Waterfall: The Role of Hydroelectricity

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The Abdullah Bin Hamad Al-Attiyah International Foundation for
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INTRODUCTION

WATERFALL: THE ROLE OF HYDROELECTRICITY

Hydropower is an important part of world electricity, and still larger than all other renewable generation combined. It is highly economic, provides reliable, dispatchable power, and avoids most greenhouse gas emissions. Even though most of the best sites in Europe and the Americas have been exploited, there is still significant room for expansion in Asia and Africa. However, dams bring significant local environmental and social impacts, including habitat loss and human displacement. Dams on multinational rivers have become highly politicised and controversial. What is the role of hydroelectricity in future energy, and how can the negative impacts be managed?

Energy Industry Report

This research paper is part of a 12-month series published by the Al-Attiyah Foundation every year. Each in-depth research paper focuses on a prevalent energy topic that is of interest to the Foundation's members and partners. The 12 technical papers are distributed in hard copy to members, partners and universities, as well as made available online to all Foundation members.

EXECUTIVE SUMMARY

- Hydropower is a mature technology and is still the largest installed form of renewable energy. It is dispatchable and has highly competitive costs and (usually) low greenhouse gas emissions.
- Hydropower growth rates remain significant, though much slower than wind and solar. Further expansion is constrained by a lack of suitable sites, but there is still room for growth in Africa and Asia in particular.
- The range of forecasts for future hydropower is much smaller than for fossil fuels or other renewables, with typical ranges of 6000-8600 TWh/year by 2050, from just over 4000 TWh/year today.
- Large hydropower schemes bring several environmental and social problems, including displacing people, drowning habitats and historic sites, disturbing ecosystems and in some locations, releasing high levels of greenhouse gases from decomposing vegetation.
- Large dams are highly political projects and are already concerned with significant disputes and controversies in parts of Africa, south-east and south Asia . Financing and constructing large hydropower is a significant component of China's Belt and Road Initiative.

IMPLICATIONS FOR LEADING OIL AND GAS PRODUCERS

- Hydropower is important for balancing variable renewables, particularly over longer timescales. Countries with a high share of hydropower resources find it easier to incorporate larger shares of solar and wind. This can affect the need for gas-fired balancing power.
- Hydropower has the possibility of expanding significantly in some areas, notably sub-Saharan Africa, and so displacing the need for fossil-fuelled power.
- However, large hydro projects, especially those planned to export power beyond the host country, are politically complicated and often face obstacles to financing and construction.

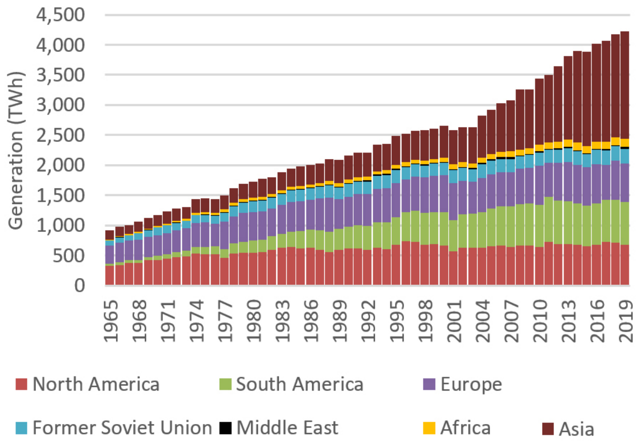
HYDROELECTRICITY IS STILL THE LEADING SOURCE OF RENEWABLE ENERGY

Hydropower generates electricity from moving or falling waters driving a turbine. This is usually from waters impounded behind a dam, but can also be 'run of river', usually by diverting part of a river through a turbine. Hydroelectricity is a mature technology with a long history, having been first developed in 1878 in the UK, with the first commercial plant at Niagara Falls in 1881. But it is still the largest form of renewable energy, providing 14.1% of world electricity in 2019 (other renewables, including wind, solar and biomass, contributed 9.0%). It also continues to maintain respectable growth rates, with a compound average growth rate (CAGR) of 2.5% since 2000.

Since 2003, Asia has emerged as the main region for hydro growth and generation (FIGURE 1). This increase has mostly been driven by massive construction of new facilities in China, such as the Three Gorges Dam (see cover image). Europe and North America remain important but have seen relatively little growth since the 1980s. Latin America has also not increased much over the last decade. Generation in the Middle East is small due to its primarily arid climate, while Africa has massive potential, but most remains underdeveloped and it has seen relatively slow growth since 2000. Hydropower generation in general is rather variable because of changing weather conditions from year to year.

