Hydropower

Supply Chain Deep Dive Assessment

U.S. Department of Energy Response to Executive Order 14017, "America's Supply Chains"

February 24, 2022

(This page intentionally left blank)

About the Supply Chain Review for the Energy Sector Industrial Base

The report "America's Strategy to Secure the Supply Chain for a Robust Clean Energy Transition" lays out the challenges and opportunities faced by the United States in the energy supply chain as well as the federal government plans to address these challenges and opportunities. It is accompanied by several issue-specific deep dive assessments, including this one, in response to Executive Order 14017 "America's Supply Chains," which directs the Secretary of Energy to submit a report on supply chains for the energy sector industrial base. The Executive Order is helping the federal government to build more secure and diverse U.S. supply chains, including energy supply chains.

To combat the climate crisis and avoid the most severe impacts of climate change, the U.S. is committed to achieving a 50 to 52 percent reduction from 2005 levels in economy-wide net greenhouse gas pollution by 2030, creating a carbon pollution-free power sector by 2035, and achieving net zero emissions economy-wide by no later than 2050. The U.S. Department of Energy (DOE) recognizes that a secure, resilient supply chain will be critical in harnessing emissions outcomes and capturing the economic opportunity inherent in the energy sector transition. Potential vulnerabilities and risks to the energy sector industrial base must be addressed throughout every stage of this transition.

The DOE energy supply chain strategy report summarizes the key elements of the energy supply chain as well as the strategies the U.S. government is starting to employ to address them. Additionally, it describes recommendations for Congressional action. DOE has identified technologies and crosscutting topics for analysis in the one-year time frame set by the Executive Order. Along with the policy strategy report, DOE is releasing 11 deep dive assessment documents, including this one, covering the following technology sectors:

- carbon capture materials,
- electric grid including transformers and high voltage direct current (HVDC),
- energy storage,
- fuel cells and electrolyzers,
- hydropower including pumped storage hydropower (PSH),
- neodymium magnets,
- nuclear energy,
- platinum group metals and other catalysts,
- semiconductors,
- solar photovoltaics (PV), and
- wind

DOE is also releasing two deep dive assessments on the following crosscutting topics:

- commercialization and competitiveness, and
- cybersecurity and digital components.

More information can be found at www.energy.gov/policy/supplychains.

Acknowledgments

This report was prepared by the managers and staff listed below at Oak Ridge National Laboratory, for the U.S. Department of Energy (DOE) Water Power Technologies Office. In addition, this report benefited from multiple one-on-one interviews with industry personnel consisting of owners, operators, utilities, consultants, suppliers, and manufactures from both the federal and private sectors. Reviews and feedback on earlier versions were provided by the DOE Office of Policy, DOE Water Power Technologies Office, and other government agencies. Additionally, DOE issued a request for information (RFI) on energy sector supply chains in November 2021 and received comments that were used to inform this report.

Principal Author
Rocío Uría-Martínez, Oak Ridge National Laboratory

Contributors
White, Dawn, Oak Ridge National Laboratory
Oladosu, Gbadebo, Oak Ridge National Laboratory
DeSomber, Kyle, DOE Water Power Technologies Office, DOE Office of Energy Efficiency and Renewable Energy
Johnson, Megan M., Oak Ridge National Laboratory

Reviewers
Smith, Brennan, Oak Ridge National Laboratory
Garson, Jennifer, Water Power Technologies Office, DOE Office of Energy Efficiency and Renewable Energy
Ryan, Nicole, DOE Office of Policy
Welch, Tim, Water Power Technologies Office, DOE Office of Energy Efficiency and Renewable Energy
Igogo, Tsisilile, DOE Office of Policy [Detailee]

Nomenclature or List of Acronyms

AM	additive manufacturing
CAD	computer-aided design
CEATI	Centre for Energy Advancement through Technology Innovation
CNC	computer numerical control
DC	direct current
DOE	Department of Energy
E.O.	Executive Order
ESIB	Energy Sector Industrial Base
FAR	Federal Acquisition Regulation
FERC	Federal Energy Regulatory Commission
GW	gigawatts
HMR	Hydropower Market Report
HPU	hydraulic power unit
HVDC	high voltage direct current
IHA	International Hydropower Association
ISO	independent system operator
LOPP	Lease of Power Privilege
kW	kilowatts
MVA	megavolt amperes
MW	megawatts
NAFTA	North American Free Trade Agreement
NHA	National Hydropower Association
NID	National Inventory of Dams
NPD	non-powered dam
NSD	new stream-reach development

O&M	operation and maintenance
OEM	original equipment manufacturer
PLC	programmable logic controller
PSH	pumped storage hydropower
PTFE	polytetrafluoroethylene
PV	photovoltaic
R&D	research and development
RFI	request for information
RTO	regional transmission organization
SF6	sulfur hexafluoride
TVA	Tennessee Valley Authority
USACE	U.S. Army Corps of Engineers
VPI	vacuum pressure impregnation

Executive Summary

Hydropower is a vital component of the U.S. Energy Sector Industrial Base. The United States has mature conventional hydropower and pumped storage hydropower (PSH) fleets with corresponding mature supply chains.[1] Given the slow pace of new construction over the past few decades, the U.S. hydropower industry primarily supports the existing domestic fleets—the U.S. conventional hydropower fleet (80.3 GW) is the 4th largest in the world and the U.S. PSH fleet (21.8 GW) is the third largest in the world. Additionally, U.S. hydropower manufacturing facilities export part of their output. This report examines the hydropower supply chain to identify potential bottlenecks, challenges, and opportunities, particularly if the U.S. demand for hydropower components grows significantly to meet decarbonization targets.

Section 1 describes the power and non-power values derived from U.S. hydropower and the drivers of future U.S. demand for hydropower. The conventional hydropower fleet produced 7.3% of electricity in the United States in 2020 (Johnson and Uría-Martínez, 2021). As for the PSH fleet, it accounted for 93% of grid-scale energy storage in 2019 (Uría-Martínez et al., 2021). Moreover, the dams to which hydropower plants are connected often fulfill multiple other beneficial purposes such as flood control, navigation, irrigation, and recreation.

With average ages of 64 years for U.S. conventional hydropower and 45 years for U.S. PSH, most of the activity of the industrial companies supporting these fleets is being directed toward maintenance and modernization.[2] Growth in U.S. demand for hydropower components and related services may arise from a combination of increased refurbishments and upgrades—partly connected to the wave of FERC relicensing expected to take place during the 2020s—and construction of the new hydropower capacity that could be needed to achieve the objective of a carbon pollution-free electricity grid in the United States by 2035.

U.S. hydropower and PSH capacity growth have been very slow since the 1990s. The annual average capacity growth rate from 1990 to 2018 was 0.03% for hydropower and 0.09% for PSH (EIA, 2021). However, substantial interest remains in developing new projects. At the end of 2020, there were 183 new projects in the U.S. conventional hydropower development pipeline with a combined capacity of 863 MW—a very small fraction of the remaining technical potential. Over 70% of this proposed capacity has already been licensed by FERC. For PSH, the development pipeline included 63 projects with combined proposed capacity of 46.7 GW at the end of 2020. Three of these projects, adding up to 2.1 GW, have FERC licenses. The number of conventional hydropower projects in the U.S. development pipeline at the end of 2020 is 15% lower than the average observed from 2016 to 2020; in contrast, for PSH projects, which is 17% higher than the 2016–2020 average (Johnson and Uría-Martínez, 2019; Johnson and Uría-Martínez, 2020; Johnson and Uría-Martínez, 2021b; Johnson and Uría-Martínez, 2021c; Johnson and Uría-Martínez, 2021d).

Additionally, at the end of 2020, there were plans for refurbishment and upgrades of 62 hydropower plants in the United States to start in 2021–2024. The estimated capital investment from these projects adds up to $4.4 billion. The most common scope items in these planned projects are turbine modernization and generator rewinds. There are also several instances of governor and controls upgrades as well as work on auxiliary systems, including gate and crane refurbishments.

Section 1 also presents data on global development activity. At the end of 2020, there were 151 GW of conventional hydropower and 30 GW of PSH under construction. Additionally, other 456 GW of conventional hydropower and 102 GW of PSH were pursuing permitting or undergoing feasibility evaluations. Given the size

[1] Throughout this report, unless specified, "hydropower" will refer to both conventional hydropower and PSH.
[2] This age calculation is based on plant age rather than turbine-generator unit age. Hydropower plants typically have multiple turbine-generator units. Individual units within a plant can be younger if they have undergone a major refurbishment or modernization.

of the U.S. development pipeline relative to that of the global pipeline, it should be expected that U.S. hydropower supply chain participants will pursue export opportunities in addition to supporting domestic fleets.

Section 2 describes the set of hydropower-specific plant components critical to unit or plant operations. Supply chains for these components are the most crucial to map and assess for risks. The set includes turbine, generator, governor, excitor, switchgear, emergency closure system, and penstock. The principal raw materials used to produce them are steel (carbon or stainless) and copper. Most of them are custom components whose replacement involves long lead times ranging from months to years.

Section 2 also discusses industry structure and top global manufacturers of hydropower turbines and generators as well as details about the number and geographical distribution of companies that are part of the U.S. hydropower supply chain. Turbine manufacturers play the role of a central hub in the hydropower supply chain. Although their manufacturing operations focus on the turbine, they typically also supply generators and other components through joint ventures and subcontracts. Thus, a turbine manufacturing plant supports the business of many other companies that also serve, although not exclusively, the hydropower industry. Machine shops are another important element of the hydropower supply chain in support of the existing fleet as they refurbish old mechanical components (e.g., gates) and reverse engineer pieces such as valves for which the original manufacturer no longer exists.

For both turbines and generators, supplier diversity is significantly larger for small units (<= 30 MW) than larger units. The three largest global turbine manufacturers (Andritz, GE Renewable Energy, and Voith) account for almost 50% of global turbine nameplate megawatt (MW) capacity installed. In the United States, their combined share is significantly larger at almost 75%. Only two of the other top nine global manufacturers (Hitachi Mitsubishi Hydro and Toshiba) have sizable market shares of nameplate capacity in the U.S. fleet. The rest of the top nine global manufacturers are Chinese, Russian, and Indian companies with more regional footprints.

Several turbine original equipment manufacturers (OEMs) have manufacturing facilities in the United States, including Voith and Andritz. For GE Renewable Energy, the manufacturing facilities serving the North American market are in Canada. Since 2000, the United States has had a near balance of imports and exports of turbines and turbine parts. From 2000 to 2020, average annual exports have been $57.8 million and average annual imports have been $57.1 million.

Based on an inventory compiled by the National Hydropower Association (NHA), the U.S. hydropower supply chain is distributed throughout the country with major clusters in a few states. The top ten states by number of hydropower companies include the three states with the largest installed hydropower capacities (Washington, California, and Oregon) but also others that have small hydropower fleets. For states like Pennsylvania (by far the one with the largest number of hydropower-related companies), Wisconsin, Ohio, and Michigan, it is their proximity to steel mills and related manufacturing that makes them attractive locations.

Development of a hydropower plant often includes extensive civil works and other supporting structures, in addition to a wide range of mechanical, electrical, and electronic components associated with controlling water and producing power. Most of the materials and services for the construction of civil works and other structures in the United States are met by domestic companies.

Section 3 presents the feedback from industry participants as to the most pressing supply chain challenges they are experiencing or foresee in a scenario of substantial increases in U.S. demand for hydropower components:

- All turbine OEMs interviewed stated that it is not possible to procure large (>10 tons) steel castings and forgings for turbine runners and other components from U.S. foundries. The steel foundries currently supplying large castings are in Brazil, China, Eastern Europe, and South Korea. This list is provided alphabetically, as it is unclear which countries provide the greatest import volume of castings.

- Generator stator windings for larger units (>100 MW) are also very difficult to procure domestically. Very few OEMs supply these large generators. Canada, Mexico, Brazil, and Europe were cited as the typical origins of imports for generator components that are not produced domestically.
- Microchips and digital components are manufactured primarily in Asia. The current microchip shortage and shipping bottleneck results in delays for the manufacturing of multiple hydropower subcomponents. Both hydropower plant owners and OEMs expressed increasing interest in tracing where materials and electronic components are manufactured. In the current environment of global supply chain disruptions, some plant owners expressed a willingness to pay a premium for domestic components.
- Concerns regarding hydropower workforce availability and level of training are widely shared across the industry. Workforce concerns extend from personnel needed for on-site operations to manufacturing and construction. The types of positions for which hiring is difficult include skilled trades such as machinists and welders but also engineers. It is especially difficult to attract and retain construction workers for work at remote sites.
- All the turbine OEMs interviewed stated that they have spare capacity at their manufacturing facilities. Potential bottlenecks in a scenario of significant growth in U.S. demand for hydropower components could arise for large castings, large windings, and workforce—all of which are inputs to the turbine manufacturing facilities. Although it is not a hydropower-specific component, large transformers were also mentioned as having very long lead times and very few options for domestic sourcing.

