An analysis performed by the Inter-American Development Bank indicated that a system-scale planning approach can identify potential conflicts earlier than project-based approaches, and for a given energy output, the former approach has the potential to reduce social and environmental impacts (IDB, 2013). Finally, for hydropower to be truly sustainable, governments should prioritise transparency by including civil society in the planning process.

Another critical element related to hydropower sustainability is sediment management. Early and consistent attention to the processes of reservoir sedimentation is needed to ensure the long-term resilience of hydropower facilities. Reservoir sedimentation reduces the storage capacity of reservoirs and damages hydromechanical equipment, posing a threat to the sustainability of hydropower, water supply and irrigation services (Annandale, Morris and Kakri, 2016).

Reservoir hydropower can increase resilience against weather-related phenomena, for example, by accumulating water before the dry season to mitigate the impact of droughts, and by managing water and mud flows during flood events. However, it is also vulnerable to changes in weather. The effects of climate change on hydropower generation are expected to be varied across different plants and countries, with some expected to receive more rainfall while others become dryer.[8]

[8] *Regions, countries and plants will all be affected differently. Not all hydropower plants are expected to be affected negatively by climate change. Some could see increased run-off, which would be beneficial for their production. These effects should be evaluated at a plant-specific level.*

Anticipating climate-change-induced changes in rainfall, water flows and extreme weather events is crucial for hydropower development planning (IEA, 2021b) as well as adequate power system planning. It is particularly important for governments, operators and decision makers to be aware of the issues that climate change can create on annual run-offs, their time distribution and sedimentation. The IHA produced a *Climate Resilience Guide*[9] for the hydropower sector, which offers a methodology for identifying, assessing and managing climate risks to enhance the resilience of hydropower projects.

4.2 INNOVATION AND FLEXIBILITY

As mentioned in Chapter 3, hydropower plants face challenges, including an ageing fleet and a changing role in power systems which has impacted their profitability. As challenging as this situation is, it also presents an excellent opportunity for modernising hydropower plants, enhancing their overall flexibility with efficiency and operating range increases, and making them more economically viable.

Digitalisation

Hydropower plants stand to gain multiple benefits from upgrading assets with components designed for modern-day operations (*i.e.* under wider operation ranges, faster ramping requirements and multiple start-stop cycles) and adopting innovative O&M schemes. As the foundation of this process, digitalisation could improve data availability, facilitate better decision making, and improve the resolution and capabilities of plant controls. The digitalisation of operations can enable plants to enhance the range and efficiency of their operations, reduce O&M costs and extend their lifetimes.

With the introduction of intelligent digital control strategies and monitoring, operators will be able to collect more data and better understand the behaviour of a plant and its components under different conditions. This will allow for better-informed decisions and better management of the plant's operations. Digitalisation will also provide input for better component designs that will enable more flexible operations. It will also open the door for implementing predictive maintenance strategies, which could reduce O&M costs and increase plant availability.

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[9] *For more information on the Climate Resilience Guide, see: www.hydropower.org/publications/hydropower-sector-climate-resilience-guide.*

The use of digital twins exemplifies innovation in this field. Digital twins are mathematical replicas of a physical plant which allow for the simulation of different operating conditions and the monitoring of various parameters and system characteristics. In this way, digital twins could be used to predict the behaviour of a plant under certain conditions which, in turn, allows for the optimisation of operations, and the improvement of maintenance schemes. Kougias *et al.* (2019) estimate that digitalisation of the world's hydropower fleet could increase annual production by 42 TWh, equivalent to roughly 1% of annual production. While this number seems relatively small, this study quantifies the annual operational savings as USD 5 billion. Other relevant tools are building information modelling and virtual design and construction, which can help to improve hydropower projects throughout the entire project life cycle. It is worth highlighting that it might not be necessary to digitalise an asset fully, and value could be added through partial digitalisation.

As mentioned before, hydropower projects are highly site specific. The unique nature of each hydropower plant, not only in terms of design but also in terms of operation, is certainly one of the main challenges to hydropower's digitalisation. This raises the importance of standardisation. Standards can facilitate the digitalisation process and enable the compatibility and sharing of information among different actors and across borders. In addition, many hydropower projects are considered critical infrastructure, and therefore increased cyber-security measures will be needed to prevent any unforeseen security-related issues.

Flexibility

For hydropower to have a relevant role in future energy systems, beyond baseload generation, it will have to contribute to the grid with both capacity (short-term flexibility) and energy (medium- and long-term flexibility) (INESC TEC, 2020). As mentioned earlier, many hydropower plants were developed decades ago under different operational circumstances. This results in plants having to operate at partial loads more frequently, and with a substantial increase in the number of start-stop cycles and load changes. Hydropower assets can greatly benefit from improvements aimed at increasing their own flexibility, and consequently, the overall system flexibility. This can be done in different ways, for example (INESC TEC, 2020):

- *Plant redesign:* Addition of storage facilities by installing pumps, reversible pump turbines or batteries. This option requires civil works, new equipment and, in some cases, a reinforced grid connection.

- *Equipment upgrades:* Older facilities can benefit from modern equipment which can increase their efficiency, capacity and operating range. For example, DOE (2018) estimates that by modernising equipment, plants can achieve a 1-3% increase in efficiency. This option requires civil works, new equipment and/or, in some cases, a reinforced grid connection.

- *"Smarter" plants:* Technology has advanced considerably in the last decade, and new sensory and testing capabilities from turbine manufacturers have resulted in software that can make operations more efficient and controllable and expand the operating range of hydropower plants. This option does not require civil works or major equipment changes.

These upgrades not only benefit the grid, they can also benefit the plants themselves by increasing their income, for example, by operating at lower loads or facilitating participation in ancillary services markets. For instance, in 2013, the Electric Power Research Institute estimated that expanding the operating range of the existing PSH plants in the United States could increase their income by 61% on average (EPRI, 2013).

Hybrid hydropower

Additional synergies can be harnessed by hybridising hydropower with other VRE technologies. Adding solar PV or wind generation to hydropower plants can offer multiple advantages. For example, pairing hydropower with floating solar PV can offer (Lee *et al.*, 2020):

- **Better land use efficiency**, avoiding the need for new land and reducing land-use conflicts.
- **Water conservation** by reducing water evaporation.
- **Improved system operation at different time scales** (seasonal, daily, hourly and sub-hourly) by taking advantage of the complementarity of these two technologies.
- **Power output compensation** during dry periods.
- **Additional energy storage opportunities** when paired with PSH and using excess solar generation to pump water.

- **Improved transmission utilisation** by providing increased power generation and offering higher capacity factors than stand-alone systems.
- **Reduced curtailment**, with the PV system supplying electricity during peak production hours and hydropower ramping up and down as needed, or by using PV generation to pump water in PSH plants.
- **Reduced transmission system interconnection costs** by using the existing transmission infrastructure.

As mentioned in section 2.3, the technical potential of installing floating solar PV on existing reservoirs worldwide reaches 4.2-10.6 PWh/year (Lee *et al.*, 2020), the latter amount being equivalent to over a third of the world's electricity generation.

Another interesting alternative for hydropower hybridisation is pairing with battery energy storage systems. By pairing batteries with a hydro generator, several benefits can be obtained, including lifetime extension by reducing mechanical stresses, additional opportunities for energy and ancillary market participation, flexible storage and an increase in the operating range (Andritz, 2022).

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Box 1 Example – hydropower battery hybrid project

The province of Alberta, Canada, has a grid that relies heavily on fossil-fuel-based generation and has limited hydropower resources. Solar photovoltaic and wind deployment are growing quickly, as is the need to compensate for their variability.

Existing facilities: **1** Ghost dam **2** Hydropower plant **3** 138 kV substation **4** Office/admin building **5** Workshop building **6** Office trailers **7** Warehouse

Note: kV = kilovolts; Temp. = temporary

While fossil-fuel-based generation can easily provide the required flexibility, a better alternative is hydropower, since it has no emissions. However, with limited hydropower assets, the challenge is maximising their flexibility.

In order to address this issue, Canadian power provider TransAlta is planning to develop the WaterCharger Battery Storage Project, which intends to add 180 megawatts (MW) of lithium-ion battery storage to the MW 56 Ghost hydropower plant.

The project will offer multiple benefits, including:

- Ensuring that the batteries are charged with clean electricity (important for a grid that heavily relies on fossil-fuel-based generation).
- Allowing the producer to extract value out of the minimum flows (required for environmental reasons) by using them to charge the batteries which could otherwise lose their value due to wind and photovoltaic energy surpluses.
- Using stored electricity in periods of higher demand or low solar and wind generation.
- Increasing the provision of ancillary services through the large increase in capacity.

The project is planned for construction in 2023 and is expected to be completed in nine months.

Source: TransAlta (2022).

Pumped storage hydropower

As the largest source of energy storage technology, PSH will undoubtedly play a major role as a flexibility provider in future power systems. With that said, there is still room for improvement when it comes to the flexibility of PSH plants. Utilising variable speed drives for the pumps could be a major upgrade for some existing PSH plants and important technology to consider for future projects. According to EPRI (2013), adding variable speed drives to PSH plants in the United States could increase their income by as much as 85%. Most PSH plants are only capable of regulating their power production output, while pumps are only able to run at full capacity. With variable speed drives, pumping power can also be regulated, allowing for more flexible operation and the ability to better integrate surplus electricity from the grid, *i.e.* pumps can run at partial capacity, making them more flexible (GE, 2016).

4.3 REGULATION AND MARKETS

Governments can be instrumental in guaranteeing the continued deployment of hydropower and, in that way, pave the way for the decarbonisation of the power sector. They can help attract the necessary investment in hydropower by providing incentives and creating a suitable business environment. Some of these incentives include (Markkanen and Plummer Braeckman, 2019):

- Relief from taxes and duties.
- Concessional grants or loans.
- Accelerated asset depreciation.
- Subsidies based on environmental performance.
- Subsidies for services provided beyond power generation (*e.g.* water management).
- Capital cost contributions (*e.g.* when a project offers benefits that are hard to monetise, such as flood control).
- Support structures for the deployment and testing of new technology.

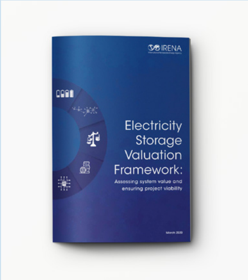
Governments can also facilitate the further deployment of hydropower by streamlining concession and licensing processes which would reduce some of the regulatory uncertainty surrounding hydropower projects and make them more attractive investments. That said, neither incentives nor regulatory streamlining alone might be enough to develop the necessary hydropower capacity. A combination of closely co-ordinated incentives and regulatory streamlining could accelerate the deployment of hydropower (Cox, 2016). Furthermore, sustainable hydropower could also benefit from being included in green bond taxonomies to funnel increased levels of investments, which is not always the case, depending on market perceptions and risk-averse behaviour from bond issuers.

Small hydropower projects could particularly benefit from these efforts, as they are disproportionately affected by capital costs associated with pre-development studies and permitting. "Larger projects can absorb licensing costs through economies of scale in a way that is not possible for smaller projects" (Levine *et al.*, 2021).

Electricity markets will also have to change to adequately remunerate the large suite of services provided by hydropower beyond just electricity generation. As the shares of variable renewables increase in power systems worldwide, hydropower's capacity to provide ancillary services becomes increasingly valuable. However, most markets do not currently recognise or remunerate this added value in full.

In some markets, hydropower would benefit from being allowed to increase its participation in energy markets, including sub-hourly markets, allowing the power system to benefit from its full flexibility. The development of forward markets could also benefit hydropower resources that must schedule their production. Additionally, developing a system through which demand response can be brought to the market would help reduce market power in both energy and reserves markets, enabling hydropower (and other generators) to receive competitive energy and ancillary service prices. In a nutshell, markets should take advantage of the flexibility offered by hydropower, while rewarding its storage capabilities and regulation services, such as dynamic reactive power support, primary frequency response and sub-hourly deployment services (EPRI, 2013).