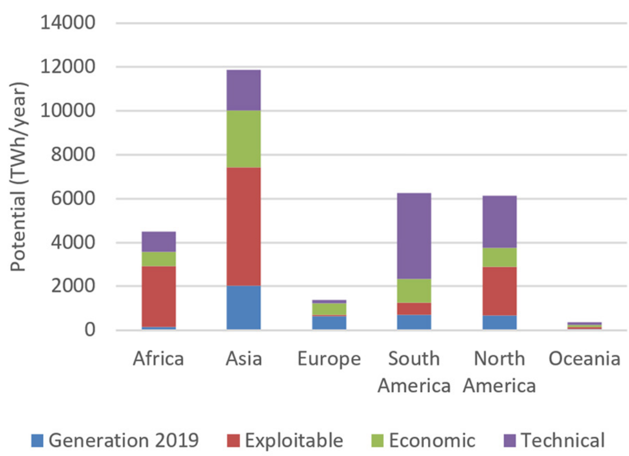
Despite its long history, significant hydroelectric potential remains worldwide (FIGURE 2). Potential is divided into technical, economic (that meeting certain cost criteria based on the size and nature of the site and distance to consumers), and exploitable (economic potential that also avoids protected areas, such as national parks, and urban areas).

FIGURE 1 HYDROPOWER GENERATION BY REGION, 1965-2019[i]



Total generation in 2019 was about 28% of the global economic resource. Europe is estimated to have exploited about 90% of its resource, South America 57%, and Africa only 5%, while the largest remaining absolute potential is in Asia, with 5410 TW/h unused. The total exploitable resource is estimated at 15 350 terawatt hours per year (TWh/y), compared to total global generation of 27 005 TWh in 2019, i.e. hydroelectricity could potentially satisfy more than half current global electricity demand. In practice, these numbers may be somewhat overestimated, but nevertheless hydropower has significant room for further growth.

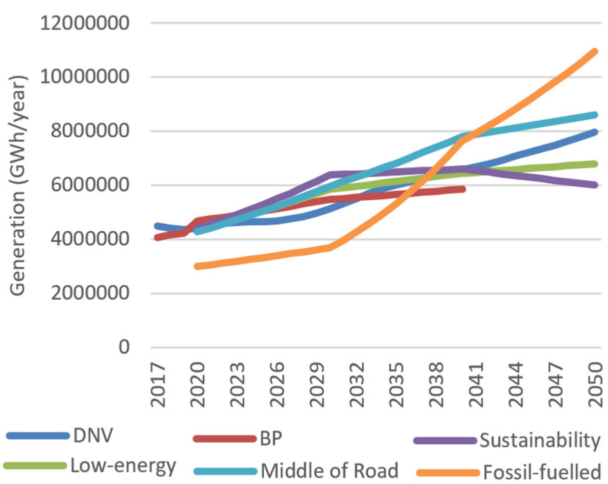
FIGURE 2 HYDROELECTRIC POTENTIAL BY REGION[ii]



HYDROELECTRICITY IS STILL THE LEADING SOURCE OF RENEWABLE ENERGY

Below, the graph in FIGURE 3 compares forecasts for hydroelectric generation to 2050. Overall, the divergence in opinion is relatively low, less than for the fossil fuels or solar or wind. Apart from the 'fossil-fuelled' scenario, which starts oddly low and then grows very quickly, the others end up at 6000-8600 TWh/year by 2050, and all show steady increases apart from the 'sustainability' scenario which plateaus after 2030 and declines after 2040. This relative similarity reflects that hydro is a mature energy source with a large installed base, that is not likely to undergo major cost or technological progress; it is limited in expansion because of a lack of suitable sites; but it is a low-cost, low-carbon, dispatchable and flexible option, which is therefore attractive for growth where possible.

FIGURE 3 HYDROELECTRIC FORECASTS 2017-50[iii]



Hydropower currently produces 15.6% of global electricity, and 43% of low-carbon electricity. Under most forecasts, its share of low-carbon generation will drop (to 16.9% in DNV's view) because of the faster growth of solar and wind, but its share of total electricity will remain about the same (13.9% in DNV's forecast). It will therefore still be an important part of meeting climate targets.