Section 4 outlines opportunities to address the challenges described and improve the resilience of the U.S. hydropower supply chain.

First, there is an opportunity for U.S. global leadership in additive manufacturing (AM) through investment in these technologies for hydropower manufacturing. Although more R&D is needed to realize this opportunity, domestic AM could provide an alternative to the imported steel castings and forgings that have been identified as an important supply chain vulnerability. AM is well suited to production of customized components with complex geometries. Moreover, the United States already has a well-developed supply chain for AM—U.S. companies build AM equipment and produce the metal powders used in AM processes—making it well positioned to become a world leader in application of these processes to the hydropower industry.

Second, rehabilitating and upgrading the existing hydropower fleet would present a significant opportunity to spur domestic supply chain growth. The U.S. hydropower fleet is among the largest in the world, but the average age of U.S. hydropower facilities is 64 years. Modernization of the existing fleet, along with new hydropower construction, could drive expansion of domestic manufacturing, reshoring, and foreign direct investment in the U.S. hydropower supply chain. One challenge associated with realizing this opportunity is the $7,032,000 threshold over which Buy American Act requirements do not apply. Hydropower is unique among energy generation technologies in that almost half of the U.S. conventional hydropower capacity is owned and operated by federal agencies. Therefore, the provisions of the Buy American Act could apply to the construction work that will take place in refurbishing and upgrading federal hydropower in the coming decades. Currently, the Buy American Act minimally impacts procurement for federal hydropower since much of the federal fleet consists of large hydropower leading to procurements costs exceeding the $7 million project value threshold.

Consideration to maximize Buy American Act provisions to support rehabilitations and upgrades of federal hydropower projects may help increase the activity of existing domestic manufacturing facilities for hydropower components or may encourage the reshoring of additional manufacturing.

Table ES- 1 summarizes the key U.S. hydropower supply chain vulnerabilities and some of the opportunities identified to address them.

Table ES- 1. U.S. Hydropower Supply Chain Vulnerabilities and Opportunities

Component/Topic	Vulnerabilities	Opportunities
Turbine	Large steel castings (> 10 tons) for turbine components cannot be procured from U.S. foundries	Stimulate growth to reshore capabilities. Investigate AM in hydropower sector.
Generator	Stator windings for larger units (>100 MW) are very difficult to procure domestically	Stimulate growth to reshore capabilities.
Turbine	Ongoing consolidation in the turbine manufacturing industry has resulted in decreased supplier diversity (particularly in the large turbine segment)	Stimulate growth to reshore capabilities.
Electronic components	Extended and opaque supply chains, high rates of obsolescence	Increase transparency.
Multiple components	Long lead times to procure new components/component replacements	Stimulate growth to reshore capabilities
Workforce	Concerns regarding hydropower workforce availability and level of training are widely shared across the industry	Increase training and early career development

Find the policy strategies to address the vulnerabilities and opportunities covered in this deep dive assessment, as well as assessments on other energy topics, in the Department of Energy 1-year supply chain report: "America's Strategy to Secure the Supply Chain for a Robust Clean Energy Transition."

For more information, visit www.energy.gov/policy/supplychains.

Table of Contents

List of Figures

List of Tables

1 Introduction

1.1 Role of hydropower in the energy industrial base sector

Hydropower is an important part of the U.S. Energy Sector Industrial Base, including the set of companies that research and develop, manufacture, and operate energy generation, storage, transmission, and distribution assets.

At the end of 2019, the U.S. conventional hydropower fleet (80.2 GW) was the fourth largest in the world by individual countries (after China, Brazil, and Canada) and the U.S. pumped storage hydropower (PSH) fleet (21.9 GW) was the third largest (after China and Japan). However, only 1.7 GW of conventional hydropower and 1.4 GW of PSH capacity were added in 2010–2019 (Uría-Martínez et al, 2021). Of this added capacity, the fraction that resulted from new builds was 33% for conventional hydropower and 3% for PSH; the rest resulted from upgrades to existing facilities. The average age of the U.S. fleet is 64 years for conventional hydropower and 45 years for PSH.[3] New capacity expansion is not anticipated to be the primary driver for the activity of domestic industrial companies supporting the U.S. hydropower fleets. Instead, the primary driver is expected to be the maintenance and modernization of the existing fleets. The exceptions could be PSH builds and some limited new small conventional hydropower plants.

In 2020, hydropower accounted for 36.7% of renewable electricity generation and 7.3% of total electricity generation in the United States (Johnson and Uría-Martínez, 2021). In some U.S. states (Washington, Idaho, Oregon, and Vermont), more than 50% of electricity generated in 2017–2019 was hydroelectric. Hydropower also provides flexibility and grid services that are essential to enable high penetrations of variable renewables and enhance grid reliability. U.S. PSH plants provide a higher percentage of many grid services than the percentage of capacity they represent in the electricity generation fleet. For instance, Gracia et al. (2019) report that hydropower provides approximately 40% of black start resources (vs. less than 10% generation capacity). The 2021 edition of the U.S. Hydropower Market Report (HMR) presents other examples of the U.S. hydropower fleet providing a larger share of ancillary services (such as frequency regulation and reserves) than the share of generation capacity it represents in several independent system operator (ISO) regions. The large shares of ancillary services provided by hydropower relative to its installed capacity are indicative of the flexibility offered by this generation technology. Additionally, PSH has been to date the preferred least-cost technology for long-duration energy storage and the demand for this type of storage asset is expected to grow substantially in the next few decades.

A robust supply chain is necessary to maintain and modernize the existing hydropower fleets and to support the grid in reliably integrating the additional variable renewable capacity needed to achieve the objective of a carbon pollution-free electricity grid in the United States by 2035. The National Hydropower Association (NHA) has compiled a list of more than 2,500 companies that report being part of the U.S. hydropower supply chain, including turbine manufacturers, machine shops, and engineering and consulting companies, among others.[4] In 2018, the number of jobs supported by the U.S. hydropower industry was estimated at 66,500 (Keyser and Tegen, 2020). The manufacturing and utilities sectors accounted for 27% and 26% of those jobs, respectively. The rest were distributed among professional and business services, trade and transportation, and construction sectors. Using a combination of data and input from stakeholder interviews, this report identifies vulnerabilities, challenges, and opportunities for the U.S. hydropower supply chain.

[3] This age calculation is based on plant age rather than unit age. Individual units within a plant can be younger if they have undergone a major refurbishment or modernization.
[4] https://www.hydro.org/map/supply-chains/

1.2 Power and non-power benefits of hydropower dams

Hydropower provides multiple electricity-related value streams to the national power grid. In addition to clean, low-cost electricity services, hydropower dams can provide valuable non-power benefits to the nation. Based on data from the National Inventory of Dams (NID), approximately 60% of the dams connected to hydropower plants in the United States are also authorized for other purposes. Large hydropower plants are more likely to provide multiple non-power services among the 12 categories listed in the NID: hydropower, irrigation, flood control and storm water management, navigation, water supply, recreation, fire protection, fish and wildlife, debris control, tailing, grade stabilization, and "other".[5] In many cases, the hydropower purpose is secondary to one or several non-power purposes.

Of all the purposes served by dams, hydropower is the one with the best-defined method for value quantification. The value of hydroelectricity is the electricity market energy price. In addition, several ISOs and regional transmission organizations (RTOs) have centralized capacity markets and conduct capacity auctions that can be an additional source of revenue for hydropower plants in those regions. In ISO/RTO regions, markets are also cleared for several of the ancillary services that hydropower provides such as frequency regulation and various types of reserves. For other services like black start, the plant owners receive payments from the ISO/RTO or balancing authority that are meant to cover the costs of providing the service.

The value of the non-hydropower uses of hydropower dams can be substantial and is estimated with valuation methods such as avoided damage costs of floods (flood control) and alternative transportation (navigation) or revenues from irrigated crops (irrigation) and water use (water supply). However, most of these economic benefits are not monetized. Applying these methodologies to federal multipurpose hydropower reservoirs (excluding PSH plants), Bonnet et al. (2015) produce estimates of the distribution of economic benefits per use for each federal agency. In the Tennessee Valley Authority (TVA) and U.S. Army Corps of Engineers (USACE) fleets, recreation is the purpose with the highest economic benefit (35%–40% of the total). Hydropower (energy revenue only) is the second most valuable purpose in the TVA fleet (~23%), and the third most valuable purpose in the USACE fleet (~17%). Irrigation is not an authorized purpose for reservoirs owned by TVA or USACE. In contrast, irrigation is an authorized purpose in most of Bureau of Reclamation's reservoirs and it accounts for 60% of the economic benefit for their fleet. The energy revenue from the hydropower purpose accounts for 10% of total economic benefit in Reclamation's fleet.

Although payments are made for some non-power services, the hydropower purpose is often the main source of revenue for financing the maintenance of the dam and enabling the provision of non-power services. Thus, indirectly, the hydropower supply chain also supports those other valuable services.

1.3 Growth potential of hydropower

This section discusses multiple estimates of growth potential for conventional hydropower and PSH, for the United States and globally. First, Section 1.3.1 presents estimates of the remaining resource potential which provide an upper bound to the additional conventional hydropower capacity that could theoretically be added given historical data on water flows and site topography. Second, Section 1.3.2 summarizes data on the capacity from projects that have been announced and are being actively pursued. Of those, only a fraction will make it to construction stage after completing all necessary feasibility evaluation studies, obtaining permits, and securing

[5] Tailing dams do not store water but the by-products from mining operations.

financing. Finally, Section 1.3.3 provides estimates of the additional global hydropower capacity that could be needed to meet selected global decarbonization objectives.

1.3.1 Technical potential

In addition to the importance of modernizing the existing conventional hydropower and PSH fleets to maintain or enhance the power and non-power values listed above, several studies conducted within the last decade on resource assessment show that significant potential remains to build new capacity, both in the United States and globally, through retrofits of non-powered dams (NPDs) and conduits, new stream-reach developments (NSD), and PSH.

For the United States, Hadjerioua et al., (2012) found a potential capacity of 12.1 GW from the retrofit of NPDs with the top three basins being the Ohio, the Upper Mississippi, and the Arkansas-White-Red. For NSDs, Kao et al., (2014) identified a resource potential of 65.5 GW after excluding national parks, wild and scenic rivers, and wilderness areas. These studies are estimates of potential energy generation based on the river flows at the selected sites; further technical and economic feasibility studies would be required to determine which sites to develop. The Hydropower Vision study produced estimates of growth potential based on results from the ReEDS model that solves for the optimal (minimum cost subject to other constraints) set of resources to meet projected electricity demand out to 2050 (DOE, 2016). Given the set of policies enacted as of December 2015 and the resource assessment potentials identified in the aforementioned studies, the ReEDS model finds a potential of 13 GW of new conventional hydropower capacity and 36 GW of PSH capacity by 2050.[6] If those potentials were realized, they would represent a 16% increase in conventional hydropower capacity and more than double the existing PSH capacity. Most of the new conventional hydropower would come from upgrades to existing facilities (6.3 GW) and NPD retrofits (4.8 GW).

For global potential, the International Hydropower Association (IHA) presents regional estimates derived from a review of three recent studies. The estimated capacity potentials range from 350 GW in Europe to 1,100 GW in East Asia and Pacific (IHA, 2021). These are very large numbers when compared with the global installed hydropower capacity of 1,330 GW—1,171 GW of conventional hydropower and 159 GW of PSH—at the end of 2020 (IHA, 2021b). For PSH, several recent studies conducting global searches of potential sites worldwide point to an abundance of candidate locations (Stocks et al., 2021; Hunt et al., 2020).

[6] The study assumed implementation of the Clean Power Plan which was being discussed at the time but was ultimately not enacted.

1.3.2 Development pipeline

1.3.2.1 United States

1.3.2.1.1 New projects

Studies that estimate remaining technical potential for additional hydropower capacity provide a useful upper bound, but a more informative outlook for the short to mid-term potential of new builds emerges from analyzing the project development pipeline.[7] Figure 1 and Figure 2 offer details about the composition and status of conventional hydropower and PSH projects in the U.S. development pipeline at the end of 2020.