Box 2 **IRENA's Electricity Storage Valuation Framework**



In March 2020, IRENA published the report, *Electricity Storage Valuation Framework: Assessing system value and ensuring project viability*. The report proposes a five-phase method to assess the value of storage and create viable investment conditions. It aims to guide storage deployment for the effective integration of solar and wind power. The report consists of three parts which examine storage valuation from different angles:

- Part 1 outlines the framework's process for decision makers, regulators and grid operators.
- Part 2 describes the framework's methodology in greater detail for experts and modellers.
- Part 3 presents real-world cases, including examples of cost-effective storage use and maximised service revenues.

The report's findings include:

- Storage services help to manage the variability and uncertainty that solar and wind use introduces into the power system.
- By providing multiple services simultaneously, electricity storage permits revenue stacking for greater profitability.
- Some storage technologies are intrinsically more suited than others for certain services. For instance, battery storage energy systems provide a rapid response to signals, opening the way for new, high-value system services.
- Electricity storage could accelerate off-grid electrification, enable far higher shares of variable renewable energy, and indirectly help to decarbonise the transport sector.
- Poor accounting for storage value results in so-called "missing money", with market revenues too low to entice investors.

Historically, ancillary services have mostly been provided at fixed prices through long-term contracts instead of through spot markets. The creation of innovative market structures and mechanisms that adequately remunerate the growing value of these services is critical to ensure the economic feasibility of hydropower projects – in particular PSH projects. Only a few countries presently have markets that remunerate these services adequately. A good example is Ireland, where the DS3 Programme by EirGrid, the transmission system operator, seeks to address the challenge of integrating very high shares of variable renewable generation into its grid. This programme recognises and provides payment for 14 different grid services that ensure that the system operates securely and efficiently (EirGrid, 2020). Research has shown that the value of hydropower plants can be substantially higher if they participate in both energy and ancillary services markets than if they operate only in the energy market. “This increase is the most significant for units with low water availability since they are able to earn profits providing ancillary services without using their scarce water resources” (Perekhodtsev and Lave, 2018).

4.4 CO-OPERATION

Finally, the role of international and multi-stakeholder co-operation in hydropower's future success is considerable. Industry, governments and regulators need to work together, share lessons learnt and co-operate in developing innovative solutions that will address hydropower's present challenges. River basin management is clearly one area where co-operation is critical, as it is a discipline that requires the co-ordination and co-operation of a diverse group of stakeholders that can extend across borders. International co-operation, through the sharing of experiences and best practices, can accelerate the creation of favourable policies and regulations relevant to hydropower.

There are several ongoing efforts to foster co-operation at different levels. In 2020, IRENA launched a Collaborative Framework on Hydropower[10], a platform meant to bring countries together to identify priority areas, develop concerted actions and foster international collaboration to better understand the role of hydropower in the energy transition, raise awareness on its most pressing issues and ensure its widespread deployment in the future. The framework aims to advance progress in areas relevant to hydropower, including financing, flexibility,

[10] *For more information on the Collaborative Framework on Hydropower, please contact info@irena.org*

resilience and sustainability. Furthermore, the Collaborative Framework is open to private sector participation, serving as an effective vehicle for public-private dialogue, co-operation and co-ordinated action to ensure the continued deployment of hydropower technologies.

Another initiative is the International Forum on Pumped Storage Hydropower[11] (IFPSH). The IFPSH is a government-led multi-stakeholder platform launched by the IHA and chaired by the US Department of Energy. This forum seeks to shape and enhance the role of PSH by developing guidance and recommendations on how sustainable PSH can best support the energy transition.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[11] *For more information on the IFPSH, see: https://pumped-storage-forum.hydropower.org/.*

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APPENDIX A
LIST OF COUNTRIES, AREAS AND REGIONS SHOWN IN THE FIGURES

Africa

Algeria, Angola, Benin, Botswana, Burkina Faso, Burundi, Cabo Verde, Cameroon, Central African Republic, Chad, Comoros, Democratic Republic of the Congo, Congo, Côte d'Ivoire, Djibouti, Egypt, Equatorial Guinea, Eritrea, Eswatini, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Libya, Madagascar, Malawi, Mali, Mauritania, Mauritius, Mayotte, Morocco, Mozambique, Namibia, Niger, Nigeria, Réunion, Rwanda, Saint Helena, Ascension and Tristan da Cunha, São Tomé and Príncipe, Senegal, Seychelles, Sierra Leone, Somalia, South Africa, South Sudan, Sudan, United Republic of Tanzania, Togo, Tunisia, Uganda, Western Sahara, Zambia.

Asia

Afghanistan, Bangladesh, Bhutan, Brunei Darussalam, Cambodia, China, Hong Kong SAR (China), Macao SAR (China), Chinese Taipei, India, Indonesia, Japan, Kazakhstan, Democratic People's Republic of Korea, Republic of Korea, Kyrgyzstan, Lao People's Democratic Republic, Malaysia, Maldives, Mongolia, Myanmar, Nepal, Pakistan, Philippines, Singapore, Sri Lanka, Tajikistan, Thailand, Timor-Leste, Turkmenistan, Uzbekistan, Viet Nam.

Central America and the Caribbean

Anguilla, Antigua and Barbuda, Aruba, Bahamas, Barbados, Belize, Bonaire, Sint Eustatius and Saba, British Virgin Islands, Cayman Islands, Costa Rica, Cuba, Curacao, Dominica, Dominican Republic, El Salvador, Grenada, Guadeloupe, Guatemala, Haiti, Honduras, Jamaica, Martinique, Montserrat, Nicaragua, Panama, Puerto Rico, Saint Barthélemy, Saint Kitts and Nevis, Saint Lucia, Sint Maarten, Saint Martin, Saint Vincent and the Grenadines, Trinidad and Tobago, Turks and Caicos Islands, United States Virgin Islands.

Eurasia

Armenia, Azerbaijan, Georgia, Russian Federation, Türkiye.

Europe

Albania, Andorra, Austria, Belarus, Belgium, Bosnia and Herzegovina, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Faroe Islands, Finland, France, Germany, Gibraltar, Greece, Holy See, Hungary, Iceland, Ireland, Italy, Kosovo*, Latvia, Liechtenstein, Lithuania, Luxembourg, Malta, Republic of Moldova, Monaco, Montenegro, Netherlands, North Macedonia, Norway, Poland, Portugal, Romania, San Marino, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, United Kingdom, Ukraine.

Middle East

Bahrain, Islamic Republic of Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, State of Palestine, Syrian Arab Republic, United Arab Emirates, Yemen.

North America

Bermuda, Canada, Greenland, Mexico, Saint Pierre and Miquelon, United States.

Oceania

Oceania, American Samoa, Australia, Christmas Island, Cocos (Keeling) Islands, Cook Islands, Fiji, French Polynesia, Guam, Kiribati, Marshall Islands, Federated States of Micronesia, Nauru, New Caledonia, New Zealand, Niue, Norfolk Island, North Mariana Islands, Palau, Papua New Guinea, Pitcairn, Samoa, Solomon Islands, Tokelau, Tonga, Tuvalu, Vanuatu, Wallis and Futuna Islands.

South America

Argentina, Plurinational State of Bolivia, Brazil, Chile, Colombia, Ecuador, Falkland Islands (Malvinas), French Guiana, Guyana, Paraguay, Peru, South Georgia and the S. Sandwich Islands, Suriname, Uruguay, Bolivarian Republic of Venezuela.

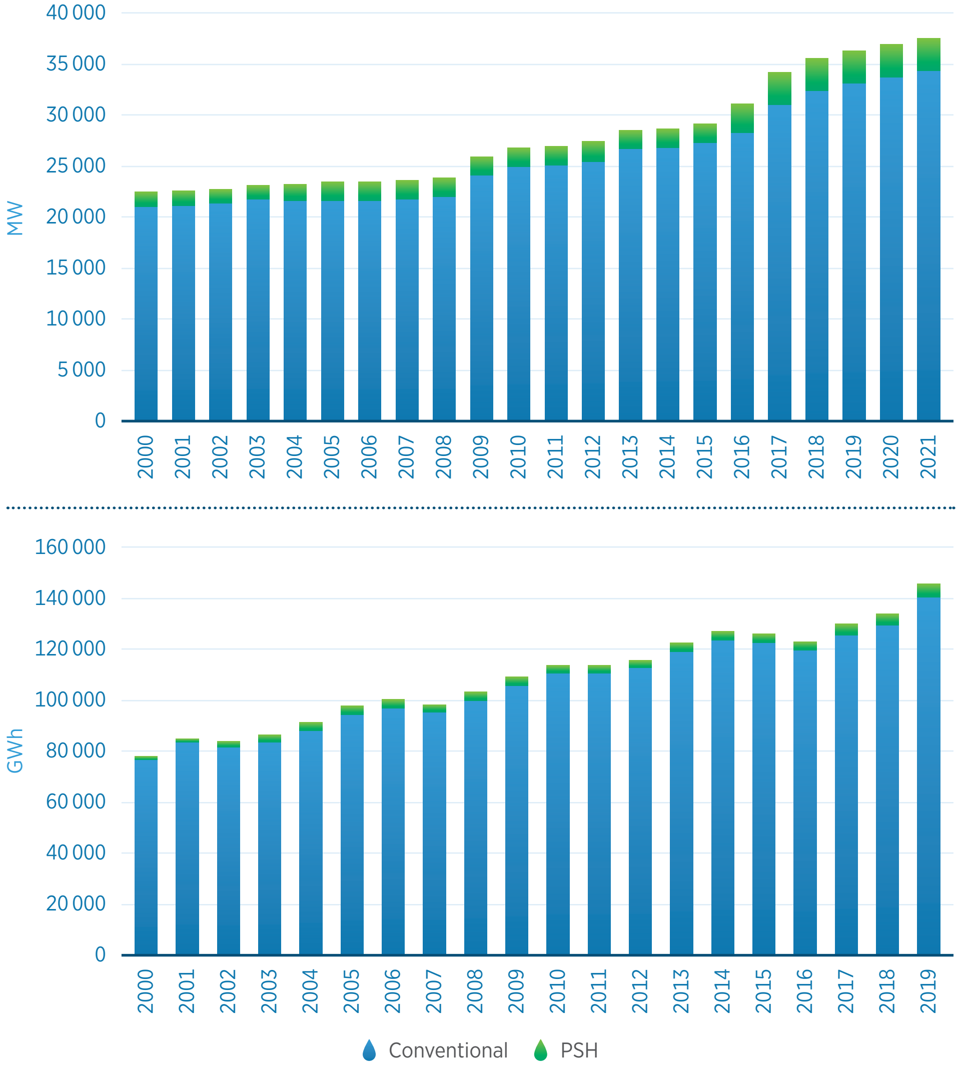
Source: UN Standard Country or Area Codes for Statistical Use (M49 List) http://unstats.un.org/unsd/methods/m49/m49.htm.