From countries' nationally determined contributions (NDCs) under the 2015 Paris Agreement on climate change, about 1300 GW of additional renewable energy is to be installed, of which 240 GW is designated for specific technologies. Of this, 110 GW is large hydropower, 80 GW solar photovoltaics, and 30 GW onshore wind. This further emphasises that, at least in the medium term, hydropower will continue to be a large source of new low-carbon electricity[iv].

HYDRO IS THE MOST COST-COMPETITIVE FORM OF LOW-CARBON DISPATCHABLE GENERATION

Costs for hydroelectricity vary widely depending on the site, the size of storage chosen, and distance to markets. In remote locations, a captive industrial facility such as an aluminium smelter may make use of a nearby dam for power. In good locations, hydropower is the cheapest form of dispatchable electricity generation. There are some opportunities for cost reduction in hydropower, mostly related to better civil engineering, but this is probably outweighed by the fact that the best and most accessible locations have already been developed[v]. Large hydropower has costs in the range \$0.02-0.06/kWh, and small hydropower \$0.03-0.115[vi].

HYDRO IS GEOGRAPHICALLY LIMITED, BUT STILL HAS LARGE POTENTIAL FOR NEW SITES IN AFRICA AND ASIA

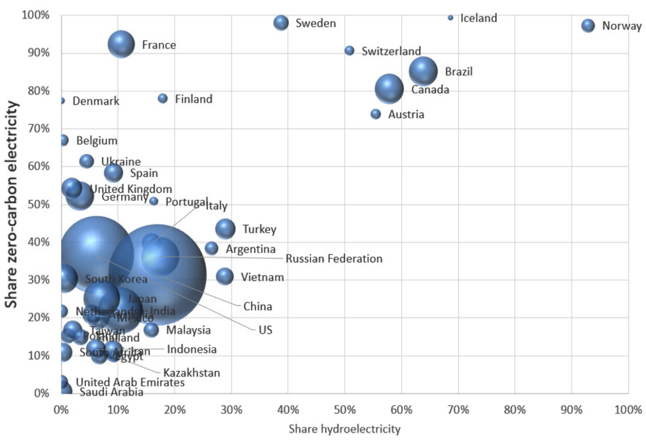
New hydroelectric projects continue to be developed. Some notable examples include:

- Grand Ethiopian Renaissance Dam (GERD) on the Blue Nile, with 6450 MW generating capacity, which will be the largest hydroelectric plant in Africa when completed. Filling of the reservoir is scheduled to start in July 2020. The cost is about $4.8 billion.
- Grand Inga on the Congo in the Democratic Republic of Congo. Existing capacity is 1775 MW, with an additional 4800 MW under construction, with potential eventual capacity of 42000 MW at a cost of $80 billion[vii].
- Rufiji in Tanzania, 2115 MW[viii].
- Belo Monte in Brazil, under construction, with 11233 MW planned capacity, the third largest in the world, at a cost of $26 billion[ix].
- Site C in British Columbia, Canada, costing $6.3 billion, with capacity of 1098 MW[x].
- Owens Valley pumped hydro plant in California, with 5200 MW capacity[xi].
- Jinsha River on the upper Yangtze in China, with total planned capacity from 20 dams of 76638 MW.
- Yarlung Tsangpo project in Tibet, on the upper part of what becomes the Brahmaputra River in India, with potential capacity of 50000 MW.
- Sankosh in Bhutan, 2500 MW at a cost of $1.65 billion[xii].
- Myitsone in Myanmar (Burma), 6000 MW[xiii] costing $3.6 billion.
- Snowy 2.0 pumped hydro plant in New South Wales, Australia, costing $3.62 billion for 2000 MW additional capacity, planned to be completed by 2024.

LARGE-SCALE HYDRO IS KEY FOR BALANCING ELECTRICITY SYSTEMS

Large-scale hydropower is important for balancing electricity systems because of its low operating cost and dispatchability. Indeed, most countries that have reached high shares of low-carbon power generation have done so with hydropower (FIGURE 4). In this chart, low-carbon electricity includes hydropower, other renewables (solar, wind, geothermal, etc) and nuclear. A few countries, such as France and Belgium, have reached high shares of low-carbon generation with nuclear power, and others have done it with non-hydro renewables, mostly wind and biomass (Denmark and Finland). But several other nations, including quite large power systems as in Brazil and Canada, have more than 50% hydropower and more than 80% low-carbon generation.