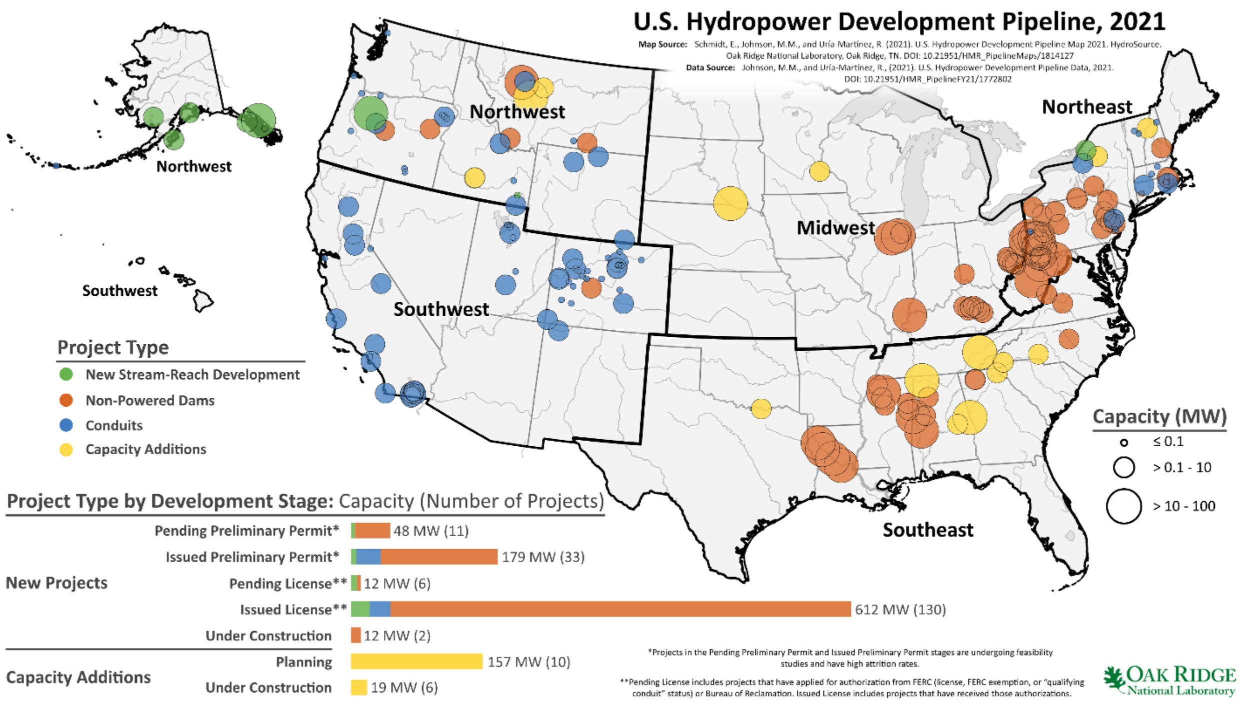

Figure 1. US. conventional hydropower project development pipeline by project type, region, size, and development stage (as of December 31, 2020).

Source: Schmidt et al. (2021)

Note: This map is available for download at https://hydrosource.ornl.gov/map/us-hydropower-development-pipeline-2021

[7] The development pipeline numbers presented here include projects that have formally expressed interest in developing a conventional hydropower or PSH project that would require a FERC authorization (license, exemption, or approval as qualifying conduit) or a Bureau of Reclamation's lease of power privilege (LOPP). For the FERC pipeline, the following development stages are included: pending preliminary permit, issued preliminary permit, pending license (or exemption), issued license (or exemption), and projects under construction. For the LOPP pipeline, the following development stages are included: pending preliminary lease, issued preliminary lease, issued LOPP. To limit the number of categories shown in Figure 1, the stages of the LOPP process are presented under the most similar stage of the FERC development process. Pending preliminary lease is shown as Pending Permit, issued preliminary lease is shown as Issued Permit, and issued LOPP is shown as Issued License.

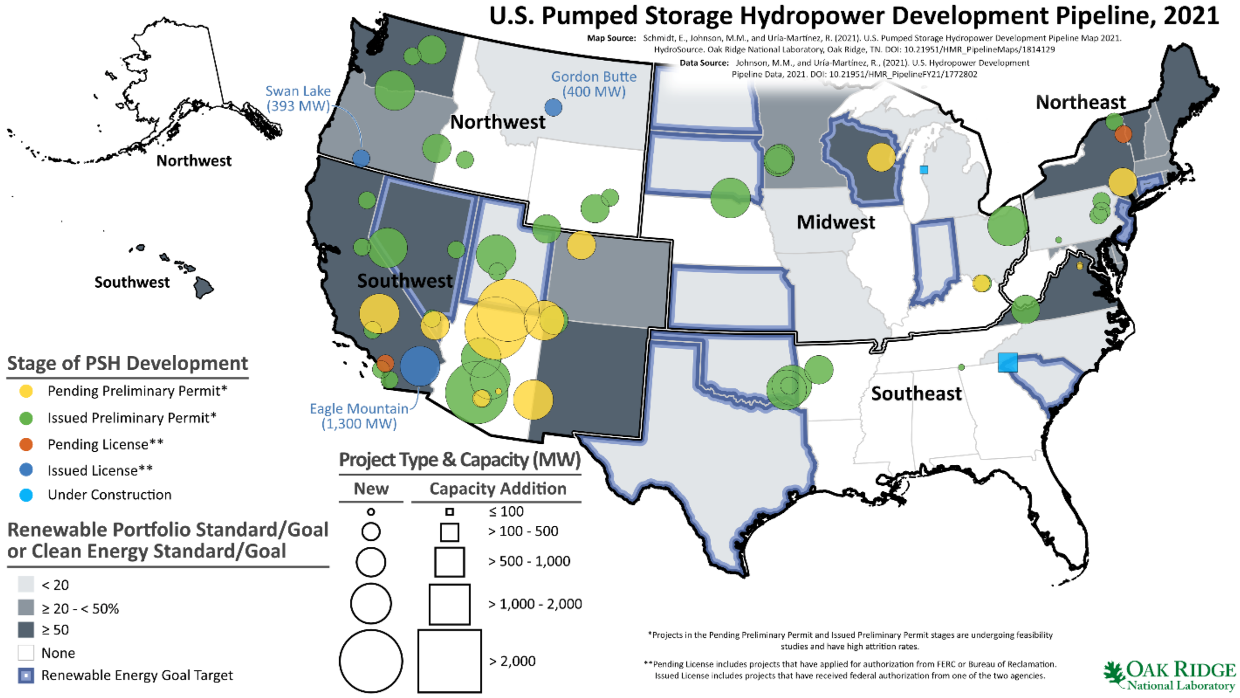

Figure 2. PSH project development pipeline by region and status in relation to state-level renewable energy targets (as of December 31, 2020)

Source: Schmidt et al. (2021b)

Note: This map is available for download at https://hydrosource.ornl.gov/map/us-pumped-storage-hydropower-development-pipeline-2021

At the end of 2020, there were 183 new projects (80 NPD retrofits, 94 conduit retrofits, and 9 NSD projects) in the U.S. conventional hydropower development pipeline, which is 15% lower than the average number of projects in the pipeline in 2016–2020. These 183 projects have a combined proposed capacity of 863 MW. The median capacity varies significantly across project types, from 89 kW for conduit retrofits to 4.5 MW for NPDs. The largest conventional hydropower project in the pipeline is the Uniontown Hydroelectric project in Indiana (66.6 MW). Most conduit retrofits are proposed in the Western half of the country and most NPDs are in the Eastern half. Eight of the nine NSD projects are either in Alaska or the Pacific Northwest. Over 70% of proposed capacity already has an issued Federal Energy Regulatory Commission (FERC) license; only two projects (two NPDs with combined capacity of 12 MW) were under construction at the end of 2020. Most other projects are at a much earlier stage of feasibility evaluation in which attrition rates have typically been very high.

The U.S. PSH development pipeline included 63 projects with combined proposed capacity of 46.7 GW at the end of 2020 (see Figure 2). This number is 17% higher than the average number of PSH projects in the pipeline in 2016–2020. Project sizes range from 10 MW to 3,600 MW and the median size is 500 MW. Twenty-two states had at least one PSH project in the pipeline at the end of 2020, with the greatest number of PSH projects in California, Nevada, and Arizona. Seventy percent of these PSH projects have preliminary permits to conduct feasibility evaluation studies. At the feasibility evaluation stage, just like with conventional hydropower, the attrition rate is very high. Three projects—Eagle Mountain (California, 1,300 MW), Swan Lake (Oregon, 393 MW), and Gordon Butte (Montana, 400 MW) already have a FERC license. No new PSH projects are currently under construction.

Aside from new projects in the development pipeline, 18 ongoing upgrades would add 176 MW to the existing conventional hydropower fleet and 250 MW to the existing PSH fleet.

1.3.2.1.2 Refurbishments and upgrades

The project development pipeline is only one dimension of U.S. demand for hydropower components, with substantial uncertainty as to the fraction of projects that will eventually be constructed. Since 1990, new construction has added 2.4 GW of conventional hydropower and 2.9 GW of PSH—3% and 13% of total installed capacity as of 2021, respectively. Most of the domestic activity for the U.S. hydropower supply chain in the past 30 years has been geared toward maintaining, refurbishing, modernizing, and upgrading the existing fleet.

Uría-Martínez et al. (2021) report that at least $7.8 billion were invested in refurbishing and upgrading the U.S. conventional hydropower and PSH fleets during the 2010s. Turbine runner replacement or refurbishment, generator rewinds, installation of digital governors, and replacement or upgrades of floodgates or transformers were the most common items in the scope of the 339 tracked projects.

At the end of 2020, Industrial Information Resources reported planned new refurbishment and upgrade investments for 62 hydropower plants in the United States to start from 2021 to 2024. The estimated capital investment from these projects adds up to $4.4 billion. Sixty percent of this investment is in the early stages of developing a project justification, conducting preliminary design, and submission of authorization for expenditures. The most common scope items in these planned projects continue to be turbine modernization and generator rewinds. There are also several instances of governor and controls upgrades, and gate and crane refurbishments.

1.3.2.2 Global

Data on global hydropower development activity are of interest to U.S. supply chain participants for multiple reasons. First, U.S. manufacturers of hydropower components export part of their production to the global market and information on which world regions have most planned new projects can help them identify key target export markets. Second, given the interconnected nature of the global supply chain for hydropower components, the volume of hydropower development activity worldwide must be considered for an analysis of potential supply chain bottlenecks for the United States. This is especially the case for large turbines and generators where the number of suppliers is very limited.

The map in Figure 3 introduces the nine world regions considered through this report and shows where major conventional hydropower clusters are located.

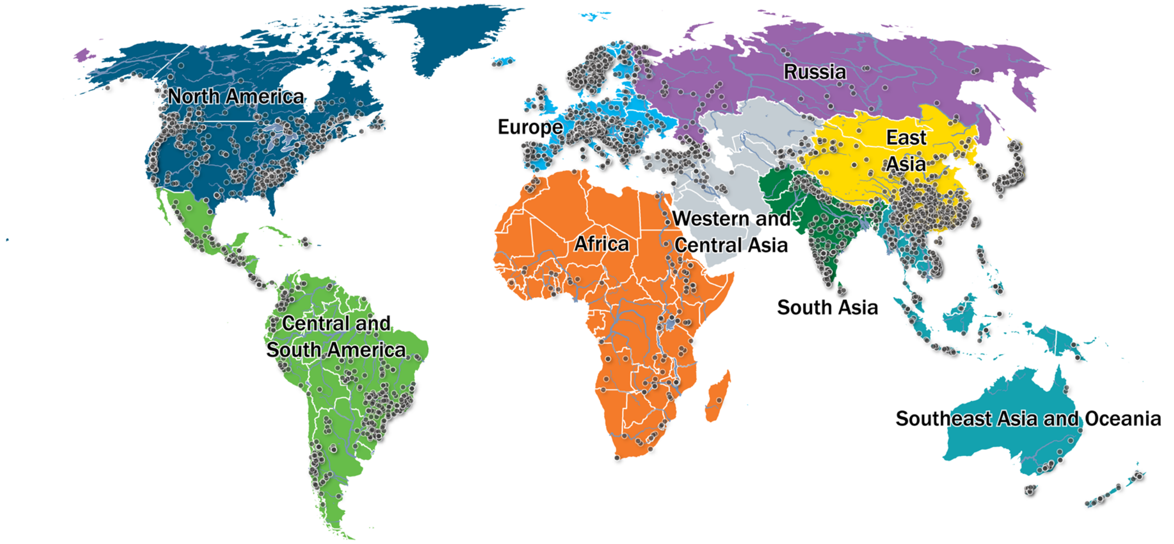

Figure 3. Map of operational conventional hydropower plants by world region

Source: Industrial Info Resources

Note: The dots represent the location of operational conventional hydropower plants

Based on data from GlobalData, a commercial provider of intelligence on key world industries, 151 GW of conventional hydropower and 30 GW of PSH were either under construction or had completed permitting and reached financial closure around the world at the end of 2020. An additional 188 GW of conventional hydropower and 49 GW of PSH were in the permitting phase. At an even earlier stage, plans have been announced for 268 GW of conventional hydropower and 53 GW of PSH without significant progress toward permitting or financing them. If 100% of projects in the Announced, Permitting, Financed, and Under Construction stages were built, they would result in a 57% increase in global conventional hydropower capacity and an 84% increase in global PSH capacity. Figure 4 and Figure 5 show the regional distribution of capacities at the various stages.