Note: (*) Throughout this publication, the designation Kosovo is without prejudice to positions on status and in line with the United Nations Security Council Resolution 1244 (1999).*

APPENDIX B
REGIONAL FIGURES

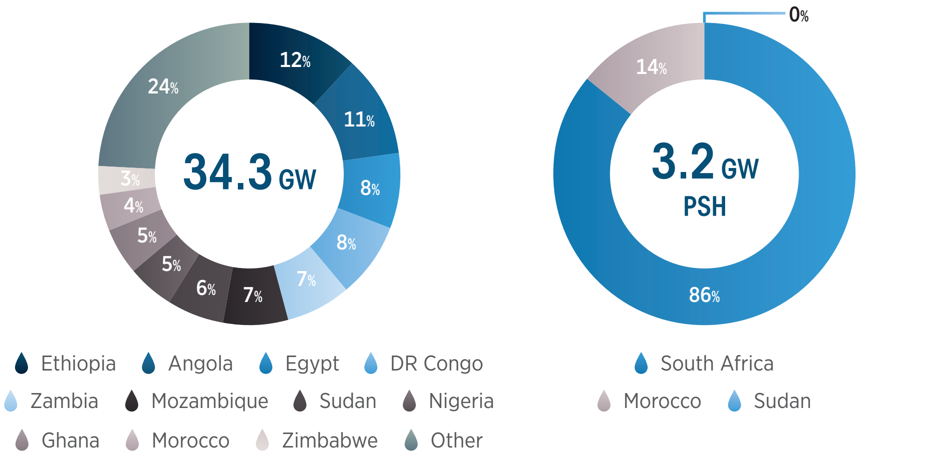
AFRICA

Figure B.1 **Hydropower capacity and generation in Africa, 2000-2021**



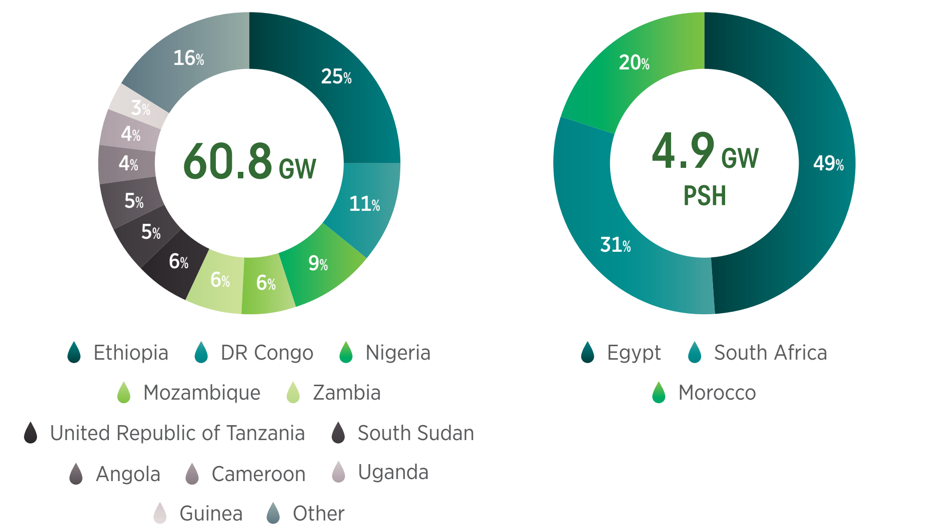
Note: GWh = gigawatt hour; MW = megawatt; PSH = pumped storage hydropower.
Source: IRENA (2022b).

Figure B.2 **Hydropower installed capacity in Africa, 2021**



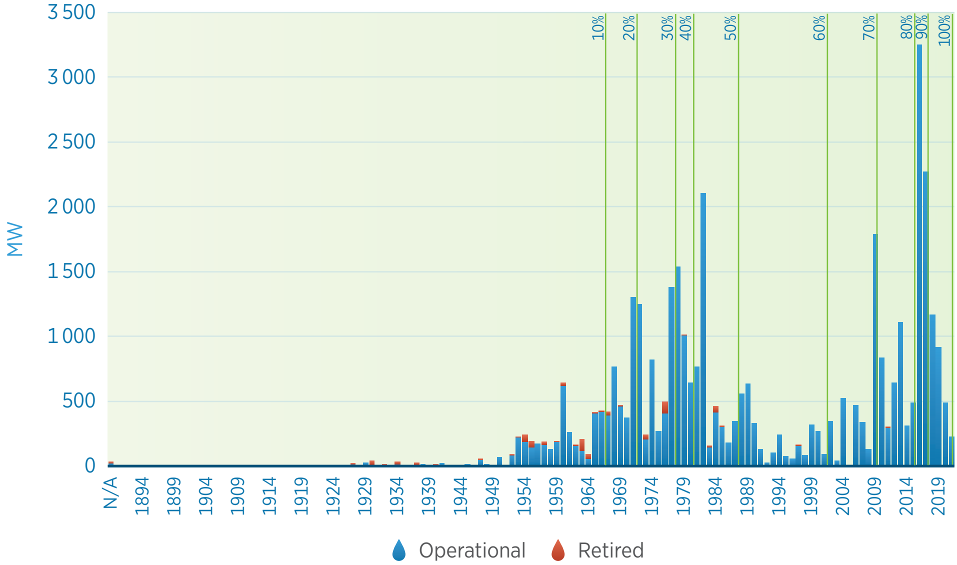
Note: GW = gigawatt; PSH = pumped storage hydropower; DR Congo = Democratic Republic of Congo.
Source: IRENA (2022b).

Figure B.3 **Hydropower project pipeline in Africa, 2022-2037**



Note: GW = gigawatt; PSH = pumped storage hydropower; DR Congo = Democratic Republic of Congo.
Based on: S&P Global (2022).

Figure B.4 **Hydropower capacity in Africa by year of commissioning**

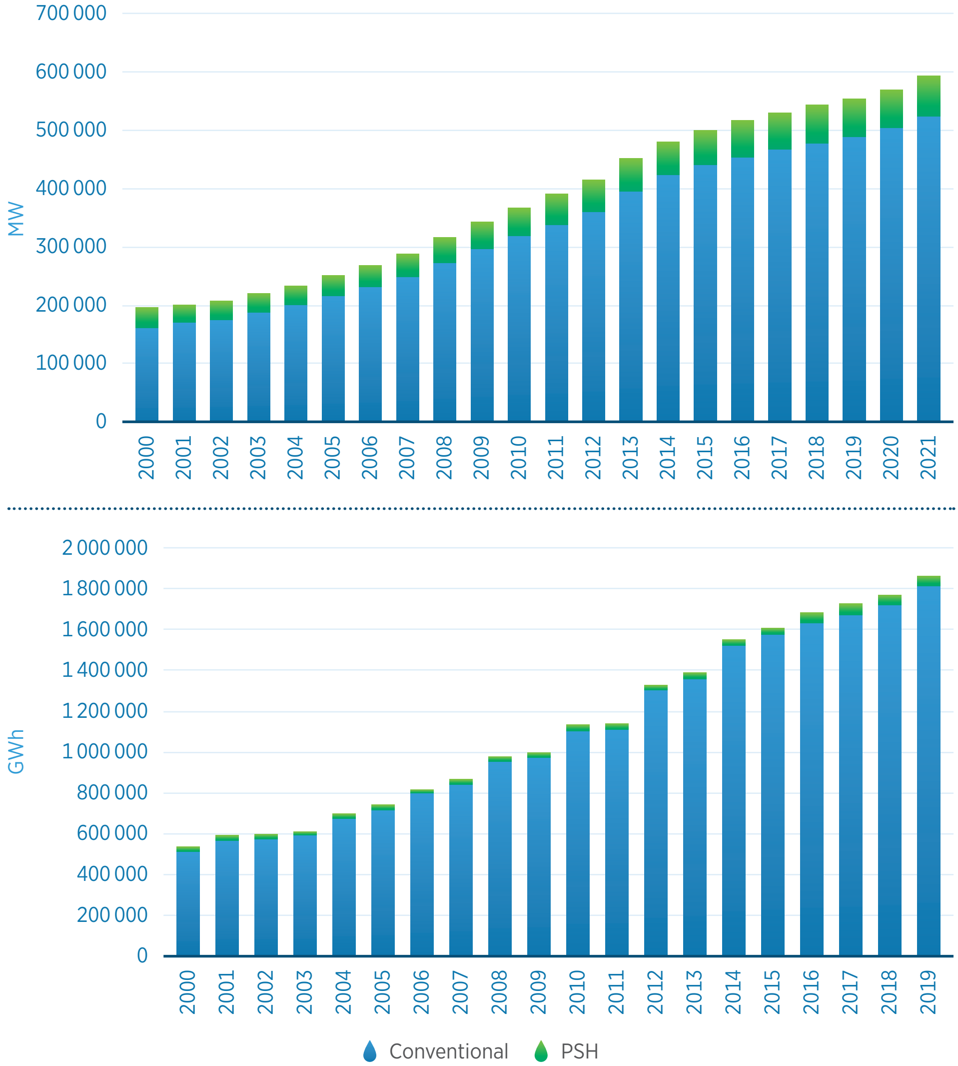


Note: Data include pumped storage hydropower. Data points with no commissioning date are grouped under N/A. MW = megawatt; N/A = not available.

Based on: S&P Global (2022).

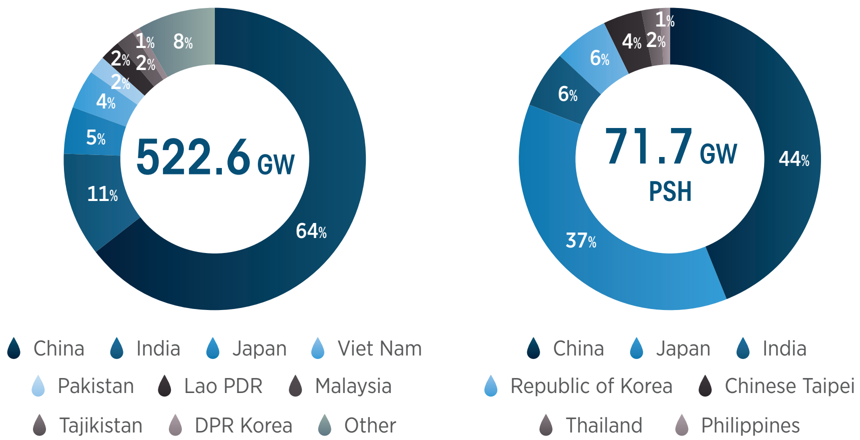
ASIA

Figure B.5 **Hydropower capacity and generation in Asia, 2000-2021**



Note: GWh = gigawatt hour; MW = megawatt; PSH = pumped storage hydropower.
Source: IRENA (2022b).

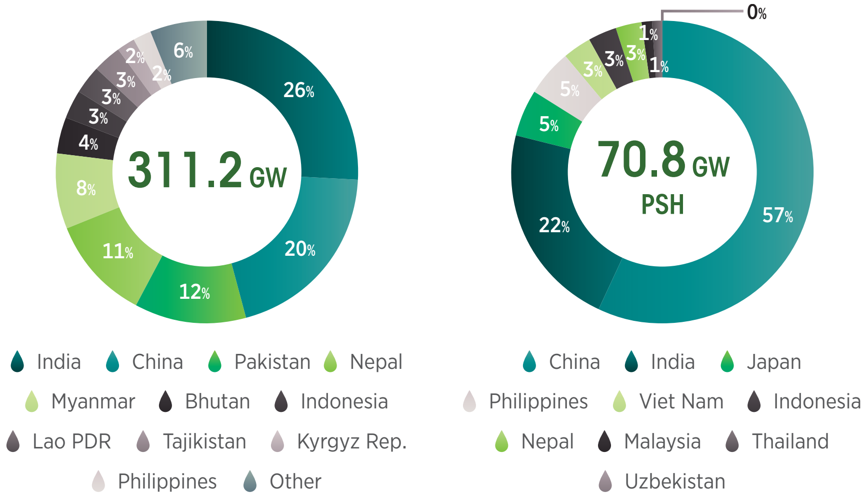
Figure B.6 **Hydropower installed capacity in Asia, 2021**



Note: GW = gigawatt; PSH = pumped storage hydropower; Lao PDR = Lao People's Democratic Republic; DPR Korea = Democratic People's Republic of Korea.

Source: IRENA (2022b).