FIGURE 4 SHARE OF LOW-CARBON AND HYDROELECTRICITY BY COUNTRY, 2019 (BUBBLE SIZE INDICATES TOTAL NATIONAL GENERATION)[xiv]

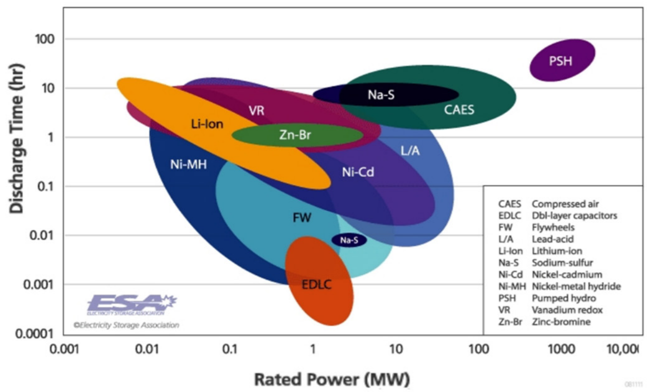


Hydropower can balance variable renewables such as wind and solar, as well as compensating for demand fluctuations better than less-flexible generation such as coal and nuclear.

Pumped hydro storage uses cheap off-peak electricity to pump water back uphill into a reservoir, then releases it at times of peak demand. Pumped hydro can be implemented without requiring a natural river – it just needs hydraulic head (i.e. a height difference). Pumped hydro schemes have been implemented using seawater in coastal locations, abandoned mines and artificial islands. Round-trip efficiency is high, in the range 75-85%.

With a growing share of variable renewables in many countries, storage is increasingly important. Some of this may be taken by thermal storage, compressed air, batteries, and other emerging technologies. But pumped hydropower remains the main option for long-term, high-volume storage (FIGURE 5).

FIGURE 5 ELECTRICITY STORAGE SYSTEMS BY SIZE AND TIME [xv]



To reach very high shares of renewable energy in power systems, it has been suggested to install much larger turbines at hydroelectric sites, and to use variable renewables to run them as pumped storage systems capable of meeting high peak loads[xvi]. However, the practical feasibility of this may be doubtful given the other functions dams perform (namely, water regulation).

DAMS HAVE OTHER APPLICATIONS BEYOND POWER GENERATION

Unlike most other forms of power generation, dams have other concurrent applications. Indeed, dams do not have to feature power generation at all. Of dams worldwide, 25% have the primary purpose of hydroelectricity, 34% are for irrigation, 8% for water supply, 2% for flood control, and the rest have other functions[xvii]. Another significant ancillary use is for leisure (sightseeing, water sports) and aquaculture, including fishing.

These uses, particularly water control, have economic value which serve to reduce the effective cost of power generation from a dam. However, they can also reduce the flexibility of operation, for example when water must be released for irrigation use at a time when the dam's power is not needed.

Hydropower is also dependent on climate, and generation can vary significantly between years, particularly in drier climates. For example, China's Three Gorges Dam (22.5 GW), the world's largest, had a capacity factor of 50% in 2014, while Itaipu in Brazil / Paraguay, the second-largest, had a capacity factor of 79% in 2016, because of the steadier flow of the Paraná River. In relatively arid Iran, overall capacity factors were 20-30% up to 2007 but have since fallen off significantly and were just 9.4% in 2018.

LARGE-SCALE HYDRO HAS DAMAGING ENVIRONMENTAL CONSEQUENCES

Despite their low-carbon generation, hydroelectric projects are not environmentally harmless.

Impounded (dam-based) hydropower floods large areas, causing a loss of natural and cultural sites and habitat. Hydro projects are often in scenic upland areas, and important historic remains are frequently located in river valleys. The city of Hasankeyf on the Tigris in Turkey may be one of the oldest continuously inhabited settlements in the world, but is now being flooded by construction of the Ilısu Dam.

Major dams disrupt ecosystems. For instance, they prevent upriver fish migration to breeding grounds. Even when fish migratory channels are provided, the warmer water in the lake behind the dam can be unsuitable for spawning. Silt accumulates heavy metals and other pollutants.