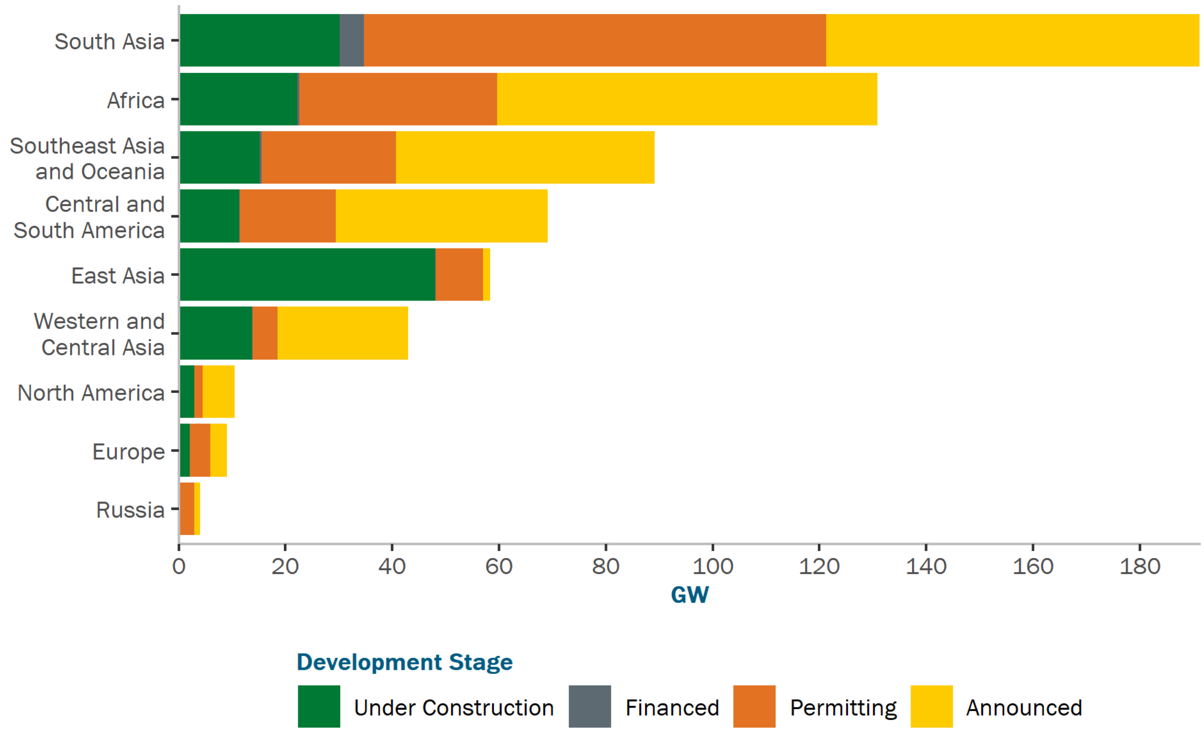

Figure 4. Global conventional hydropower development pipeline by region and development stage

Source: GlobalData

South Asia and Africa are the only two regions with more than 100 GW of conventional hydropower in the pipeline. East Asia leads the ranking in terms of conventional hydropower under construction (48 GW). North America, Europe, and Russia—the regions with the oldest conventional hydropower fleets—are the regions with the least amount of new capacity in the pipeline. For North America, 86% of the capacity shown in Figure 4 corresponds to projects located in Canada.

For conventional hydropower, given the size of the U.S. development pipeline relative to the global development pipeline, it should be expected that U.S. hydropower supply chain participants will pursue export opportunities in addition to supporting the domestic fleets.

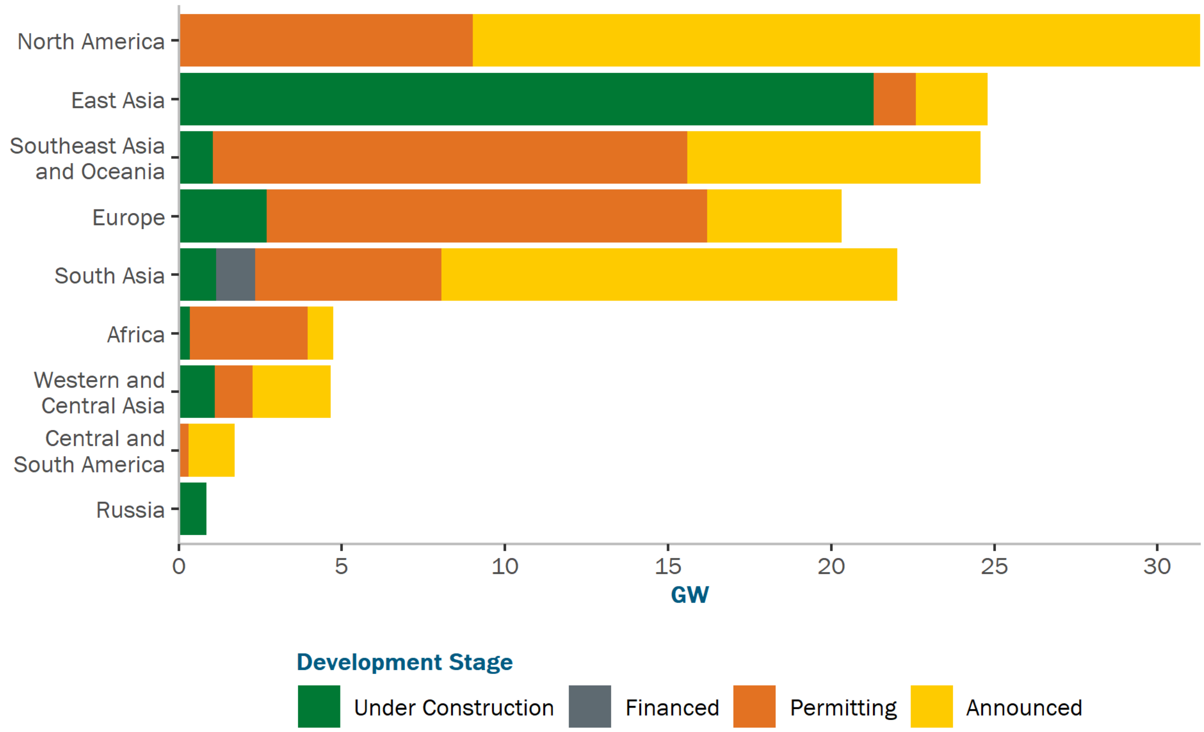

Figure 5. Global pumped storage hydropower development pipeline by region and development stage

Source: GlobalData

North America (defined here as the United States and Canada) leads the PSH pipeline and 45 of the 48 projects tracked by GlobalData in this region are in the United States.[8] However, none of the projects are under construction. North America and Central and South America are the only two regions with no PSH construction currently underway. In contrast, the region with the second largest PSH pipeline (East Asia), has 86% of the 25 GW in its pipeline under construction. Of the 23 PSH plants in the pipeline in that region, 18 are in China, 2 in Japan, and 3 in Mongolia. Europe and North America are the only two regions with more PSH capacity than conventional hydropower capacity in their development pipelines.

1.3.3 New hydropower required to meet decarbonization objectives

Figure 6 compares global hydropower installations in 2000–2018 with the estimated average annual global installations needed out to 2050 to meet different decarbonization objectives. IHA (2021) provides estimates of total hydropower capacity needed by 2050 for a scenario in which global warming is kept under 2 °C (850 GW) as well as the forecasted new hydropower needed based on the IEA's Net Zero Roadmap (1,300 GW).

[8] GlobalData covers projects in all world regions, but its coverage of the U.S. development pipeline is not as complete or up-to-date as that in the U.S. dataset presented in Section 1.3.1.1. leading to some differences in the number of projects and capacity for the United States across the two datasets.

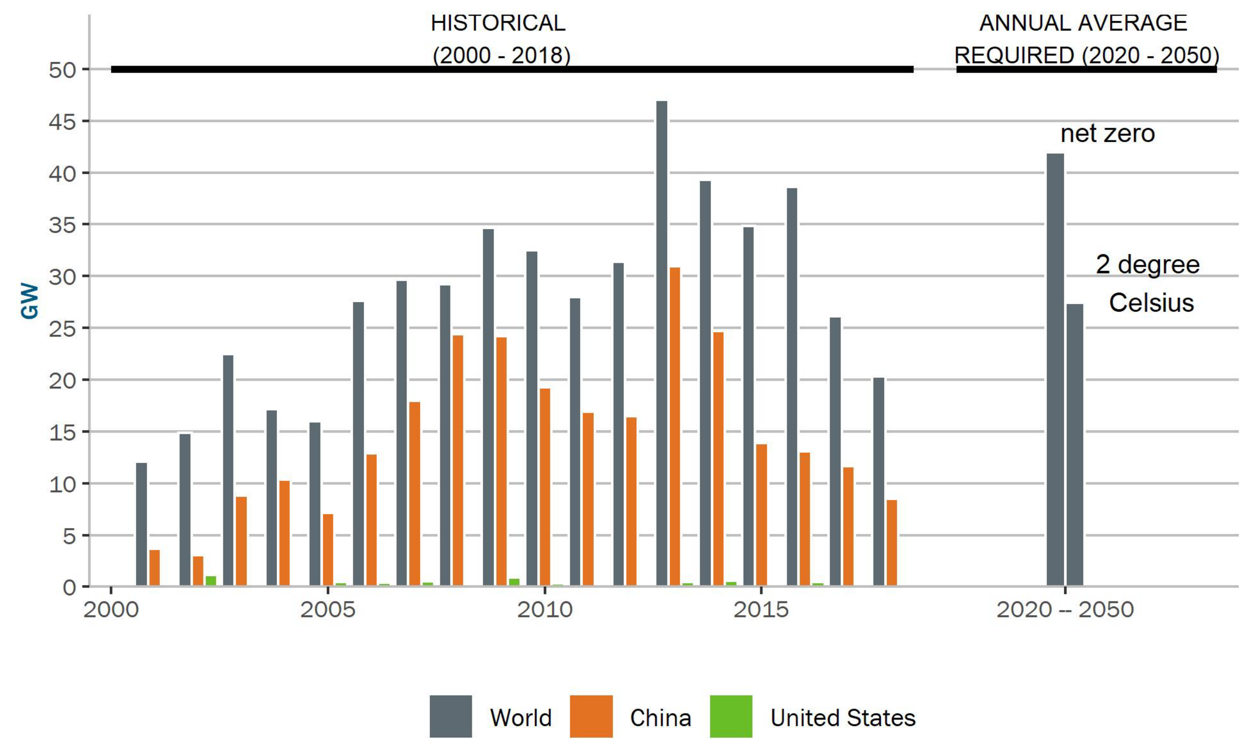

Figure 6. Recent hydropower (including PSH) installations versus average annual needs to 2050 to meet alternative decarbonization objectives.

Source: EIA, IHA (2021)

On average, from 2000 to 2018, 27 GW of hydropower (including PSH) were added globally per year. Maintaining that annual average from 2020 to 2050 would add 810 GW, very close to the estimated 850 GW needed by 2050 to keep global warming below 2°C. However, a substantial scale-up in construction would be required to construct the 1,300 GW estimated as necessary for a net zero energy sector by 2050. For comparison, the total capacity (conventional hydropower plus PSH) in the development pipeline at the end of 2020, presented in Figure 4 and Figure 5, would add 739 GW of which 321 GW are at a very early stage of development with substantial uncertainty about their progressing to construction.