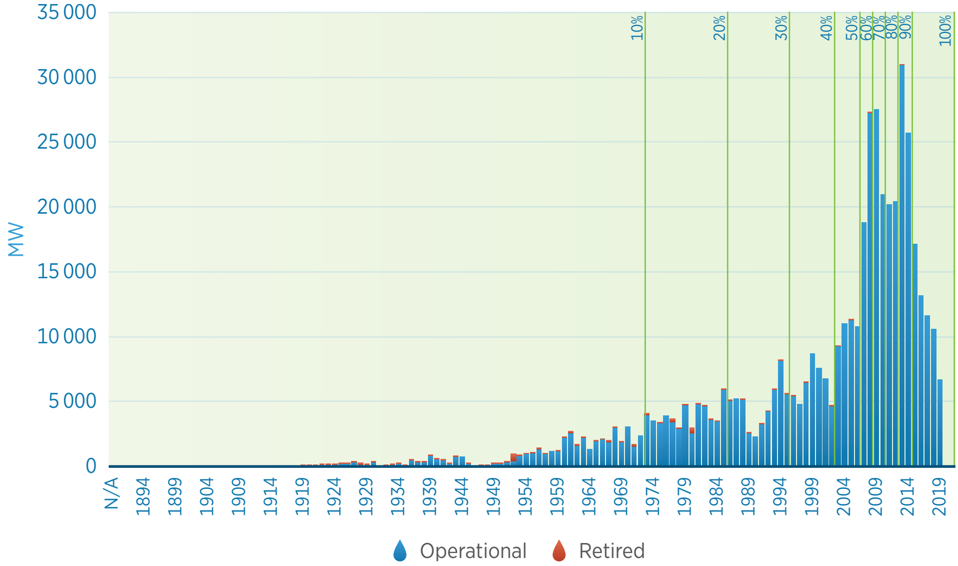
Figure B.7 **Hydropower project pipeline in Asia, 2022-2037**



Note: GW = gigawatt; PSH = pumped storage hydropower; Lao PDR = Lao People's Democratic Republic.

Based on: S&P Global (2022).

Figure B.8 **Hydropower capacity in Asia by year of commissioning**

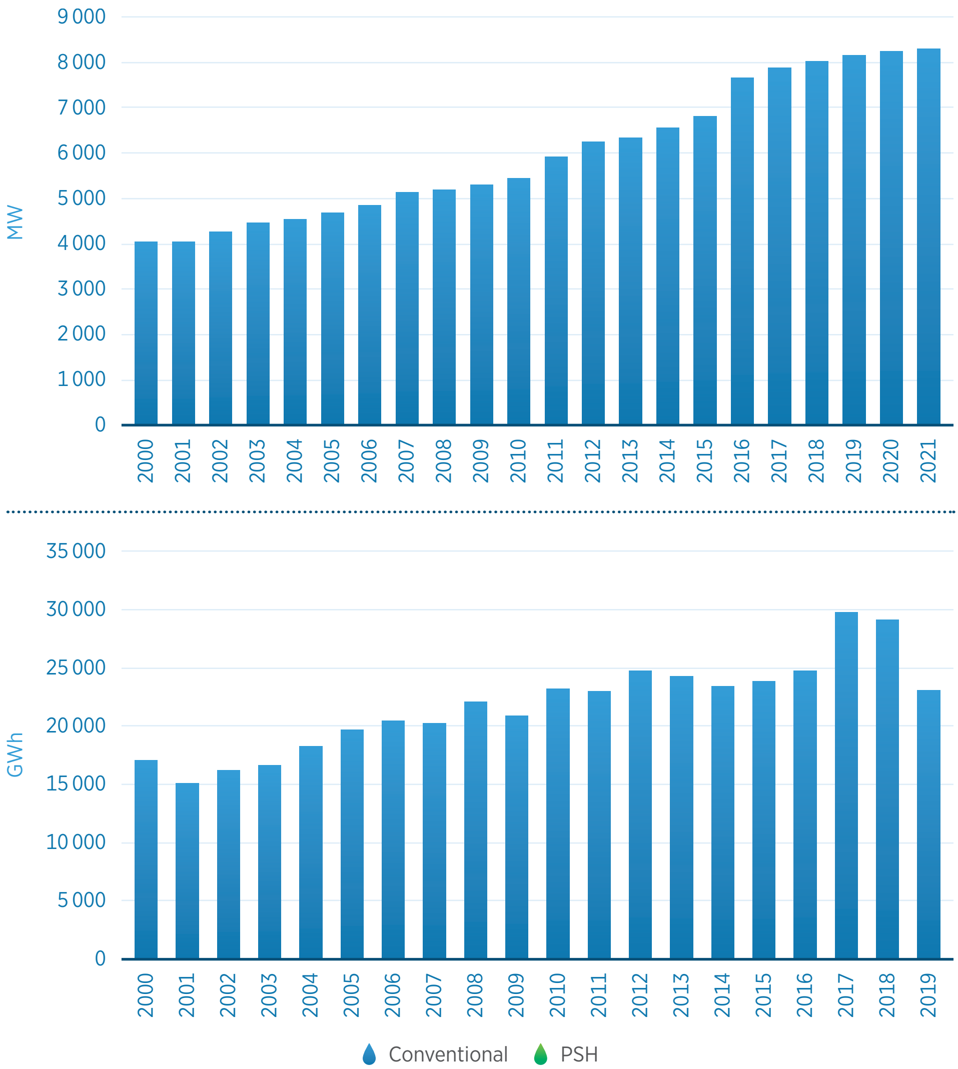


Note: Data include pumped storage hydropower. Data points with no commissioning date are grouped under N/A. MW = megawatt; N/A = not available.

Based on: S&P Global (2022).

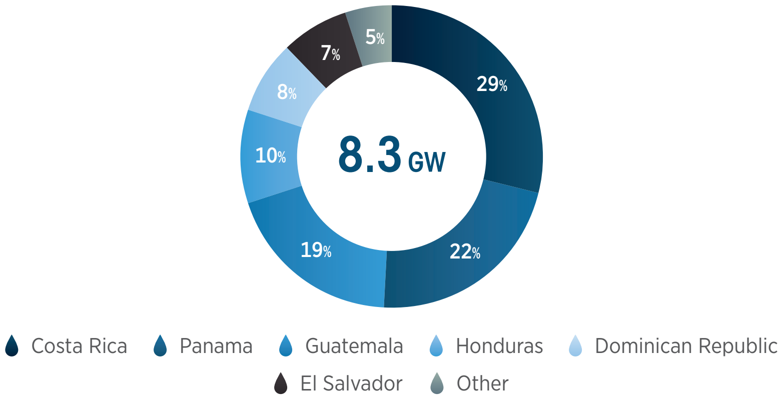
CENTRAL AMERICA AND THE CARIBBEAN

Figure B.9 **Hydropower capacity and generation in Central America and the Caribbean, 2000-2021**



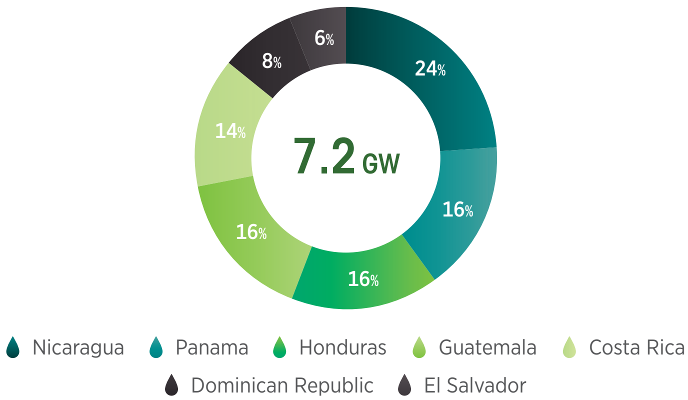
Note: GWh = gigawatt hour; MW = megawatt; PSH = pumped storage hydropower.
Source: IRENA (2022b).

Figure B.10 **Hydropower installed capacity in Central America and the Caribbean, 2021**



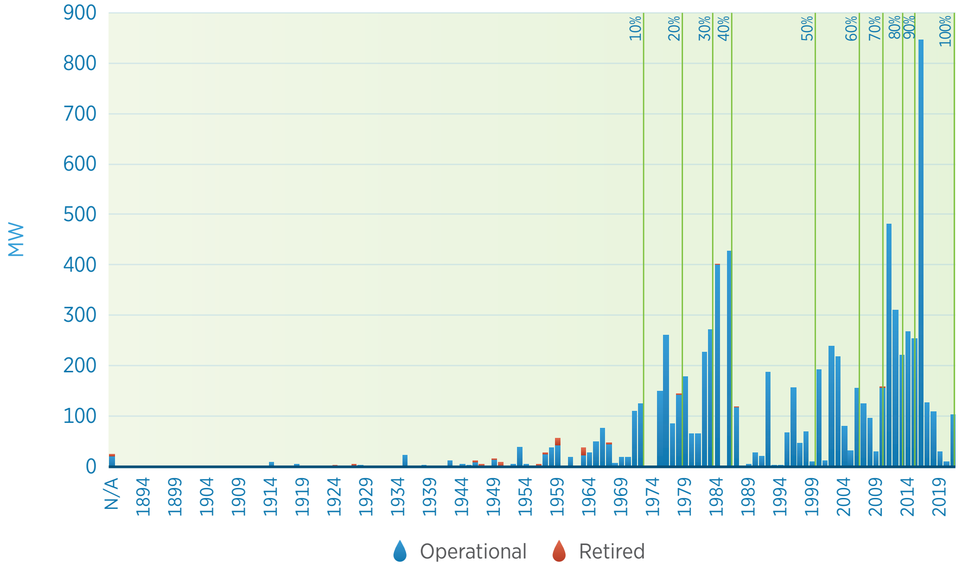
Note: GW = gigawatt; PSH = pumped storage hydropower.
Source: IRENA (2022b).

Figure B.11 **Hydropower project pipeline in Central America and the Caribbean, 2022-2037**



Note: GW = gigawatt; PSH = pumped storage hydropower.
Based on: S&P Global (2022).

Figure B.12 **Hydropower capacity in Central America and the Caribbean by year of commissioning**

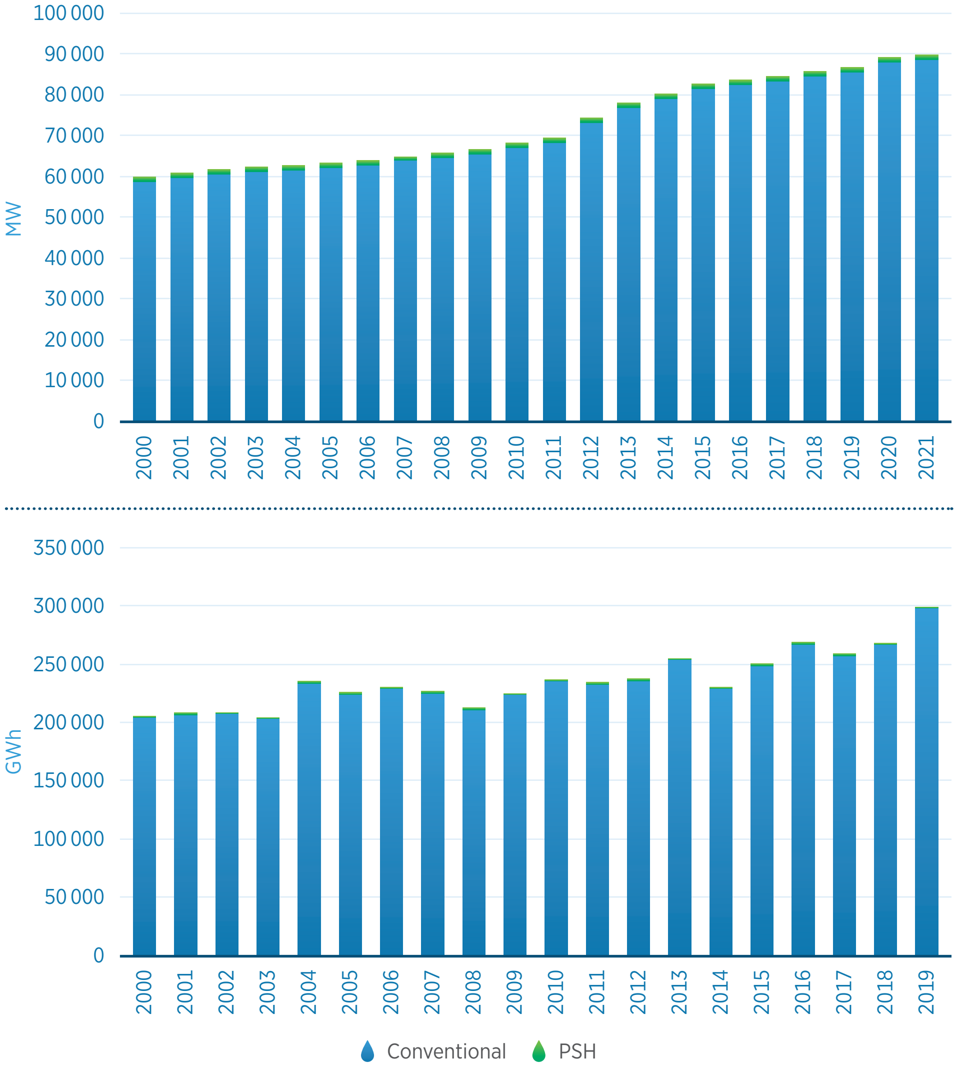


Note: Data include pumped storage hydropower. Data points with no commissioning date are grouped under N/A. MW = megawatt; N/A = not available.