Evaporation in the impounded lake reduces overall water flow. Evaporation rates are enormously variable depending on the size, shape, altitude, and local climate of the dam. For example, evaporation from Lake Nasser behind the Aswan High Dam in Egypt can be estimated at about 16 billion cubic metres (BCM) annually[xviii], a significant amount compared to the 55.5 BCM allocated to Egypt under the Nile Waters Treaty of 1959[xix]. With rising temperatures due to global warming, evaporation rates will increase.

Dams silt up over time, at highly variable rates depending on the sedimentary load of the feeding river, and this can cause storage to reduce at 0.1-2.3% annually[xx]. The loss of silt downstream reduces fertilisation of land and can cause shoreward retreat of the delta at the eventual point of reaching the sea.

Dams do contribute greenhouse gases (GHGs). Their construction requires large quantities of concrete, causing indirect emissions from cement manufacture. Nevertheless, the overall lifecycle GHG footprint of hydropower, excluding reservoir emissions, is low at less than 10 grams CO^2 equivalent per kilowatt hour (gCO^2e/kWh), compared to 307 gCO^2e/kWh for a highly-efficient gas-fired combined cycle plant, or 16-57 gCO^2/kWh for solar photovoltaic power[xxi].

However, reservoir emissions can be very significant. They are caused by the decomposition of vegetation underwater, releasing carbon dioxide and the more powerful GHG methane[xxii]. This decomposition is most significant in tropical climates, particularly where the lake level rises and falls repeatedly, allowing plant growth on the banks. Including reservoir GHGs, the median GHG footprint of hydropower is estimated at 18 gCO^2e/kWh; however, 16% of reservoirs have emissions greater than 100 gCO^2e/kWh[xxiii] a point which begins seriously to erode their climate benefits. Reduction of GHG footprints can be done by careful design, by raising the dam's power density (i.e. generating more power from a given area of impounded lake), and by avoiding dams in hot, tropical climates. However, as noted, many proposed new dams are in sub-Saharan Africa and south-east Asia.

Dams also present some safety issues. The stress of large masses of water can trigger earthquakes. It has been suggested that the 7.9 magnitude Sichuan earthquake of 2008, which killed 80,000 people, was triggered by the Zipingpu dam nearby, which had been filled three years earlier[xxiv]. Dams in earthquake-prone areas also must be designed to resist seismic shocks.

LARGE-SCALE HYDRO HAS DAMAGING ENVIRONMENTAL CONSEQUENCES

The Mosul Dam in northern Iraq is built on soluble gypsum and requires continuous injection of grouting to prevent collapse as the foundations dissolve. This operation was interrupted during the occupation of the dam by the terrorist group ISIS during 2014, leading to fears that Mosul and even Baghdad could be inundated by the dam's collapse.

Ageing dams are increasingly stressed by climate change. Heavy flooding can overtop the structure when the spillway is inadequate[xxv].

Obsolete, dangerous or environmentally damaging dams are now being gradually removed in parts of Europe and the US, such as Washington State, helping to restore fish habitats[xxvi].

RUN-OF-RIVER HYDRO CAN BE LESS ENVIRONMENTALLY DAMAGING

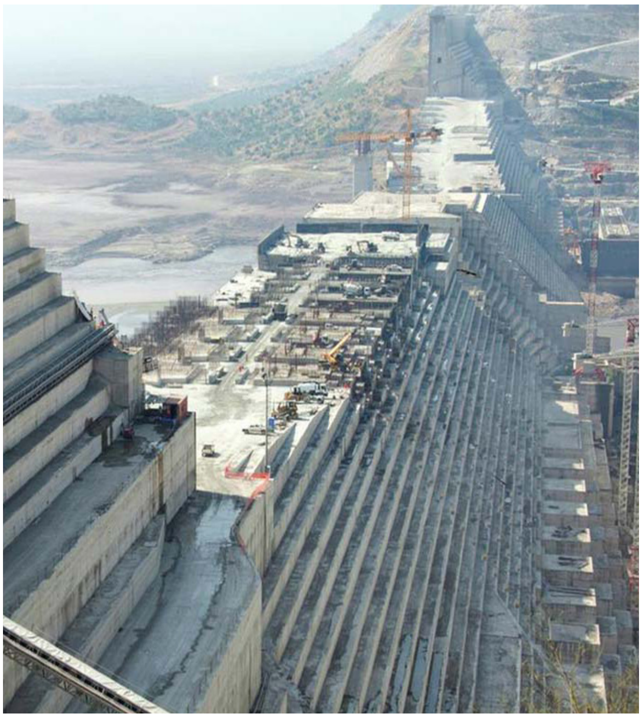
Run-of-river plants offset some of the disadvantages of large-scale hydropower with dams. Because they do not impound water, they do not flood areas or disrupt the natural course of the river. However, this also means they follow seasonal variations in river flow and cannot store power. They save on the expenses of a dam, but this may be offset by lower average usage factors on the turbines.