Of the global capacity added from 2000 to 2018, 51% has been in China. If decarbonization-driven development substantially changes the regional fractions of new construction going forward, the supply chain might need to adjust accordingly in terms of manufacturing locations, workforce etc.

The manufacturing capacity required to service global demand for hydropower-specific components in the next three decades does not depend on greenfield projects alone. Figure 6 shows capacity added in new projects as well as through installation of additional turbine-generator units at existing plants and uprates (i.e., power rating increases) of existing units. However, Figure 6 does not include refurbished capacity. In some regions, most of the demand for hydropower components results from refurbishment or modernization of existing plants without adding significant new capacity. This is especially true for the United States where turbine manufacturers stated that refurbishments and upgrades have accounted for 90% or more of the domestic demand in recent years. On the other hand, globally, one major turbine manufacturer mentioned that their work has typically been in a ratio of one brownfield project to two greenfield projects. To reach a net zero energy sector, the hydropower supply chain would need to be scaled so that it can meet the demands for refurbishments, upgrades, and new construction.

2 Supply Chain Mapping

2.1 Technology Overview

The following is a brief description of hydropower energy generation to illustrate the key components. A hydropower plant converts potential energy, in the form of an elevated body of water, into kinetic energy through water flow, into mechanical energy by rotating the turbine, and then into electrical energy by rotating the generator. As the turbine spins so does the generator rotor whose outer surface is covered in electromagnets (field poles). As those electromagnets move past the copper windings covering the surface of the generator stator, alternating current is generated. A step-up transformer converts the alternating current to high voltage current that can be transported over the electric transmission grid. Water flow into the turbine is controlled through gates and valves, which allows for isolation of the turbine-generator units during maintenance or emergencies.

A hydropower plant often has multiple turbine-generator units which limits the number of single points of failure to plant operations. Figure 7 shows the major components of a Kaplan type turbine-generator unit. The configuration of hydropower plants is highly site-specific, with multiple custom components that require long lead times for their replacement. This section describes in more detail the characteristics and function of a list of hydropower plant components. All of them are critical to turbine-generator unit operations making their supply chains the focus of this study. Hydropower facilities contain highly customized components combined into systems that are designed to fit the specifics of their environment. This environment is dictated by water availability in terms of head and flow. Since components and overall facilities are unique, general arrangements will be similar, but interchangeability of components is limited.

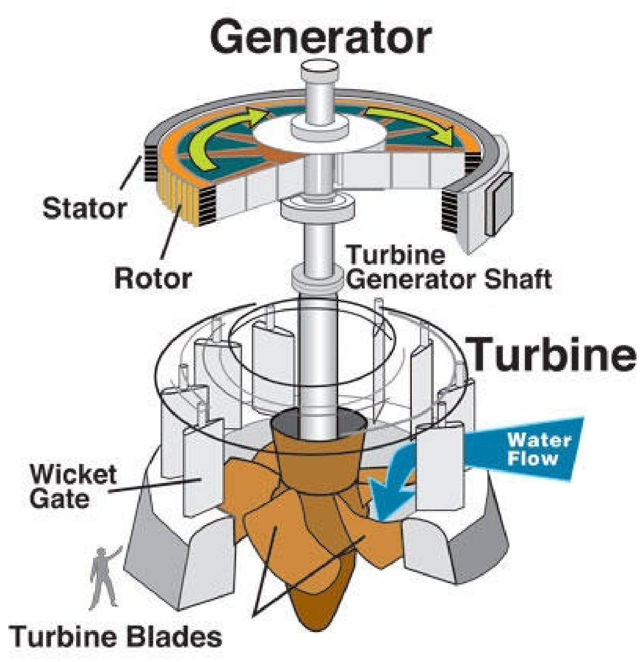

Figure 7. Diagram of a Kaplan-type hydroelectric turbine-generator unit

Source: Courtesy of U.S. Army Corps of Engineers. Wikimedia: Creative Commons License.

2.1.1 Turbine

There are multiple types of turbines and selection depends on the combination of water flow and head—the difference in elevation between the water intake point and the water discharge point—available at the site, among other factors. The two major families of turbines are impulse and reaction turbines. Reaction turbines, such as Francis and Kaplan, are fully immersed in water and are ideal for low-head, high-flow systems. Impulse turbines, such as Pelton, operate in air and driven by high-velocity jets of water and are the typical choice in high-head sites (Canyon Hydro, n.d.). Selecting the appropriate curvature for the turbine blades and high-quality casting materials are among the choices that help maximize the generation efficiency of the resulting unit.

The hydropower turbine has several components, mostly made of steel (carbon or stainless), that require custom design and fabrication:

- Scroll case: It is a custom-made, steel spiral casing that surrounds the turbine runner. It is the first component reached by the water flow as it exits the penstock. These are typically made of fabricated carbon steel plate.
- Runner: Blades (in reaction turbines) or buckets (in impulse turbines) designed to capture the maximum energy from the water passing through. Runners and blades are custom-made from steel (carbon or stainless) castings, forgings, and in some cases, plate.
- Wicket gates: Adjustable gates/vanes to control the flow of water through the turbine, made of steel (carbon or stainless) castings or forgings.
- Draft tube (only applies to reaction turbines): It connects the turbine outlet to the tailrace. They are custom-designed civil structures made of cemented concrete with a cast steel lining to avoid cavitation. The draft tube brings the pressure of the water flowing out of the turbine back to atmospheric pressure. Draft tubes are typically fabricated from carbon steel plate.
- Headcover: It provides separation of the wet turbine elements, including runner and wicket gates, from the dry powerhouse elements, including the generator and wicket gate operating servomotors. Headcovers are engineered to be pressurized on the water side and to support wicket gate elements. Components of the headcover may be constructed from steel plate, castings, and forgings.
- Bearings: Turbine guide bearings are typically bushings, made of babbitt, composite, or Polytetrafluoroethylene (PTFE), a Teflon-type material.

2.1.2 Generator

The description in this section draws primarily from a design manual for hydropower generators published by Bureau of Reclamation (Bureau of Reclamation, 1992). Generators, particularly for large units such as those with power rating greater than 100 MW, require custom design and fabrication. The major parts of a generator are:

- Shaft: It connects the generator with the turbine. It is typically made of forged steel.
- Rotor: It is the rotating part of the generator. It rotates at a fixed speed determined by the turbine. The rotor is connected to the shaft and its outer surface is covered with field poles.
  - The field poles are built from thin laminations of magnetic material.
  - The rotor spider transmits torque and rotation from the shaft to the rotor rim and poles and provides supporting structure for the poles. It is often made of forged and fabricated steel.
- Stator: It concentrates the magnetic field from the rotor to produce the induced voltage in the armature.

    - The stator frame provides the structure to support the stator core and windings. It is made of thick fabricated steel plates.
    - The stator core is made of stacked thin laminations of electrical grade steel and coated on each side with insulation. It is built inside a cage which is then attached to the stator frame (GE Energy, n.d.).
    - The stator windings are coils made of copper and insulating material and they are wedged into stator core slots. They are custom-made for each installation and spares must be acquired when the generator is first purchased to ensure availability when the need for repair arises.
        - Insulation materials for stator windings have changed over time and the standard base materials are now glass fibre, mica dust, or polyester fiber. There are also multiple options for the insulation binder materials. The standard used to be asphalt before the 1960s and since then polyester-vacuum pressure impregnation (VPI) hybrids and several kinds of epoxy have also been introduced (BBA, 2019).
- Bearings: Generator bearings may be roller type or journal type bushings. Thrust bearings are used to support the generator in vertical units, or to resist the hydraulic forces imparted by water on the turbine in horizontal reaction turbines. Typical bearing material is babbitt, composite, or PTFE material. Roller type bearings are used in some applications as well.

2.1.3 Governor

The governor regulates the rotational speed, power output, and system frequency of the turbine-generator units by controlling the flow of water through opening/closing of the wicket gates. It involves control and actuating components. Governors are hydraulic systems with common components across many industries. The below summary discusses how these hydraulic systems have changed over time.

- Speed sensing devices have changed over different generations of governors. Early mechanical-hydraulic governors had a fly-ball type pendulum. The second generation of electro-hydraulic governors had a frequency transducer as speed sensing device (Vu and Agee, 1998). In modern digital governors, the speed signals are provided by a digital control algorithm and electronic circuits.
- Hydraulic pressure units (HPUs) include a pressure oil tank, oil sump, air compressor, oil filtration system, oil pump or motor, and piping. Their function is to supply pressurized oil to a servomotor to adjust the position of the wicket gates. For emergency shutdowns (i.e., loss of station power or grid), systems will be equipped with an air-over-oil pressure tank or a bladder accumulator to stop water flow through the turbine.
- Controls can be mechanical, analog, or digital.
    - Digital governors help increase plant automation, include built-in diagnostic tools for better fault detection, and allow more precise turbine control. A digital governor is required by system operators for a plant to qualify for provision of certain ancillary services. A potential downside from digital governors is their frequent obsolescence that forces replacement of the programmable logic controllers (PLCs) every five to 15 years despite not having experienced any failures. Also, at least in some cases, a digital governor eliminates the option for manually controlling a unit.

2.1.4 Excitation system

The excitation system, consisting of electronic circuitry and components, supplies and regulates the amount of direct current (DC) needed by the generator rotor windings. Hydropower exciters are typically shaft-mounted rotating systems energized through contacting brushes. These are being replaced with modern equivalents, including:

- Static exciter: Static excitation systems can be of two types (inverting and semi-inverting) depending on the speed of generator field suppression required.
- Brushless or rotating rectifier exciter: It uses rotating rectifiers that are directly connected to the generator field poles, eliminating the need for brushes. It is used in smaller hydropower generators where large excitation current is not needed.

2.1.5 Switchgear

The generator switchgear is located between the generator and the step-up transformer and serves to synchronize the frequency, voltage, and phase of the electricity exiting the generator with those of the grid.

- Circuit breakers: There are four types depending on the medium they use for arc interruption: air, oil, sulfur hexafluoride (SF6), or vacuum.
- Surge arresters: They protect the generators from overvoltage.

2.1.6 Emergency closure systems

When closed, intake gate closure systems stop water from the dam reservoir from reaching the turbine. They are made of fabricated steel. For emergency deployment, they can be operated via accumulators on the hydraulic system, gravity deployment, or automated cranes. For normal operation, they can be operated with a hydraulic system, a wire rope hoist system, or a crane (Gore et al., 2001).

2.1.7 Penstock

The penstock is the conduit transporting water flow from the intake point to the turbine. A hydropower plant can have multiple penstocks to convey water to different units. Alternatively, a single penstock can be bifurcated or trifurcated to distribute the flow to multiple turbine-generator units.

Steel is the most common raw material for penstocks, but they can also be made from other materials, including wood stave (largely out of use for new installations but still present in some old projects), fiberglass, and high-density polyethylene plastic. Multiple materials and various wall thicknesses (as pressures increase) may be utilized in a single installation.

2.1.8 Bypass systems

In the event of inflow greater than turbine capacity, or turbine(s) being offline, alternative passages of water are required at hydroelectric generation plants.

- Spillways: Gated concrete structures having ideal shapes to pass flow. These are typically gated with large steel structures that operate using wire rope hoists or hydraulic hoists.
- Overflow spillway: These spillways are unregulated, meaning water is not controlled as it passes. Water will reach a specific elevation, then overflow this type of spillway. It is constructed of concrete.

- Turbine bypass: In facilities where the powerhouse is a significant distance away from the dam or spillway, a bypass system is required. These are typically valve-controlled systems within the penstock where a turbine inlet valve will be closed and a bypass valve opened on a parallel water passage route. A dissipation valve or structure will be placed at the bypass outlet to minimize energy in the water jet being discharged. The bypass and valve structures are largely made of steel, cast steel, and stainless steel.

2.1.9 Balance of plant

This category includes auxiliary systems such as compressed air systems, oil delivery and storage, plant temperature control, hoists, and components that are not hydropower-specific but still critical to plant operation such as batteries, transformers, and cranes.

2.2 Industry Structure

Along with a whole range of mechanical, electrical, and electronic components associated with moving water and operating the powertrain, consisting of the turbine and generator, a hydropower plant often includes extensive civil works and other supporting structures. Most of the materials and services for the construction of civil works and other structures in the United States are met by domestic companies.

Turbines and large generators are the key hydropower-specific components built by companies (or company divisions) exclusively dedicated to serve the hydropower sector. Thus, the industry structure discussed in this section focuses largely on the turbine-generator manufacturing supply chain.

