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by Deloitte

Innovation in hydropower

Accelerating environmentally sustainable hydro expansion

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Hydropower production is the largest source of low-emissions electricity globally, and production needs to double by 2050, according to the International Energy Agency's (IEA) Net Zero Emissions Scenario.[1] But opposition to the construction of big dams, high development costs, and the growth of wind and solar power have slashed investments in hydropower.[2] Technological innovations have the potential to boost hydropower production with new methods at lower ecological and social costs.

Conventional hydropower generation forces environmental tradeoffs

Hydropower has the benefit of providing clean, baseload electricity, unlike wind and solar which are intermittent. But it has typically involved large dams and their reservoirs. These can interfere with water flow and submerge vast tracts of land, which can be ecologically destructive and decompose organic matter releasing methane, a potent greenhouse gas.[3] Large dams can also displace people, disrupt livelihoods, and have seismic consequences. Consequently, the building of large, new reservoir-based hydro projects has declined compared to past decades, according to the United Nations.[4] Dams are even being removed in places; sixty-five were removed in the United States alone in 2022.[5] In this environment, technological innovations may become a key to expanding hydro capacity.

Innovative hydropower technology makes a splash

Innovations in hydropower turbine technology are expanding its potential. Today it is possible to generate power in new locations, with simpler, lower-cost installation, and fewer environmental impacts. Some turbines can operate with relatively low water flow or "head" (height of fall). Some systems reduce or eliminate the need to stop running water or allow easier passage of sediment and fish. See **Table 1**. There are dozens of turbine manufacturers, but venture and growth equity investment in turbine tech is modest so far, totaling just over US$400 million raised across 59 companies according to data from PitchBook and CB Insights. By comparison, 138 long-duration energy storage companies have received nearly US$6.1 billion, according to PitchBook data. Relatively low investment levels in hydro may reflect a preference for other segments of the clean energy sector. It may also reflect less awareness of the potential for innovative hydro technologies.

Table 1. Select turbine innovations

Technology	Brief description	Technology readiness	Availability (# of vendors)	Select potential benefits	Select potential challenges
Very-low head turbine[6]	Innovations on axial flow or other turbine types for <4.5m head	Commercial — E.g., irrigation canal in Italy (100 kW)	17 of 59	• Easier installation with lower civil work cost versus usual Kaplan turbines • Fish-friendly given slow rotor	• Relatively higher equipment cost • Larger space requirement • Sediment passage can be a challenge
Modular versions of conventional turbines[7]	Standardized, small-scale forms of turbines such as bulb, Francis, Kaplan, and Pelton	Commercial — E.g., dam in Indiana, US (2.5 MW)	9 of 59	• Optimized for low heads and flows • May cut customization costs and complexity • Can allow pre-fabrication for faster installation with less civil work	• Doubts persist on standardization given diverse site conditions • May be less efficient than larger conventional turbines • Popular designs such as Francis and Kaplan may harm fish and struggle with sediment passage
Archimedes hydrodynamic screw turbine[8]	Low- to medium-head turbine, with water flowing along a screw-like structure to rotate it	Commercial — E.g., river in Scotland (92 kW)	8 of 59	• Good efficiency • Fish-friendly • Allows sediment passage	• Heavy and large • Can be challenging to construct, transport to site, and install
Pump-as-turbine[9]	Centrifugal pumps operated in reverse mode	Commercial — E.g., paper mill wastewater system in Germany (53 kW)	6 of 59	• Available in many standard sizes for a range of flows and heads • Low cost with easy installation and easily available spares	• May be less efficient than a turbine, especially in suboptimal water conditions • Performance can be unpredictable
Vortex turbine[10]	Low-head turbine, with water entering a basin and exiting at its bottom to form a rotor-pushing vortex	Commercial — E.g., riverside school in Indonesia (13 kW)	4 of 59	• Simple, cost-effective design • Installs in smaller spaces without needing dams, reservoirs, or much installer expertise • Low to no challenge to passing of water, sediments, or fish	• Often less efficient than other hydro turbines though improvements are being made • Relatively new technology, hence performance mechanisms are still being understood
Restoration hydro turbine[11]	Mainly low-head Kaplan-type axial flow turbine	Commercial — E.g., Irrigation canal in Oregon, US (300 kW)	1 of 59	• Good efficiency • Fish-friendly • Compact and cost-effective design • Less complex to install	• Relatively new hence long-term in-field performance may need to be observed
Vertical axis hydrokinetic turbine[12]	Water flows perpendicular to the rotor shaft to turn the blades	Prototype — E.g., Canal in Colorado, US (5-25 kW per turbine)	3 of 59	• Installs without need for dams or reservoirs, hence lower civil work cost • Minimal environmental disruption	• May be relatively less efficient than conventional turbines