Based on: S&P Global (2022).

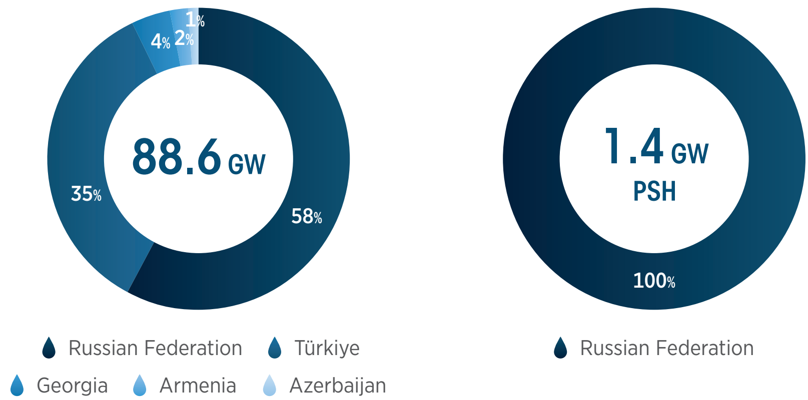
EURASIA

Figure B.13 **Hydropower capacity and generation in Eurasia, 2000-2021**



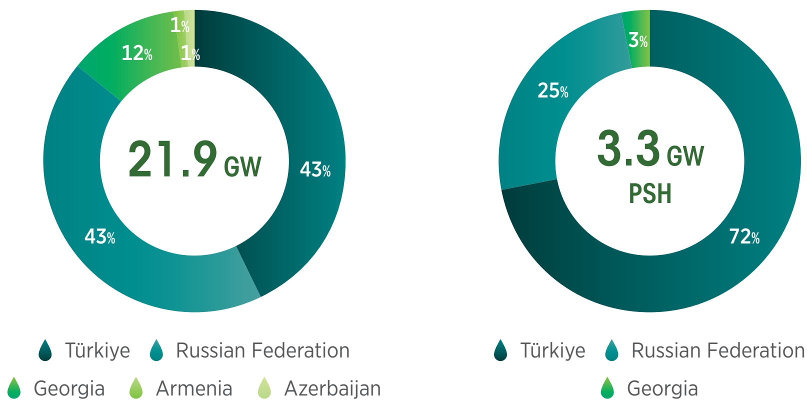
Note: GWh = gigawatt hour; MW = megawatt; PSH = pumped storage hydropower.
Source: IRENA (2022b).

Figure B.14 **Hydropower installed capacity in Eurasia, 2021**



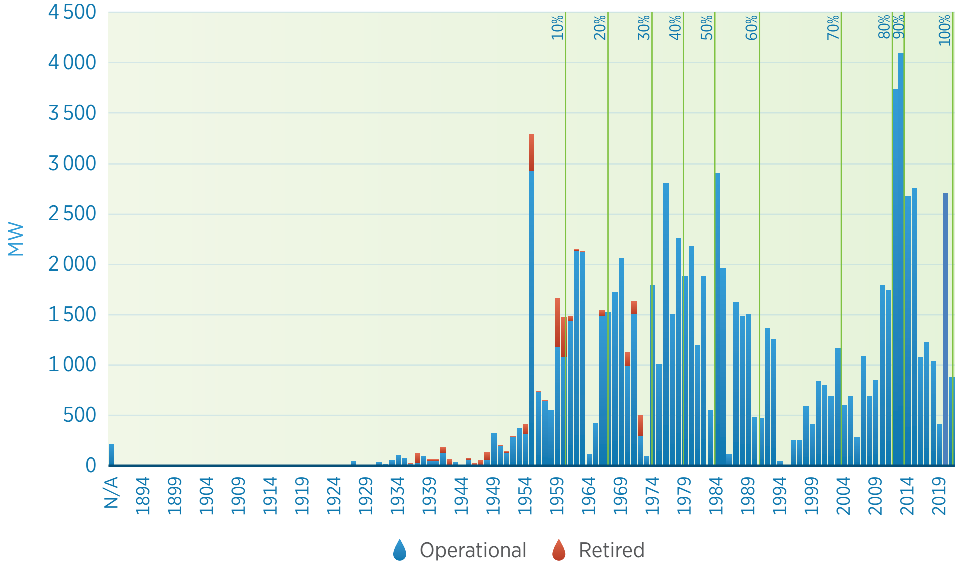
Note: GW = gigawatt; PSH = pumped storage hydropower.
Source: IRENA (2022b).

Figure B.15 **Hydropower project pipeline in Eurasia, 2022-2037**



Note: GW = gigawatt; PSH = pumped storage hydropower.
Based on: S&P Global (2022).

Figure B.16 **Hydropower capacity in Eurasia by year of commissioning**

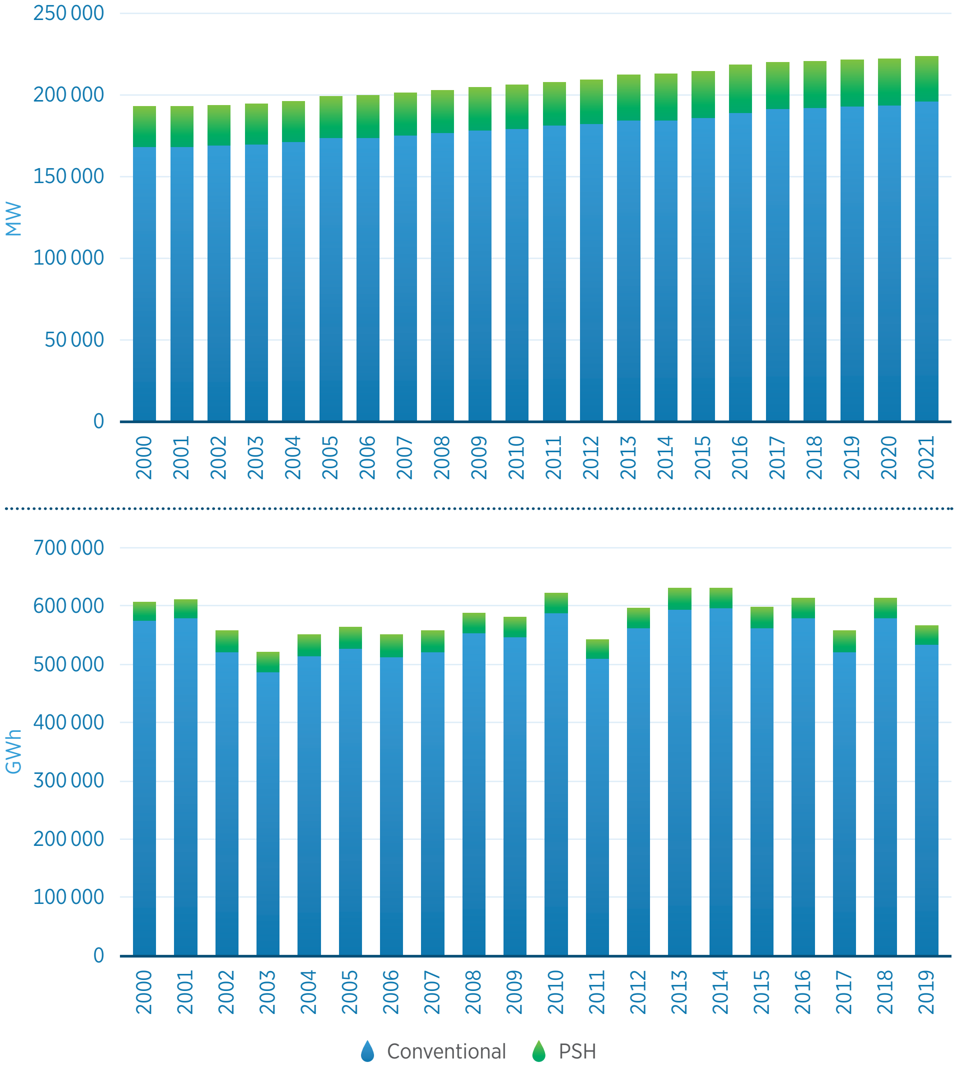


Note: Data include pumped storage hydropower. Data points with no commissioning date are grouped under N/A. MW = megawatt; N/A = not available.

Based on: S&P Global (2022).

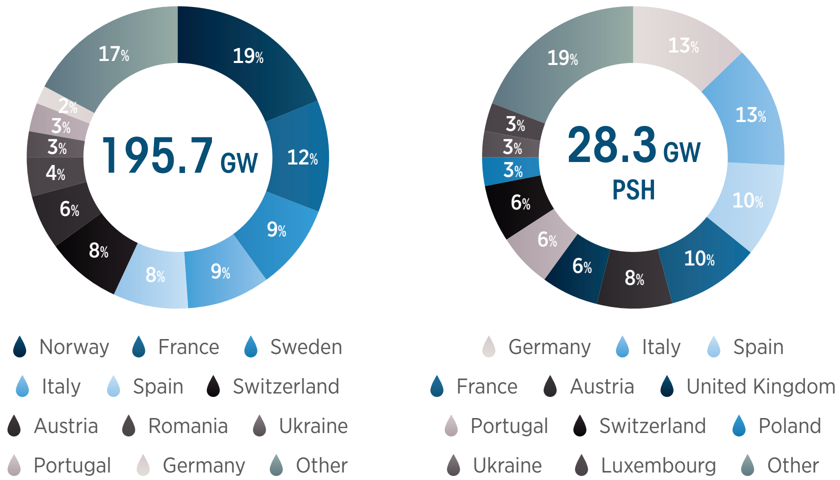
EUROPE

Figure B.17 **Hydropower capacity and generation in Europe, 2000-2021**



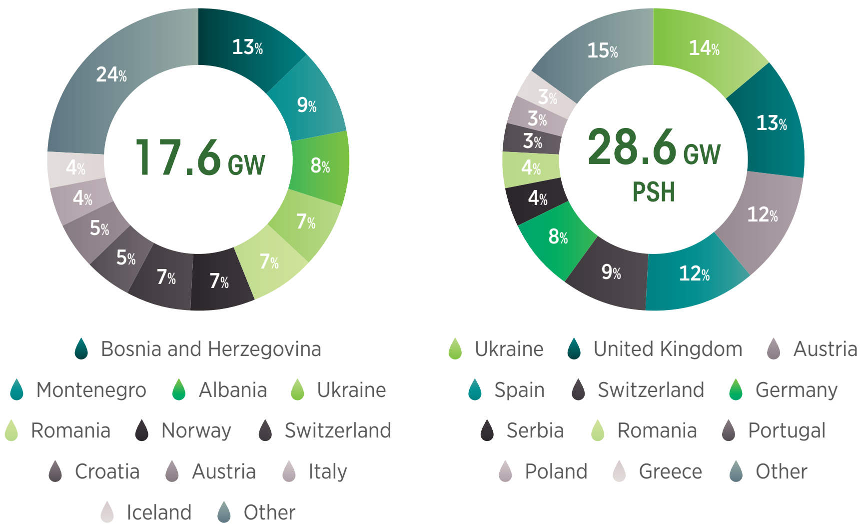
Note: GWh = gigawatt hour; MW = megawatt; PSH = pumped storage hydropower.
Source: IRENA (2022b).