Small-scale hydro projects can be useful for bringing power to remote or off-grid sites.

LARGE DAMS CAN BE HIGHLY POLITICAL

Several large hydropower projects have attracted major political controversy. This is usually because of some combination of three factors:

- Local and community opposition to environmental damage, loss of land, etc.
- Dams built in small countries, where most the funding and intended market is in another country, creating worries about debt dependency, inadequate local benefits, etc. This applies to the Myitsone dam (where 90% of the power was originally meant to be sold to China), the Grand Inga dam (with Chinese financing, and half of the power contracted to South Africa), and to Bhutanese dams intended to supply India.
- Worries from downstream countries about interruptions to their water supply. Examples include the proposed Yarlung Tsangpo project, with India concerned about Chinese control of the headwaters of the Brahmaputra; and Ethiopia's GERD, with opposition from Egypt.



Egyptian companies are financing the Rufiji Dam in Tanzania, apparently partly as a demonstration that Egypt is not against hydropower development in other African countries. However, much of sub-Saharan Africa suffers from an inadequate grid, meaning that hydro projects serve large cities, big consumers such as mines, and export markets, with local rural populations seeing disruption but not much benefit.

China's Belt and Road Initiative has been particularly prominent in financing and constructing hydroelectric projects, particularly in the Greater Mekong region in south-east Asia and in Africa, including a four-dam project in Nigeria costing $5.8 billion, Zambia's Kafue Gorge Lower dam, and the Gilgel Gibe III dam in Ethiopia.

Dams have contributed to the drying-out of wetlands in the Sahel area of Africa, disrupting downstream communities and leading some members to join violent extremist groups such as Boko Haram, or to resort to risky people-smuggling routes. Large-scale projects in Turkey and Iran have reduced water flows into Syria and Iraq, already suffering from poverty, drought, agricultural decline, and conflict[xxvii].

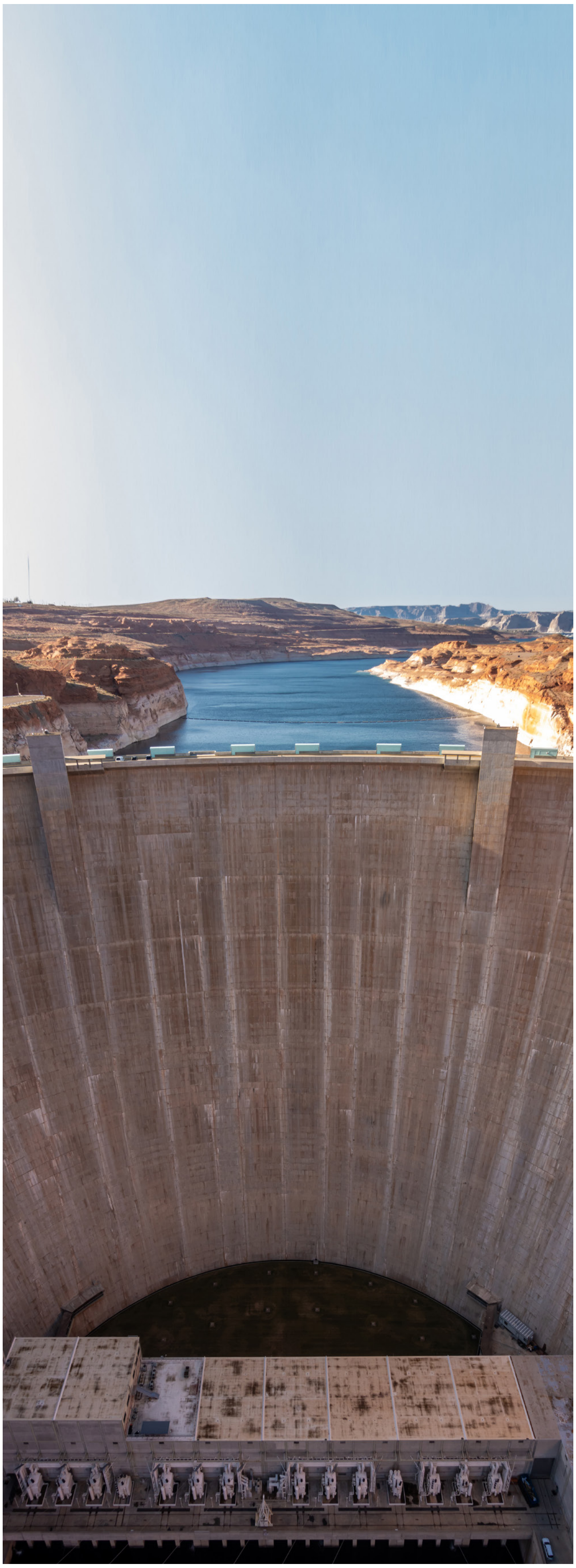
These concerns are likely to become more acute due to population and economic growth in some sensitive river basins, geopolitical confrontations (for instance, China versus India), and climate change leading to changes of precipitation, glacier melting and reduced and/or less predictable river flows. These concerns relate mostly to the hydrological aspect of dams more than their electricity generation, but still poses a challenge to new projects.