- **Availability:** Number of vendors offering the technology out of 59 large and small global hydropower turbine vendors analyzed by Deloitte US. Some of the 59 offer none of the above innovations while others offer more than one.
- **Bulb, Francis, Kaplan, and Peloton:** common conventional turbine forms
- **Axial flow turbine:** water runs parallel to the rotor axis to push blades
- **Head classification:** low (2-20 m), medium (20-150 m), and high (150+ m)
- **Turbine efficiency:** ratio of turbine's output power to power of water head/current[13]

Decentralizing and democratizing hydropower

Many of the turbine innovations mentioned above make it possible to harness new hydro resources for power without new dams. Non-powered dams (NPDs) are one such resource. Built for irrigation, flood control, or other purposes, NPDs lack generating equipment and electricity infrastructure. Retrofitting known NPDs can add nearly 60 GW of hydro generation capacity worldwide, according to 2021 estimates by researchers at Baylor and Kansas State universities.[14] Compact turbines that can function efficiently in locations with low water head and flow, and some that do not need to stop water flow, can be used to help generate power in rivers, streams, and human-made conduits such as water supply and agricultural canals.[15] Globally, "run-of-river" projects may add nearly 30 GW in 2021-2030 based on IEA's "main case" or base scenario estimates.[16] In-conduit projects could add up to 1.4 GW of generation capacity in the United States alone, according to its Department of Energy.[17]

Avoiding the need to construct big dams can democratize the production of hydropower. In the US, private entities own 66% of non-hydropower dams, including organizations involved in banking, agriculture and forestry, hospitality and sports, mining and minerals, oil, real estate, religion, and others.[18] Hydropower generation need not be reserved for large utilities or federal agencies. Enterprises, communities, and other stakeholders can examine the potential of harnessing rivers, canals, and unconventional sites, such as sewage plants and factory drainage systems.[19] Some examples are listed in **Table 2**.

Table 2. Sample of unconventional hydropower stakeholders and locations

Nature of entity	Project location	Turbine	Capacity	Details and benefits
Educational institute in Kentucky, US[20]	Existing river lock	Modular semi-Kaplan	2.64 MW	• US$10.2 million project, with existing lock infrastructure cutting costs • Institute benefits by selling power to local energy cooperative • County public schools benefit from project property taxes
Local government in Scotland[21]	River	Archimedes screw	92 kW	• Expected income of £90,000-120,000 from power against annual operating cost of £15,000
Water utility in Scotland[22]	Wastewater pipeline	Unknown pre-fabricated	42 MWh per year	• Covers 13% of the treatment plant's annual electricity needs • Cuts 64 tons of CO_2 annually
Restaurant in Maine, US[23]	Mill on a stream	Restoration hydro	32 kW	• Leverages existing dam infrastructure associated with mill • Powers restaurant operations and the surrounding community
Farm in Chile[24]	Irrigation conduit	Vortex	15 kW	• Fast and easy installation
Water utility in Colorado, US[25]	Supply canal	Vertical axis hydrokinetic	5 – 25 kW per turbine	• Power fed to the local grid generates credit on utility bills, which offsets energy consumption elsewhere in operations
Government ecological agency in Australia[26]	Public aquarium water filtration system	Low-head propeller type	1.0 – 1.1 kW continuous power	• Recovers 10% of energy used for pumping water • Cuts 7.9 tons of CO_2 annually • Return of 2.6 to 5.8 AU$ per dollar invested considering social and electricity value