Figure B.18 **Hydropower installed capacity in Europe, 2021**



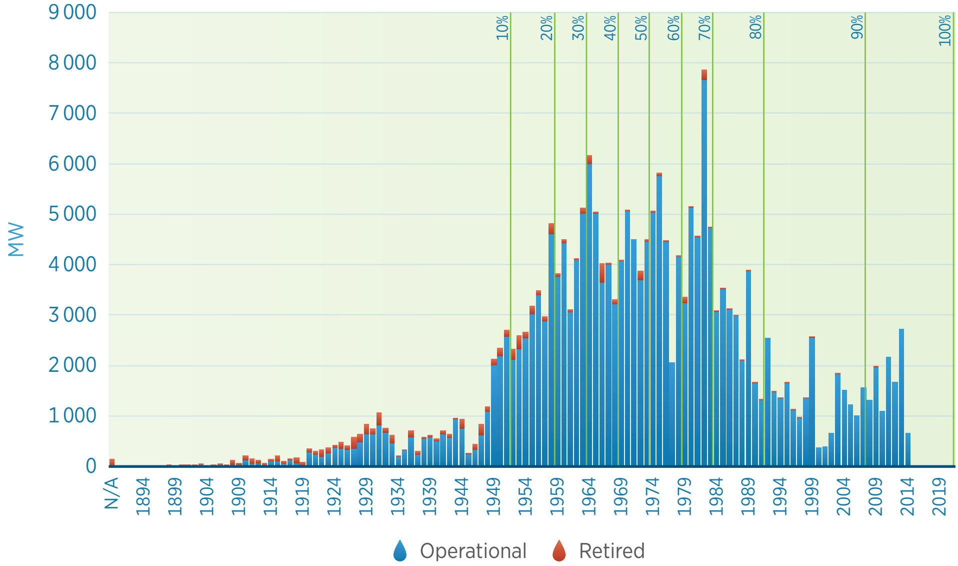
Note: GW = gigawatt; PSH = pumped storage hydropower.
Source: IRENA (2022b).

Figure B.19 **Hydropower project pipeline in Europe, 2022-2037**



Note: GW = gigawatt; PSH = pumped storage hydropower.
Based on: S&P Global (2022).

Figure B.20 **Hydropower capacity in Europe by year of commissioning**

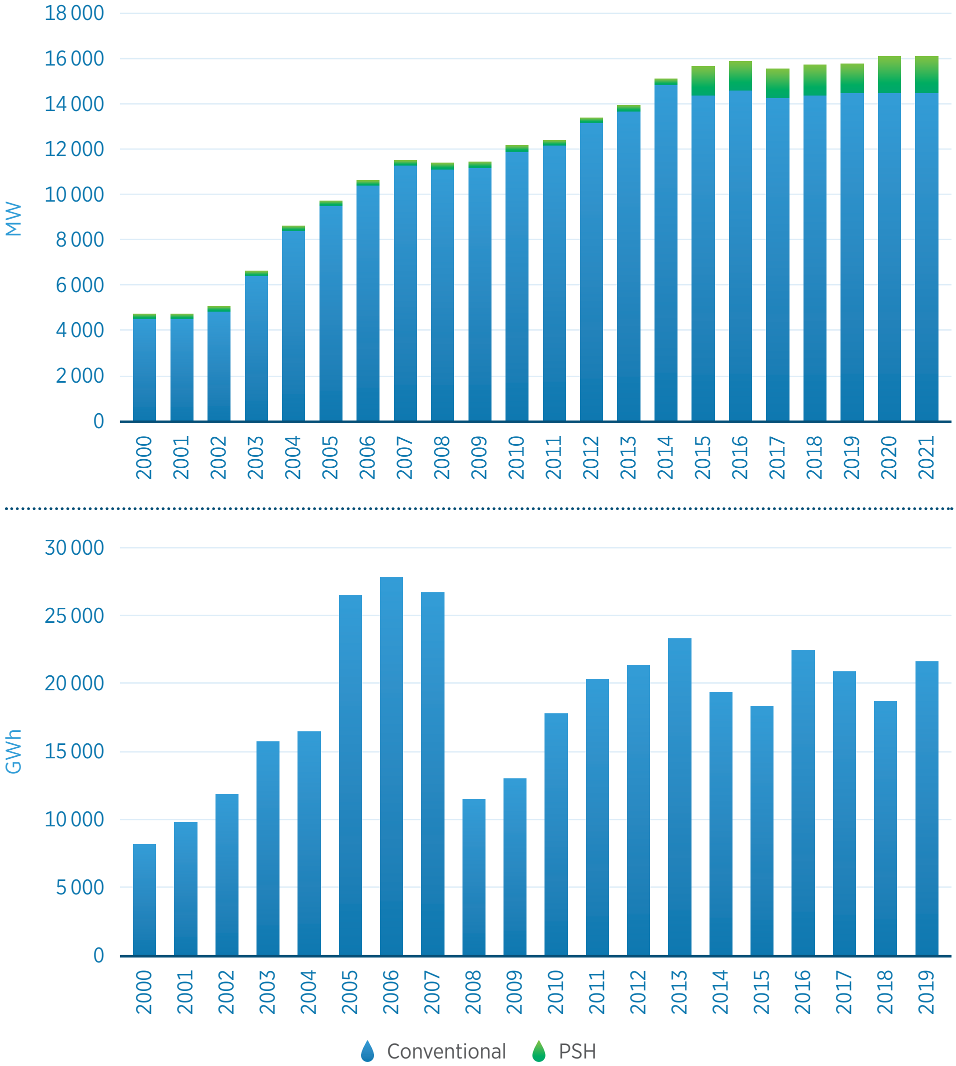


Note: Data include pumped storage hydropower. Data points with no commissioning date are grouped under N/A. MW = megawatt; N/A = not available.

Based on: S&P Global (2022).

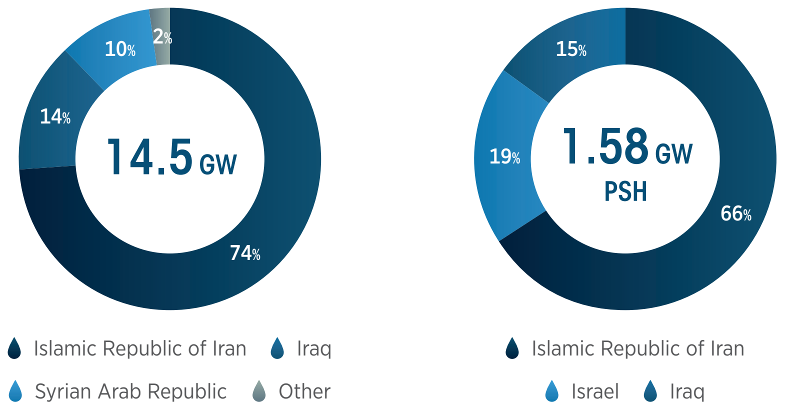
MIDDLE EAST

Figure B.21 **Hydropower capacity and generation in the Middle East, 2000-2021**



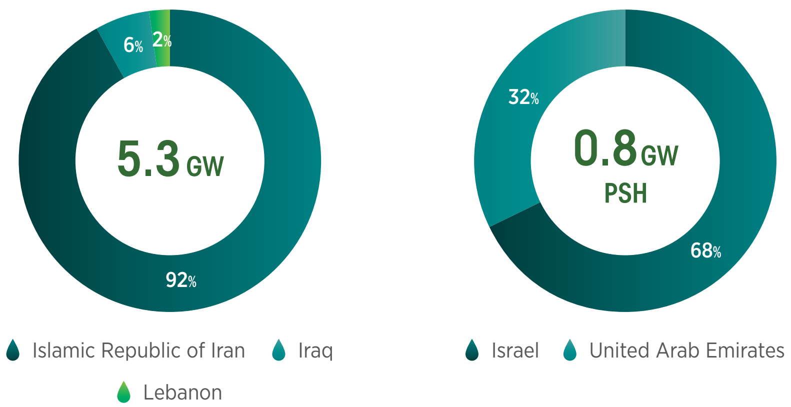
Note: GWh = gigawatt hour; MW = megawatt; PSH = pumped storage hydropower.
Source: IRENA (2022b).

Figure B.22 **Hydropower installed capacity in the Middle East, 2021**



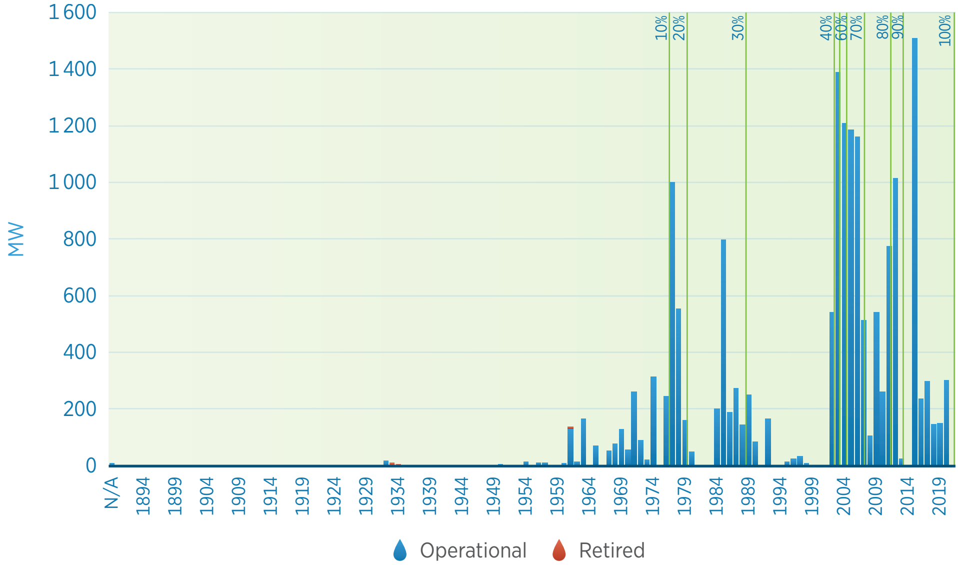
Note: GW = gigawatt; PSH = pumped storage hydropower.
Source: IRENA (2022b).

Figure B.23 **Hydropower project pipeline in the Middle East, 2022-2037**



Note: GW = gigawatt; PSH = pumped storage hydropower.
Based on: S&P Global (2022).