CONCLUSIONS

There is relatively more consensus on the role of large hydropower than of fossil fuels, other renewables or nuclear power. Hydropower is highly economically viable in good sites, and overall environmentally favourable, despite some significant drawbacks. It is mainly constrained by the lack of suitable sites. Numerous projects have been proposed in sub-Saharan Africa, but here they face challenges of limited financing and small local power markets.

Since high levels of hydropower are favourable to incorporating large renewable shares, they have an important influence on the amount of gas-fired balancing a country is likely to require. Pumped hydro storage will be increasingly employed to balance variable renewables over longer (seasonal) periods, where local geography is suitable.

Hydropower can therefore be treated largely as a 'known' quantity in the future energy system. It is likely to grow significantly but not rapidly or unpredictably. Nevertheless, specific projects are worth watching because they can have a major impact on national or regional energy balances, and they are vulnerable to delay or cancellation from community, political or environmental causes.



APPENDIX

i. From data in BP Statistical Review of World Energy 2020
ii. . 2019 generation from BP Statistical Review of World Energy 2019; other data from Zhou et al. (July 2015), https://www.researchgate.net/publication/279911353_A_Comprehensive_View_of_Global_Potential_for_Hydro-generated_Electricity
iii. From data in BP Energy Outlook 2019, DNV Energy Transition Outlook 2019, https://data.ene.iiasa.ac.at/iamc-1.5c-explorer/#/workspaces/2. Where data is not available for intervening years, it has been interpolated assuming constant growth rates.
iv. https://irena.org/-/media/Files/IRENA/Agency/Publication/2017/Nov/IRENA_Untapped_potential_NDCs_2017.ashx
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xii. https://www.thethirdpole.net/2019/06/24/bhutan-prioritises-reservoir-hydropower/
xiii. https://www.hydroreview.com/hydro-projects/#gref
xiv. From data in BP Statistical Review of World Energy 2020
xv. Electricity Storage Association, https://na.eventscloud.com/file_uploads/05612c1b0b638b14d1ede35138c07afc_EnergyStorage_HRS_2019-02-04.pdf
xvi. https://www.sciencedirect.com/science/article/pii/S2096511719301045
xvii. https://energypolicy.columbia.edu/research/report/power-river-introducing-global-dam-tracker-gdat
xviii. https://www.sciencedirect.com/science/article/pii/S1110982317300340
xix. https://transboundarywaters.science.oregonstate.edu/sites/transboundarywaters.science.oregonstate.edu/files/Database/ResearchProjects/casestudies/nile.pdf
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xxi. https://www.climatebonds.net/files/files/Hydropower%20Criteria%20Background%20Paper.pdf
xxii. https://pubs.acs.org/doi/10.1021/acs.est.9b05083#
xxiii. https://www.hydropower.org/news/study-shows-hydropower%E2%80%99s-carbon-footprint
xxiv. https://www.wsj.com/articles/SB123391567210056475
xxv. https://www.cnbc.com/2020/05/21/more-dams-will-collapse-as-aging-infrastructure-cant-keep-up-with-climate-change.html
xxvi. https://blogs.ei.columbia.edu/2011/08/29/removing-dams-and-restoring-rivers/
xxvii. https://energypolicy.columbia.edu/research/report/power-river-introducing-global-dam-tracker-gdat

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