Steel, stainless steel, and copper are the main raw materials needed to build many of the components listed in the previous section; they are the raw material industries most important for hydropower supply chains.

Even though turbines and generators operate as a unit, they are sometimes produced by separate companies. In the past, there was a greater separation between companies that supply turbines and generators as they require different types of expertise. The Bureau of Reclamation (1992) explains that, during the decades in which most of its fleet was constructed, there was only one U.S. manufacturer and a few international manufacturers that could provide both the turbine and the generator. To increase their procurement options, they typically announced requests for bids separately for turbines and generators. Nowadays, the major turbine manufacturers also provide generators either through self-production, where turbine manufacturers have acquired or merged with generator manufacturers to enhance their ability to supply the entire powertrain, or through joint ventures with generator manufacturers. For small units, several manufacturers offer “water-to-wire” packages where the turbine and generator are supplied as a set along with other components such as automated controls, turbine inlet valve, and switchgear.

The manufacturing process for a new turbine or turbine runner takes multiple years and involves many steps as designs are dictated by the water flow and head criteria of the specific site. The unit is first designed and tested computationally using Finite Element Analysis and Computational Fluid Dynamics methods. Then, for a new turbine runner design, a prototype might be produced and further tested, a step that can add one year to the process. The manufacturing process traditionally starts by ordering a steel casting from a foundry. The casting process involves heating up the material to its melting point and pouring it into a mold to obtain the desired shape. The resulting casting is then machined to introduce features that cannot be produced during the casting process. It has become standard to use computer numerical control (CNC) machining rather than conventional machining. CNC machining is a subtractive manufacturing process, where a tool chips away steel shavings from the initial single piece to achieve the desired shape, guided by computer-aided design (CAD) software (Formlabs, n.d.). Finally, turbine runners are manually polished to achieve a smooth finish.

The manufacturing process described in the previous paragraph follows subtractive manufacturing principles where the starting point is a solid block from which material is removed until the desired shape is achieved. In contrast, additive manufacturing (AM) is characterized by the absence of a mold, die, machine (e.g., mill, grinder), or other tool designed to produce the target geometry. Instead, AM processes involve depositing layers of materials and consolidating them to create a solid object. A wide range of metals or polymers are used in these processes and some final machining is often needed to achieve the exact dimensions required. This can be accomplished via post-build machining or with the use of a hybrid system in which there is a subtractive function available, along with the additive process, to provide more accurate geometry. AM processes are mostly still in the research and development (R&D) phase for applications in the hydropower industry, but some manufacturers have started applying them to the manufacturing of hydropower turbines either to produce components like blades in small turbines or to 3D-print casting molds.

Other turbine components such as the scroll case, head cover, wicket gates, or draft tube are also made of steel using manufacturing processes such as turning, forging, rolling, and bending. The various turbine components are finally welded together (Kafle et al., 2020).

For generators, many of the parts are made of steel using similar processes and tooling as discussed for turbine components. However, the stator winding coils require an entirely different manufacturing process. At a coil manufacturing facility, strands of copper to manufacture the copper windings are drawn from copper reels. The two main coil structures typically used in hydropower generators are single-turn bars or multi-turn coils. In multi-turn coils, strands are insulated. Multiple strands form a turn and additional insulation is applied at the turn level. Then, the turns are assembled into full loops and a spreading machine is used to create the basic coil shape. Next, ground wall insulation tapes are applied and the coils are cured. Single-turn bars do not make a full loop; they are “half-coils”. For small units, the coils are placed into the stator slots at the factory; for large units, placement into the stator slots takes place at the plant site.

Specialized machining shops are also key components of the hydropower supply chain to serve the needs of plant owners facing extinct supply chains for some of their plant components (e.g., some machine shops are able to reverse engineer old mechanical governor components) or needing refurbishment of custom components such as gates.

Once manufactured, transportation of the turbine and generator components within the United States can be by barge, rail, and/or truck depending on the size and weight of the components as well as the plant site location. Transportation logistics are considered by manufacturers in deciding whether the product can be shipped fully assembled or broken into multiple parts that can more easily be transported via truck for final assembly at the plant site. Barge transportation is used frequently for transporting large components to plants that are located on navigable main river stems. When manufacturing takes place overseas, ocean shipping is almost always the chosen transportation mode. However, there are also instances of air shipping when the dimensions of the component allow it and it is especially urgent for the plant owner to receive it.

The turbine-generator package is typically designed first, with the conveyance system and powerhouse designed around it. The turbine production and civil construction are typically parallel efforts. As the turbine and generator are being manufactured, there is significant back and forth between the turbine designers, facility design engineers, and construction companies. The foundation of the turbine-generator system is critical for alignment with the conveyance system, discharge system, and bypass system. The design and construction of the powerhouse will occur on a timeline to accept the turbine-generator package when it is shipped to the site. Climate-controlled shipping and storage may be considerations for the generator due to its sensitivity.

At the end of its operational life, hydropower plant materials for which there is an active market (steel, copper) are typically recycled. The value of these materials is often factored in as a credit in contractor bids. Some of the stakeholders interviewed acknowledged not giving much thought to other initiatives to avoid landfilling given the long operational life of most hydropower plant components and the recycling practices already in place. Some examples were mentioned where old turbine runners are used by the manufacturers for training schools or testing purposes.

Disposal of hazardous substances also receives special attention. The list of hazardous substances in a hydropower plant may include oil, asbestos (typically found on generator windings and insulations for units constructed from the 1930s to the 1980s), and lead (found sometimes in old turbine runners). Presence of hazardous substances associated with the copper or steel components can make their recycling more difficult.

2.3 U.S. Production Capabilities

NHA's inventory of U.S. hydropower supply chain companies contains more than 2,500 entries but no easy way to categorize the goods or services provided by each company. Table 1 shows the top 10 states by number of companies in NHA's inventory; together they account for more than 60% of the total number of companies.

Table 1. Top 10 States by Number of Companies in the U.S. Hydropower Supply Chain

State	Number of Companies
Pennsylvania	324
California	247
Washington	202
Wisconsin	147
Ohio	133
Illinois	129
Alabama	121
Oregon	109
Michigan	83
Massachusetts	80

Source: NHA

The ten states in Table 1 include the three with the largest installed hydropower capacities (Washington, California, and Oregon) but also others that have small hydropower fleets. For states like Pennsylvania (by far the one with the largest number of companies), Wisconsin, Ohio, and Michigan, it is their proximity to steel mills and related manufacturing that made them attractive. In fact, a large fraction of the companies that serve the hydropower supply chain are not exclusively dedicated to it. For instance, machine shops serve a variety of industries as do companies producing pipes or even those manufacturing small generators or industrial controls.

For the electrical and machining shops serving the hydropower industry, hydropower can be a small fraction of their overall business.

Figure 8 shows the location of U.S. suppliers/manufacturing facilities for some of the key hydropower plant components. Two of the three largest turbine manufacturers globally—Andritz, GE Renewable Energy, and Voith—have manufacturing facilities in the United States: Voith in York (PA) and Andritz in Spokane (WA). The production capabilities at each of these sites largely depend on the machines available (e.g., turning machines, boring machines, lathes) and the maximum load and unit dimensions they can handle. The surface area of the two sites is mentioned here as an initial proxy for the number of operations that can be performed and/or number of units that can be produced in each per year. The production area of Voith's facility in York covers an area of 215,000 square feet (Voith, n.d.). As for the Spokane facility, Andritz recently invested in its expansion from a 20,000 square-foot building to 48,000 square feet (Williams, 2014). For GE Renewable Hydro, the primary manufacturing location serving Canada and the United States is in Sorel-Tracy (Quebec). Other turbine suppliers with manufacturing facilities in the United States are American Hydro also in York (PA), Canyon Hydro in Washington, and Natel Energy in California.

As previously discussed, most of the major turbine manufacturers also provide generators either through joint ventures or subcontracting some or all the components from other companies. Thus, the major turbine manufacturers noted above can be considered generator suppliers. Of the 27 companies shown in the map under the Turbines category, eight also supply generators. Most of the remaining generator manufacturers in Figure 8 are likely to be non-hydropower specific and providing generators for smaller hydropower units and other markets.

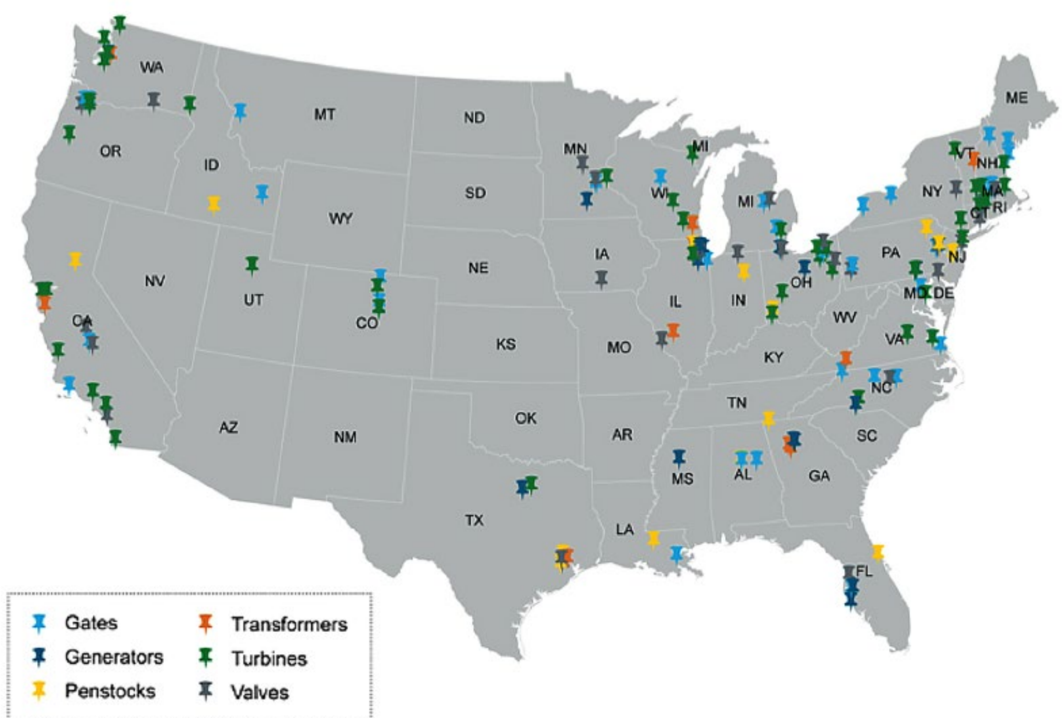

Figure 8. US suppliers/manufacturers for selected hydropower plant components

Source: Uría-Martínez et al. (2015)

Note: This map is not intended to include all hydropower supply chain participants but to provide insight on the location of domestic manufacturers for key hydropower electromechanical and civil equipment components. Those facilities in the "Turbines" category can include turbines and any combination of generators, transformers, and/or gates. Some of the companies in the "Turbines" category do not manufacture turbines but smaller components such as bearings that are part of the turbine.

For governors, the manufacturing companies have evolved with the technology. Among the companies manufacturing the early mechanical governors in the United States were Woodward Governor Company, Lombard Governor Company, and Sturgess Governor Company (Fasol, 2002). The digital governors that are the standard for new hydropower plants today are often supplied by the turbine manufacturer. American Governor is a major U.S. manufacturer specialized in governors. Its Hydro Design Center is located in Pennsylvania. It manufactures digital governors but also provides spare parts and support for plant owners that continue to rely on mechanical governor systems.

2.3.1 Turbine imports and exports

Trade balance data for hydropower-specific components helps to assess the robustness of the U.S. hydropower supply chain. The only hydropower plant components for which the U.S. International Trade Commission (USITC) publishes hydropower-specific data on import and export trade values are turbines and turbine parts. Figure 9 summarizes the trends in U.S. turbine/turbine parts import and export values from 1996 to 2020.