Figure B.24 **Hydropower capacity in the Middle East by year of commissioning**

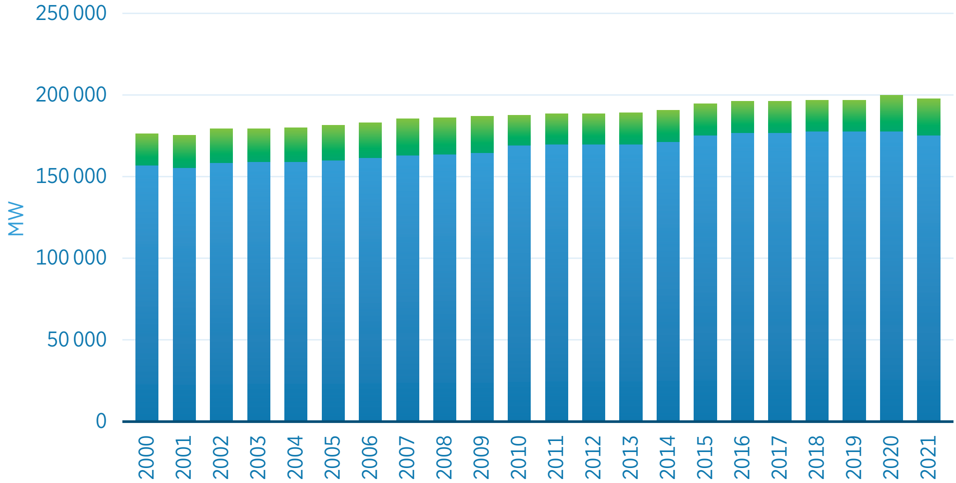


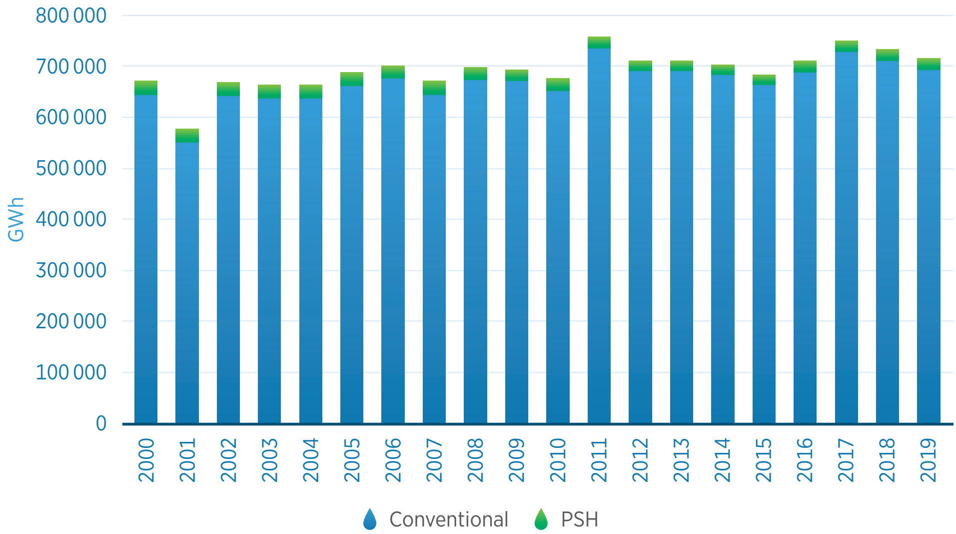
Note: Data include pumped storage hydropower. Data points with no commissioning date are grouped under N/A. MW = megawatt; N/A = not available.

Based on: S&P Global (2022).

NORTH AMERICA

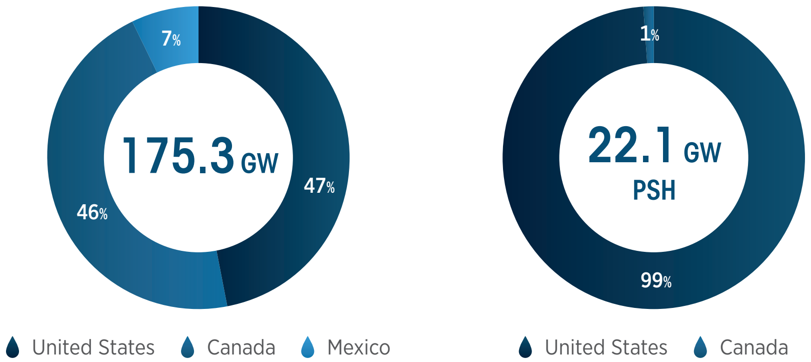
Figure B.25 **Hydropower capacity and generation in North America, 2000-2021**





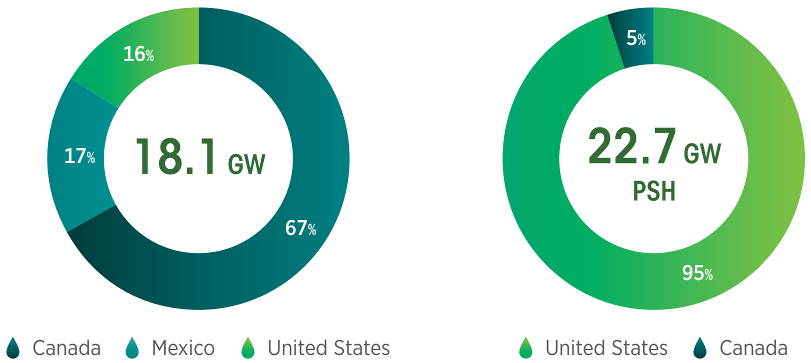
Note: GWh = gigawatt hour; MW = megawatt; PSH = pumped storage hydropower.
Source: IRENA (2022b).

Figure B.26 **Hydropower installed capacity in North America, 2021**



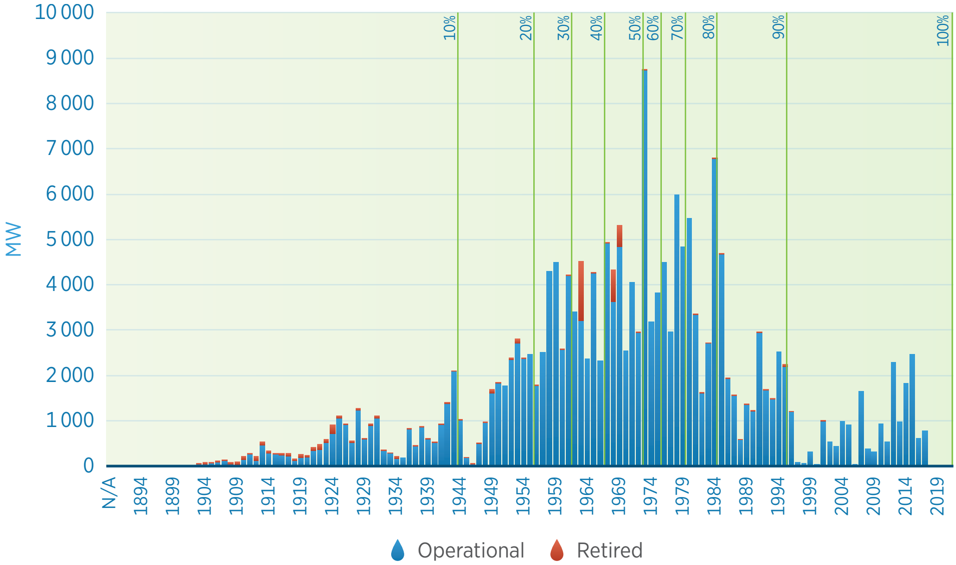
Note: GW = gigawatt; PSH = pumped storage hydropower.
Source: IRENA (2022b).

Figure B.27 **Hydropower project pipeline in North America, 2022-2037**



Note: GW = gigawatt; PSH = pumped storage hydropower.
Based on: S&P Global (2022).

Figure B.28 **Hydropower capacity in North America by year of commissioning**

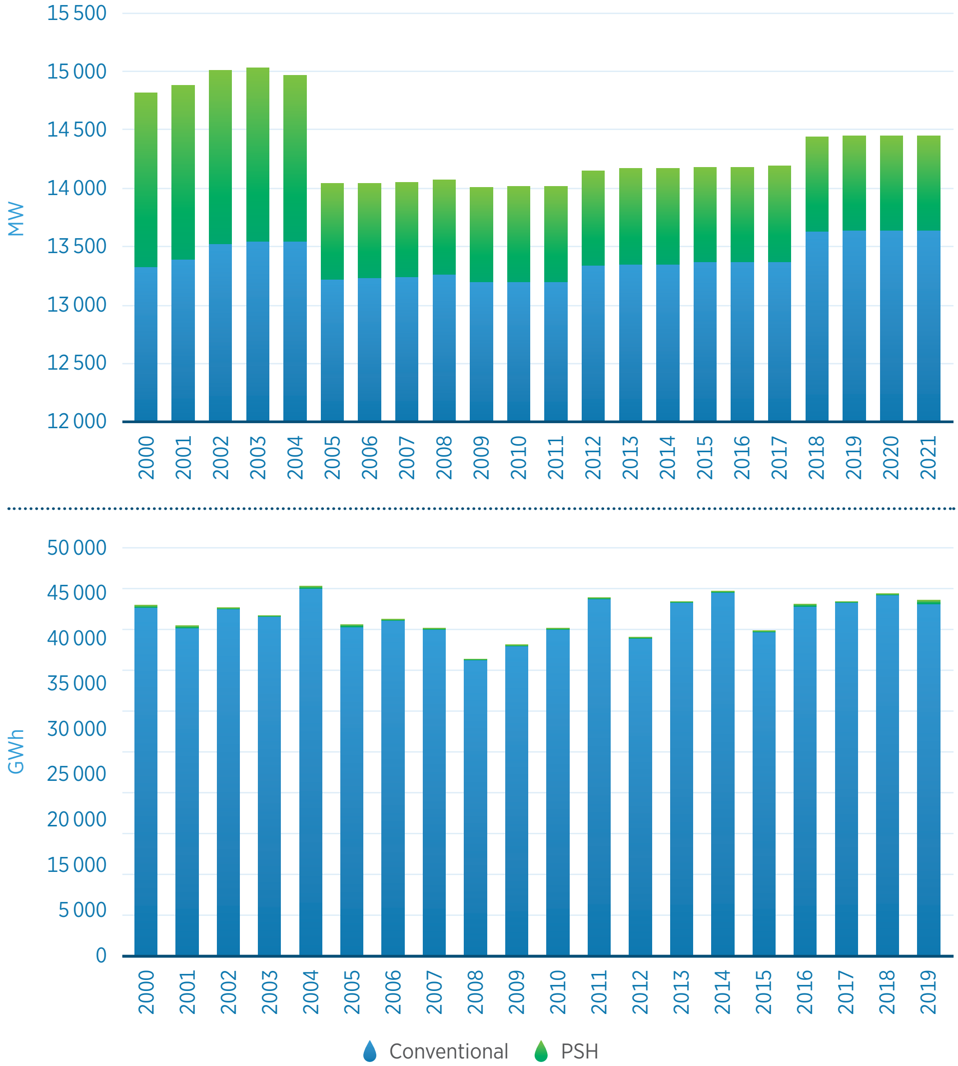


Note: Data include pumped storage hydropower. Data points with no commissioning date are grouped under N/A. MW = megawatt; N/A = not available.

Based on: S&P Global (2022).

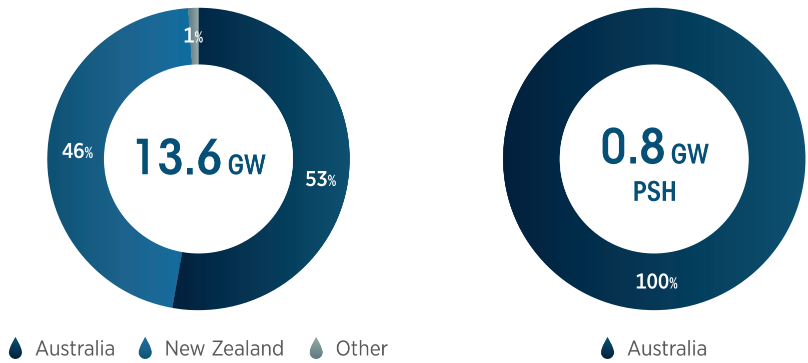
OCEANIA

Figure B.29 **Hydropower capacity and generation in Oceania, 2000-2021**



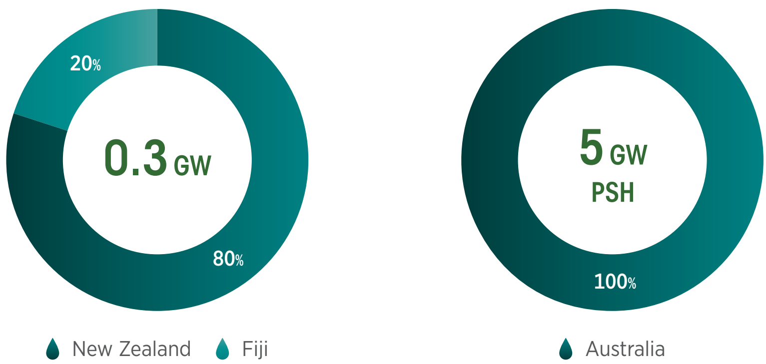
Note: GWh = gigawatt hour; MW = megawatt; PSH = pumped storage hydropower.
Source: IRENA (2022b).