Modernizing existing facilities can increase capacity and efficiency

Building new hydropower facilities is not the only path to increasing hydropower resources. Modernizing existing aging facilities has the potential to boost output as well. According to the IEA, nearly 40% of global hydro generation capacity is more than 40 years old and performance can deteriorate with age.[27] The International Hydropower Association (IHA), a trade group, says that replacing equipment like-for-like can raise output by 5% to 10% and upgrading can boost output by 10% to 30%.[28] For example, the capacity of an 88 MW facility established more than 40 years ago in Washington state, US will increase to 100 MW post upgrade.[29]

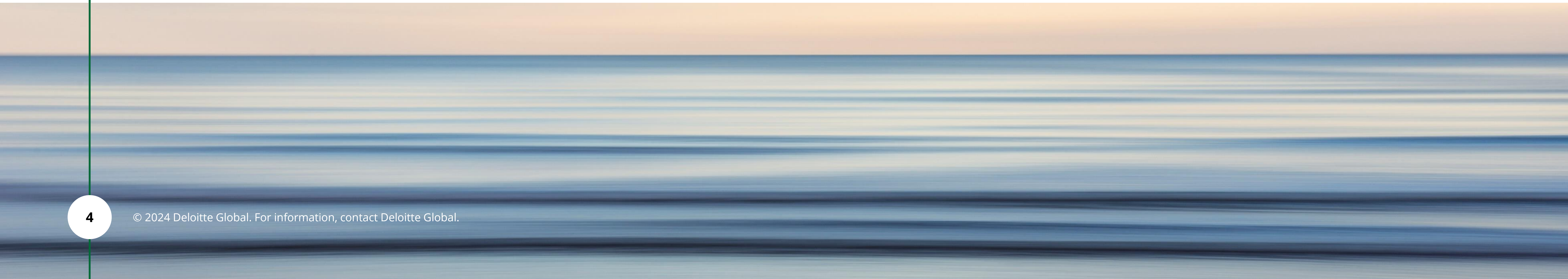
Adding power generation to non-powered dams, or modernizing or expanding existing hydropower installations, can yield power at a lower cost than greenfield projects. IEA figures suggest that power generation from brownfield projects—that leverage pre-existing civil infrastructure such as in NPDs or conduits, expand established plants, or refurbish them—tends to be substantially cheaper than from greenfield projects. That is because expenses for civil works, permits, and environmental impact mitigation have already been incurred.[30] Brownfield may in some cases even be cost-competitive with average wholesale electricity prices and solar photovoltaic (PV) or onshore wind projects (see **Table 3**).

Table 3. Average levelized cost of electricity (LCOE)

Type of hydro project	Scale	Average LCOE (US$/MWh)	
		US	**Europe**
Greenfield	Small	66	99
	Large	48	58
Using existing civil infrastructure	Small	53	79
	Large	34	41
Expanding established plant	Small	33	49
	Large	19	23
Refurbishing established plant	Small	27	39
	Large	15	17
Comparative power prices (US$/MWh)			
Yearly wholesale electricity price		40	48
Solar PV		50	55
Wind onshore		35	50

- Small hydro: <10 MW; Large hydro: ≥10 MW
- Europe here excludes Turkey
- Yearly wholesale electricity price is for 2016–2019
- Weighted average cost of capital for LCOE calculation: 5% (hydro), 3%–6% (solar PV), and 4%–7% (wind onshore)

Source: IEA data, 2021[31]



Digitalization to enhance hydro

Digital innovations can offer other ways of improving the efficiency of existing hydropower plants. Digitally enabled capabilities such as predictive maintenance and water inflow forecasts can help boost annual hydro generation by 11% and cut costs, according to research in Europe.[32] While some hydro sites are piloting such offerings, others have been leveraging them for years.[33] Digital twins, or virtual representations of hydro assets, are another digital tool attracting attention in the industry. US national laboratories have developed a platform to enable digital twins that the industry may use to gain insights and predictions to optimize operations and reduce downtime.[34]