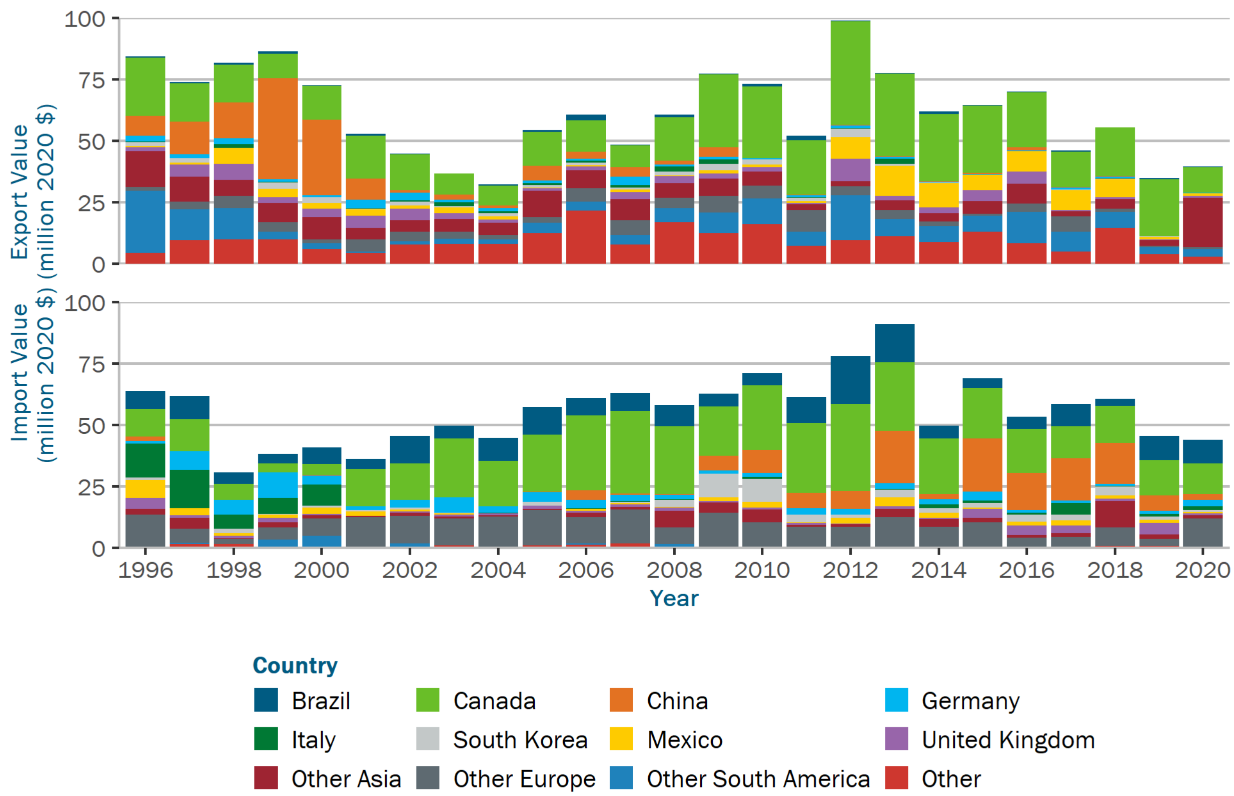

Figure 9. U.S. hydropower and PSH turbine/turbine parts import and export values by country

Source: USITC

Note: A turbine or turbine part imported from a certain country can have been manufactured, at least in part, in a third country. Turbine-generator sets are not included because they are reported under a different USITC code that is not specific to hydropower.

Except for a few years in the late 1990s where exports were double or more the value of imports, the United States has had a close balance between imports and exports of turbines and turbine parts. From 2000 to 2020, average annual exports have been $57.8 million and average annual imports have been $57.1 million.

For most years in 2000–2020, Canada has been the most important trading partner in hydropower turbines for the United States. Exports to the other North American Free Trade Agreement (NAFTA) country, Mexico, became sizable in 2012 and were stable until 2018 but have dwindled to almost zero in 2019–2020. China was a net importer of U.S. hydropower turbines and parts in the late 1990s. Exports to China progressively declined during the 2000s as that country scaled up its manufacturing capacity and have been almost zero since 2009, the same year when the United States started increasing its imports from China.

Every year from 2010, except for 2020, half or more of U.S. turbine exports stayed in the Americas (Canada + Mexico + Brazil + Other South America). On average, from 2010 to 2020, the share of U.S. exports going to other countries in the Americas was 63%; the rest went to Europe (14%), Asia (12%), and rest of the world (10%).

The origin of U.S. imports has been concentrated in fewer regions than the destination of U.S. exports. From 2010 to 2020, the average share of imports coming from the rest of the Americas was 51%, 27% came from Asia, and 21% from Europe. Less than 1% came from elsewhere.

The USITC data also reports, for each country and year, how much of the U.S. trade flows were turbine parts versus full units. For imports, on average, more than 90% of the value corresponds to turbine parts over the 1990–2016 period. For exports, turbine parts account for an average of 72% of the value each year during that same period. Exports of full turbine units with power rating of less than 1 MW have represented an average of 22% of the total export value during the 2010s.

Additional detail regarding which specific turbine parts are being traded would be valuable as it would allow for a richer interpretation of the trends discussed in this section. This additional detail would also make it possible to identify any specific imported parts that the United States relies heavily on and to analyze the reasons why those parts are not produced domestically.

2.4 Key Global Manufacturers

Turbines and generators are the hydropower-specific components for which comprehensive data are available to estimate global market shares. The number of companies manufacturing large turbines (>30 MW) or generators is much smaller than the number of companies manufacturing small units. This is likely due to the higher barriers to entry, from specificity of the expertise needed to the magnitude of capital investment requirements, for manufacturing large units.

2.4.1 Turbines

The three largest global turbine manufacturers (Andritz, GE Renewable Energy, and Voith) were founded a century or more ago. Their size today is partly the result of a process of consolidation involving numerous mergers and acquisitions. As the next set of plots shows, they have the largest market shares both globally and in the United States. However, another set of manufacturers outside of the Americas and Europe has developed in parallel, with a focus on markets in other world regions.

Figure 10 shows U.S. and global hydropower (including PSH) turbine market shares based on a representative sample of turbine capacity installed. The top nine manufacturers based on global capacity installed are:

- Andritz (Austrian company)
- GE Renewable Energy (headquartered in France following GE's re-entry into turbine manufacturing with the acquisition of Alstom's hydropower division in 2015; its parent company (GE) is a U.S. company).
- Voith (German company)
- Harbin Electric (government-owned Chinese company)
- Dongfang Electric (government-owned Chinese company)
- Power Machines (Russian company)
- Hitachi Mitsubishi Hydro (Japanese company)
- Toshiba (Japanese company)
- Bharat Heavy Electricals Ltd (government-owned Indian company)

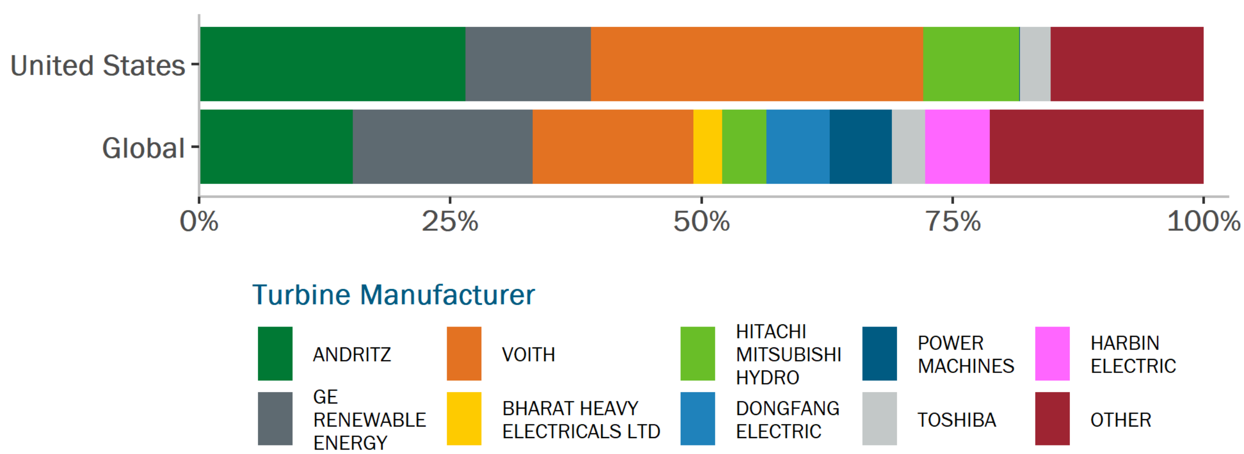

Figure 10. U.S. and global market shares of the global top nine turbine manufacturers by installed capacity

Source: GlobalData

Note: The plot includes information for 18,302 turbines globally (either installed in plants that are operational or to be installed in plants that are under construction) with a combined capacity of 972 GW, which is approximately 72% of global hydropower (including PSH) installed capacity. For the United States, the information in the plot covers 1,592 turbines with a combined capacity of 76 GW which is approximately 75% of U.S. capacity installed.

Andritz, GE Renewable Energy, and Voith account for almost 50% of global turbine capacity installed. In the United States, their combined share is significantly larger, close to 75%. Only two of the other top nine manufacturers (Hitachi Mitsubishi Hydro and Toshiba) have sizable shares of turbines in the U.S. fleet. As shown in Figure 11, the rest of the top nine manufacturers have a more regional footprint.

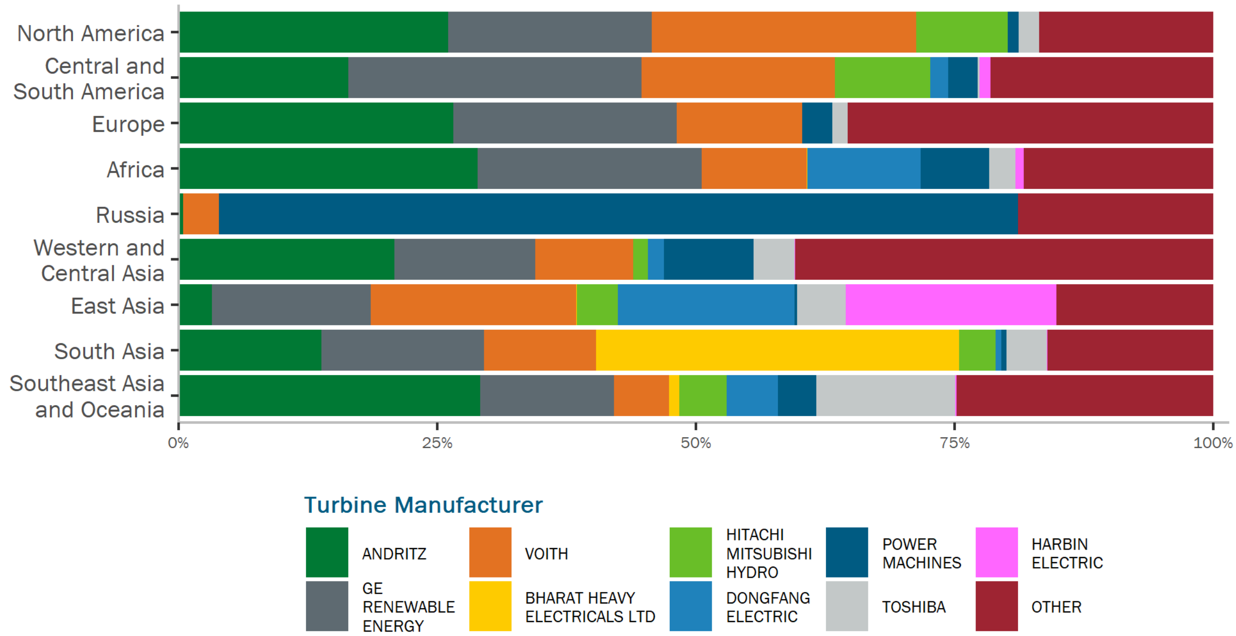

Figure 11. Regional market shares of the global top nine turbine manufacturers by installed capacity

Source: GlobalData

Note: The plot includes information for 18,302 turbines globally (either installed in plants that are active or to be installed in plants that are under construction) with a combined capacity of 972 GW, which is approximately 72% of global hydropower (including PSH) installed capacity. For the United States, the information in the plot covers 1,592 turbines with a combined capacity of 76 GW which is approximately 75% of U.S. capacity installed.

In Figure 11, North America only includes Canada and the United States and it is the region with largest combined market share by Andritz, GE Renewable Energy, and Voith. Those three manufacturers have combined market shares of 60% or more in three other regions (Central and South America, Europe, and Africa). The Russian fleet is the only one where these three companies have not manufactured at least a third of the turbine capacity. In Russia, Power Machines has a market share of 77%. Harbin Electric and Dongfang Electric are most present in East Asia, with shares of approximately 20%. East Asia, which includes China and Japan, has the largest hydropower fleet in the world (350 GW of hydropower and 61 GW of PSH at the end of 2019). Dongfang Electric also has a significant market share in Africa and Southeast Asia and Oceania. All the turbines installed by Dongfang Electric in Africa entered operation in 2009 or later; this is one of the markets China is pursuing in its Belt and Road global infrastructure development strategy. Bharat Heavy Electrical Ltd is mostly focused on the Indian market where it is the largest turbine supplier, with a market share of 35%.