Figure B.30 **Hydropower installed capacity in Oceania, 2021**



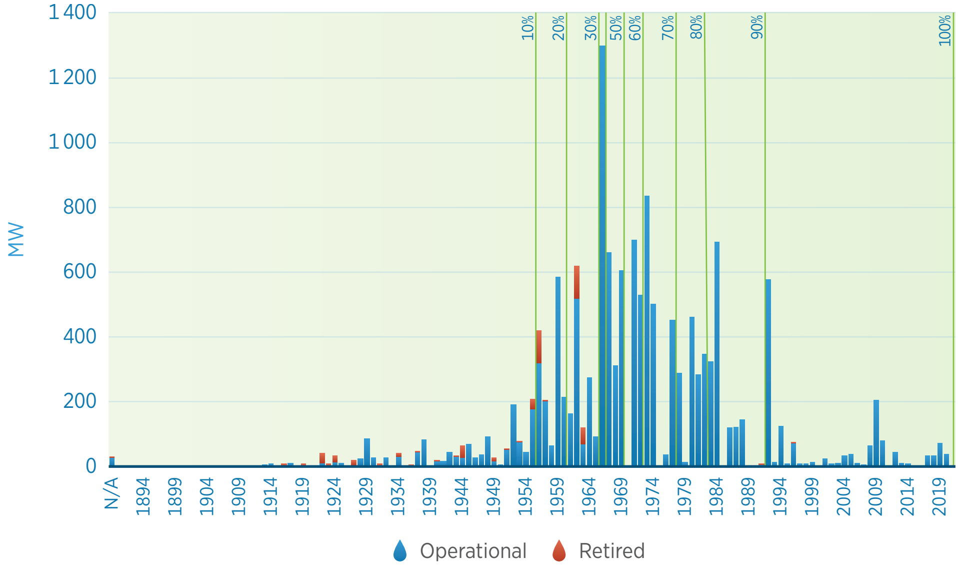
Note: GW = gigawatt; PSH = pumped storage hydropower.
Source: IRENA (2022b).

Figure B.31 **Hydropower project pipeline in Oceania, 2022-2037**



Note: GW = gigawatt; PSH = pumped storage hydropower.
Based on: S&P Global (2022).

Figure B.32 **Hydropower capacity in Oceania by year of commissioning**

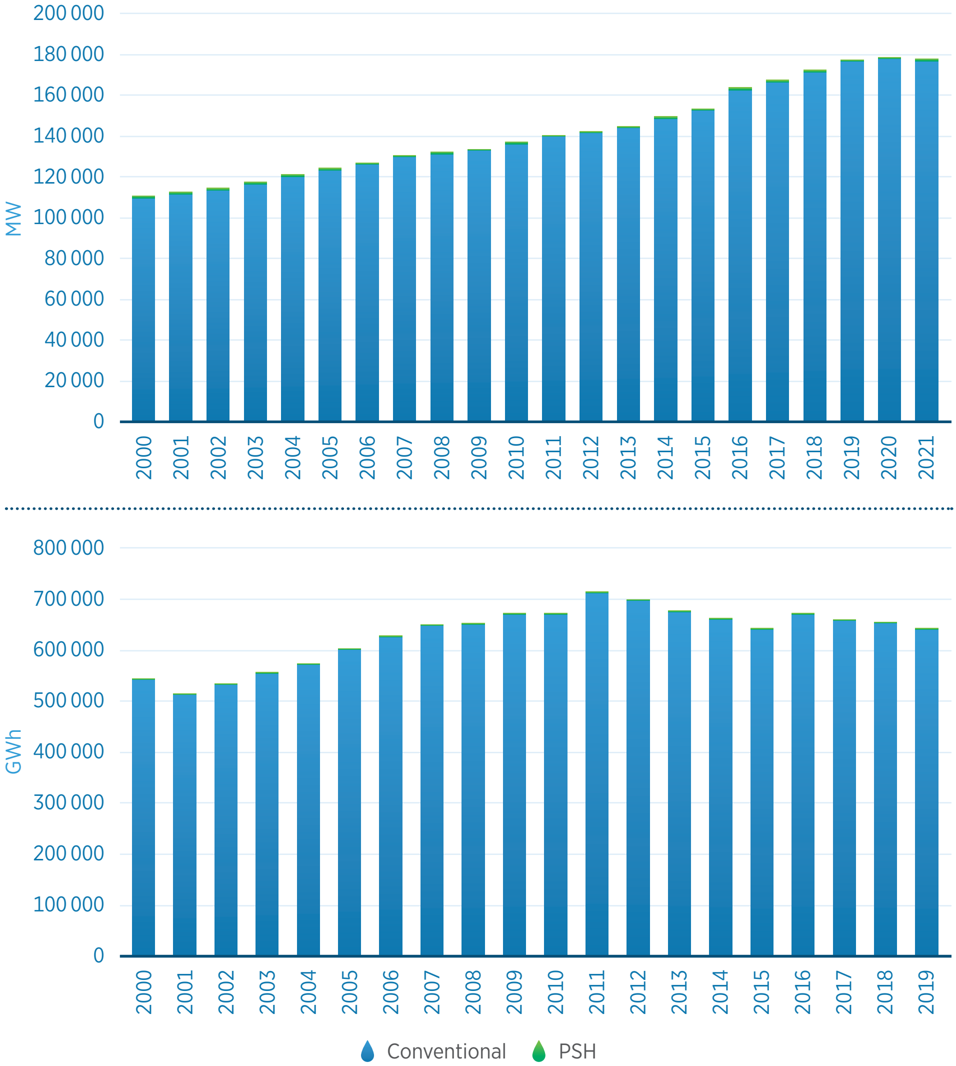


Note: Data include pumped storage hydropower. Data points with no commissioning date are grouped under N/A. MW = megawatt; N/A = not available.

Based on: S&P Global (2022).

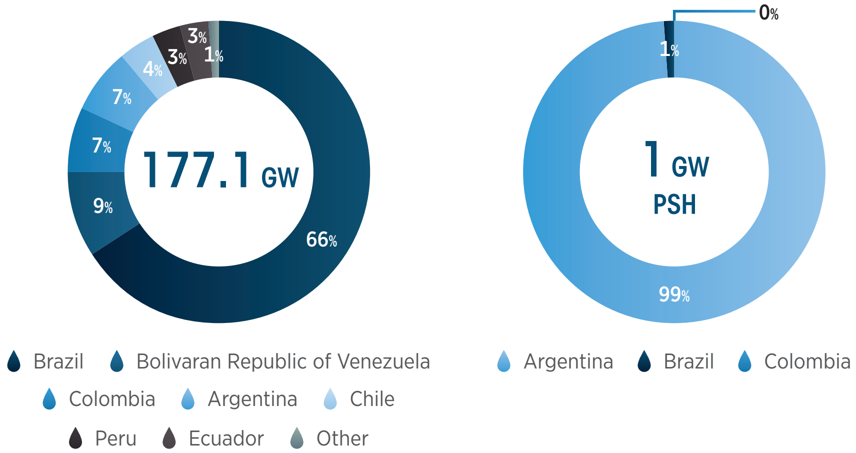
SOUTH AMERICA

Figure B.33 **Hydropower capacity and generation in South America, 2000-2021**



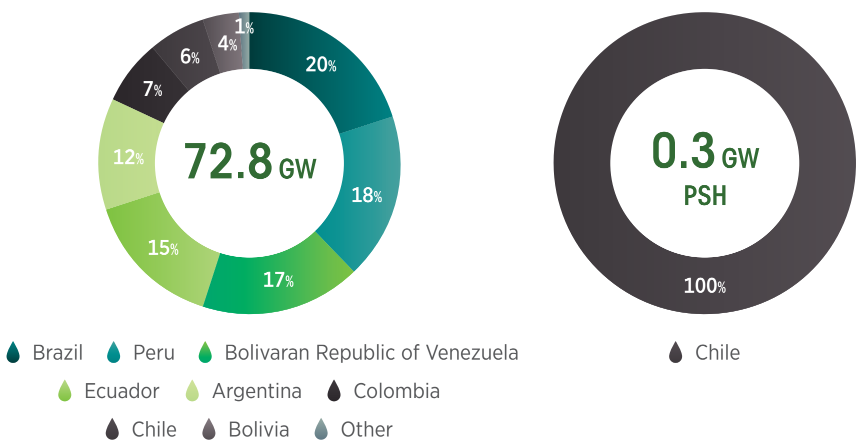
Note: GWh = gigawatt hour; MW = megawatt; PSH = pumped storage hydropower.
Source: IRENA (2022b).

Figure B.34 **Hydropower installed capacity in South America, 2021**



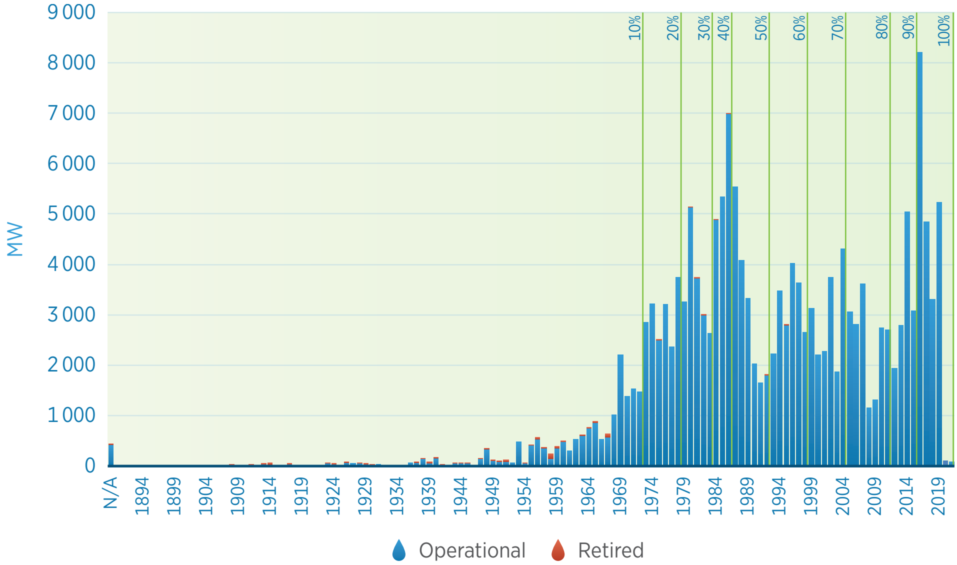
Note: GW = gigawatt; PSH = pumped storage hydropower.
Source: IRENA (2022b).

Figure B.35 **Hydropower project pipeline in South America, 2022-2037**



Note: GW = gigawatt; PSH = pumped storage hydropower.
Based on: S&P Global (2022).

Figure B.36 **Hydropower capacity in South America by year of commissioning**



Note: Data include pumped storage hydropower. Data points with no commissioning date are grouped under N/A. MW = megawatt; N/A = not available.

Based on: S&P Global (2022).

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