Below the surface

Besides generating electricity, hydropower plays an important role in energy storage, in the form of pumped storage hydropower (PSH). Here too, innovations in hydro appear to be making an impact. PSH stores energy by using electricity to pump water to an upper reservoir. It generates electricity when the water flows through a turbine to a lower reservoir. At around 161 GW, PSH today accounts for more than 90% of global grid-scale energy storage.[35] And as the use of renewable power increases, demand for energy storage will likely increase with it. However, PSH traditionally involves the construction of vast on-ground reservoirs, which can cause environmental damage.[36] New PSH technologies that leverage existing subterranean spaces may mitigate this issue (see **Table 4**). According to the IEA, worldwide PSH capacity could increase at a record pace by 65 GW from 2021 to 2030, with some of that capacity using existing infrastructure such as old mines or natural reservoirs.[37]

Table 4. Select innovations for sustainable pumped storage hydro

Technology	Brief description	Select potential benefits	Potential plant size (MW)	Estimated levelized cost of storage (US$/MWh)	Estimated technology readiness level (TRL)
Open-pit mine PSH	Uses disused open-pit mines for reservoirs	Site reuse has environmental, cost, and time benefits	Large (100–2,000)	193 for 250 MW plant	Commercial (8–9) — E.g., gold miner planning in Australia
Underground mine PSH	Disused underground mine for lower reservoir with existing surface-level hollow for upper reservoir	Site reuse has environmental, cost, and time benefits	Mid to large (20–100)	162–201 for 50 MW plant	Prototype (6) — E.g., Power utility exploring in Wisconsin, US
Geo-mechanical PSH	Water is injected down into rock layers to be held under pressure and released upward like a spring to generate power	Quick to construct, leveraging oil and gas industry capabilities to drill wells to inject water	Mid to large (16–320)	127–158 for 40 MW plant	Prototype (5) — E.g., Power utility exploring in shale layers in Texas, US
Thermal underground PSH	Upper and lower reservoirs are below ground, and geothermal energy heats the water	Fully underground allows urban proximity and cuts environmental impact. Combines energy and heat storage	Large (300–1,000)	213–258 for 500 MW plant	Prototype (4–5)

Notes[38]

- **Plant size classifications:** Small (100 kW–10 MW) and large (>30 MW) as per US Department of Energy
- **TRL classification:** As per California Energy Commission, TRL 4 to 6 is prototype and 7 to 9 is reaching/reached commercial deployment
- **Note:** The LCOS of the PSH innovations are not comparable given they are at different TRLs and for varying plant sizes.
- **LCOS in US$/MWh in 2021 for other long-duration energy storage technologies (100 MW-10 hour configuration):** Compressed air energy storage (110), typical PSH (130), lithium-ion lithium-iron-phosphate (170), thermal (180), vanadium redox flow (180), gravitational (190), lithium-ion nickel-manganese-cobalt (210), lead-acid (350), and hydrogen (350)

Source: US Department of Energy, 2022 and news articles[39]

What is old may be new again

Hydro is among the oldest sources of energy harnessed by humans. But a variety of innovations are creating new possibilities for it. These have the potential to help double current output by 2050, which the IEA estimates may be needed to help achieve net-zero greenhouse gas emissions by that year. (According to Deloitte US's modeling, the figures presented earlier suggest that, if deployed, the innovations described here could increase capacity by 25% to 40% by 2050.) While important, technological innovation will likely be only part of this story. Globally much of the new capacity will likely be delivered via the construction of traditional hydropower dams. But for more sustainable capacity, such as via NPDs, additional government support may be required to help deliver the growth that the IEA suggests is needed. For instance, IHA, the hydro industry group, recommends governments extend support including identifying potential sites, aiding research for innovative technologies, streamlining licensing processes, and providing financial incentives.[40] Still, the innovations described earlier have the potential to give a second wind, as it were, to hydropower.

Figures presented earlier suggest that, if deployed, the innovations described here could increase capacity by 25% to 40% by 2050.

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