Just as some of the manufacturers focus on specific regions, Figure 12 shows that there is also some degree of specialization by turbine type.

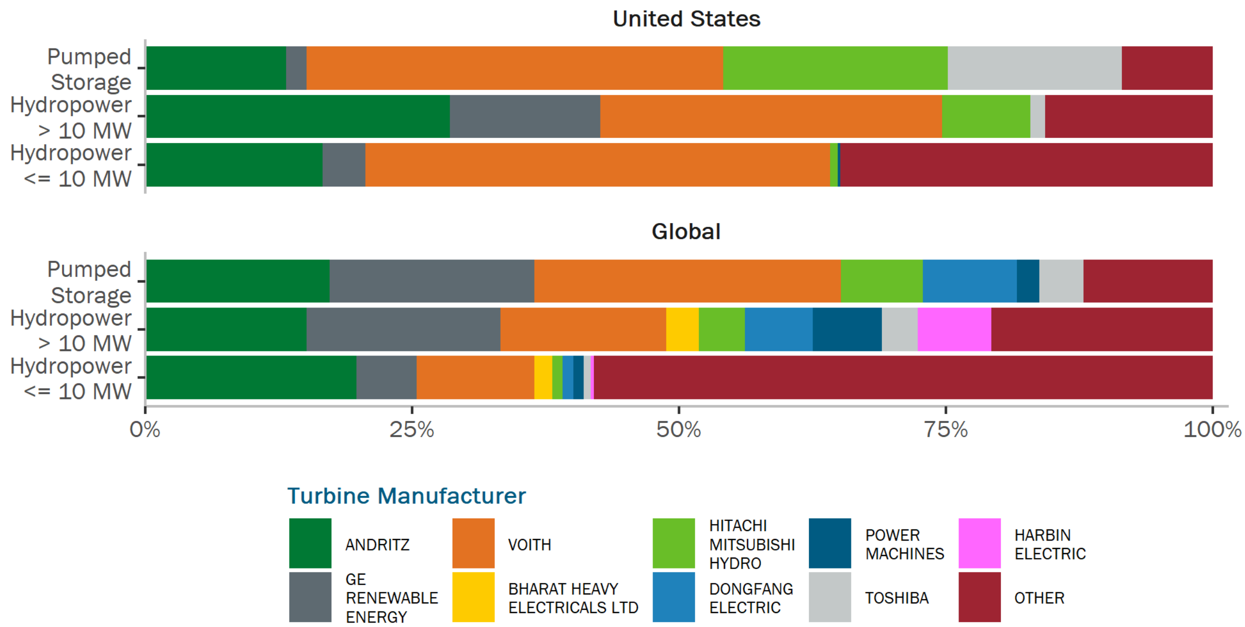

Figure 12. Market shares of the global top nine turbine manufacturers by installed capacity (by plant type and unit size)

Source: GlobalData

Note: The plot includes information for 16,261 turbines globally (either installed or under construction) with a combined capacity of 972 GW, which is approximately 72% of global hydropower (including PSH) installed capacity. For the United States, the information in the plot covers 1,529 turbines with a combined capacity of 76 GW which is approximately 75% of U.S. capacity installed.

The PSH segment has the smallest number of turbine manufacturers. The two Japanese companies (Hitachi Mitsubishi and Toshiba) have greater market shares of PSH turbines than conventional hydropower units, both globally and in the United States. The expertise of Japanese companies in PSH can be partly explained by Japan's history of being the nation with the largest PSH fleet in the world (until it was surpassed by China at the end of the 2010s). For instance, Toshiba produced the world's first adjustable speed PSH units for a Japanese plant in 1990 (Toshiba, n.d.). The greater diversity of suppliers in the small turbine segment is reflected in Figure 12 by the much larger share of turbines produced by "Other" manufacturers (35% in the United States and 58% globally).

Figure 10, Figure 11, and Figure 12 show market shares for the entire installed fleet. If only units that started operation since 2000 or are under construction were considered and the top nine global market shares recalculated, the combined share of Andritz, GE Renewable Energy, and Voith remains at ~50%. However, the global market share by Chinese manufacturers (Harbin Electric and Dongfang Electric) among the top nine increases from 13% to 22%. This increase is consistent with the very large share of global hydropower and PSH capacity additions that China has represented during this period (see Figure 6).

2.4.2 Generators

The largest three manufacturers of hydropower turbines (by installed capacity)—Andritz, GE Renewable Energy, and Voith—also hold large shares of the global market for hydropower generators. Figure 13 shows that their combined global market share is 50%. Of the other top six manufacturers by installed capacity, four are in the top nine for turbines as well. The other two are ABB (a Swiss company) and NPO Elsib (a Russian company).

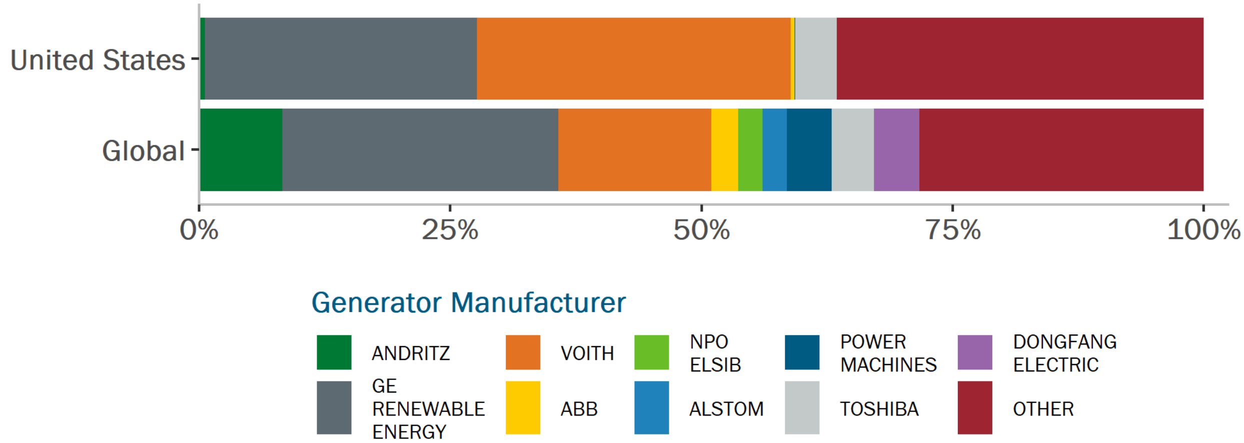

Figure 13. U.S. and global market shares of the global top nine generator manufacturers by installed capacity

Source: GlobalData

Note: The plot includes information for 11,335 generators globally (either installed or under construction) with a combined capacity of 509,000 MVA. For the United States, the information in the plot covers 1,133 turbines with a combined capacity of 38,000 MVA.

For the United States, the two main generator suppliers are GE Renewable Energy and Voith. The share of generators in the "Other" category is larger for generators than turbines in the United States largely because of a significant share of generators (15%) supplied by Westinghouse Electric. Since it did not install much generator capacity in other countries, Westinghouse Electric does not show up in the global top nine ranking. Furthermore, Westinghouse is no longer in the hydropower generator manufacturing business. Its power generation business was acquired by Siemens in 1997 (Burnett, 1997).

The composition of the ranking of top manufacturers for generators varies more than that for turbines if the ranking is created by number of units versus capacity installed (MVA). This variation reflects marked differences in the set of companies that manufacture large versus small generators. The top nine manufacturers in Figure 13 only have a 25% market share for generators of less than 10 MVA. Some of the companies that produce large numbers of generators below that rating are ABB (a Swiss company), Koncar Generators and Motors (a Croatian company), Indar Electric (a Spanish company), and Leroy Somer Marbaise Gmbh (part of the Nidec Group which is a Japanese corporation).

3 Supply Chain Vulnerabilities

To gather information on supply chain vulnerabilities, the project team complemented desk research with a set of 15 interviews with U.S. hydropower plant owners, OEMs, and hydropower consultants. Additionally, the Centre for Energy Advancement through Technological Innovation (CEATI) sent out a request for information (RFI) to its Generation Asset Management Interest Group and Hydraulic Plant Life Interest Group members with a set of questions on supply chain vulnerabilities on behalf of the Oak Ridge National Lab (ORNL) team.

The interviews and the RFI focused on the following list of hydropower-specific components that are critical to unit or plant operations:

- Turbine (scroll case, runners, wicket gates or needle valves, draft tube)

- Generator (stator and its components, rotor and its components)
- Governor (hydraulic power unit and controls)
- Excitation system
- Switchgear (circuit breakers, surge arrestors)
- Emergency closure system (gates, valves)
- Penstock
- Balance of plant (e.g., batteries, cranes, compressed air systems).

These components have different levels of criticality for hydropower generation. Turbine and generator components as well as governor, excitation system, and switchgear are critical at the unit level. Thus, if they fail, only the affected unit goes into an outage, allowing the remaining units (at a plant with multiple units) to continue generating power. The emergency closure system elements and penstock can be connected to multiple units and affect all of them if they fail.

Most of the components listed above have extended supply chains with lead times that range from months to years. An exception are surge arrestors which can be easily replaced. Lead times are longest for custom components, including all the turbine and generator components in the list as well as penstock and gates. Furthermore, many of the listed components have low diversity of suppliers. For instance, as discussed in Section 2.4, three companies supply and service most large hydropower turbines and generators in the United States. Diversity of suppliers tends to be large for balance of plant components because those are general industrial components with many uses.

Some of the key threads gathered from stakeholder input on supply chain vulnerabilities and strategies to address them are summarized in Table 2 and discussed in more detail in the rest of the section.

Table 2. U.S. Hydropower Supply Chain Key Vulnerabilities

Component/Topic	Vulnerability
Turbine	Large steel castings (> 10 tons) for turbine components cannot be procured from U.S. foundries
Generator	Stator windings for larger units (>100 MW) are very difficult to procure domestically
Turbine	Ongoing consolidation in the turbine manufacturing industry has resulted in decreased supplier diversity (particularly in the large turbine segment)
Electronic components	Extended and opaque supply chains, high rates of obsolescence
Multiple components	Long lead times to procure new components/component replacements
Workforce	Concerns regarding hydropower workforce availability and level of training are widely shared across the industry

All turbine OEMs stated that it is not possible to procure large (>10 tons) steel castings for turbine runners and other components from U.S. foundries.

One of the OEMs estimated that castings of more than 10 tons would be needed in turbine refurbishments or upgrades for roughly half of the units installed in the United States (representing a much larger fraction of installed capacity). The steel foundries currently supplying these large castings are in Brazil, China, Eastern Europe, and South Korea. This list is provided alphabetically as it is unclear which countries provide the greatest import volume of castings. The situation for large forgings is similar as for large castings although there is at least one U.S. supplier that can provide them.

The process of offshoring steel foundries capable of producing these large components has been driven by a combination of cheaper labor, less stringent occupational safety and environmental regulations, and more robust industrial policies in other countries than in the United States.

Among the options mentioned by OEMs to address this challenge are the use of smaller castings that can be welded together or potential adoption of AM processes. Both smaller castings and castings produced using AM process could be sourced domestically.

Turbine OEMs also supply generators, but many of the components are manufactured by partnering companies/subcontractors outside of the United States. Stator windings for larger units (>100 MW) are very difficult to procure domestically.

There is at least one manufacturer of coils for stator windings in the United States (National Electric Coil), but windings with the stronger insulation required for very large units can only be provided by a few companies worldwide. Canada, Mexico, Brazil, and Europe were cited as the typical origins of imports for generator components that are not produced domestically.

Diversity of turbine suppliers has decreased with the ongoing trend of consolidation in the industry (especially in the large turbine segment), but the few remaining suppliers can service all units.

There is little exclusivity in operations and maintenance (O&M) and servicing of the hydropower industry. Ownership of the intellectual property for a given turbine design is useful but not necessary to service a unit. Plant owners typically have O&M drawings from the original manufacturer. Combining these assembly drawings with some detailed measurements made at the site, most OEMs can offer upgrade parts. Major refurbishment and modernization projects are open to all manufacturers through requests for bids.

Supplier diversity decreases as the size of the unit increases because of the dimensions of the tooling and corresponding facility required for manufacturing them. Additionally, supplier diversity is also low for turbine types with specialized features/functions (e.g., aerating turbines).

The choice to use mechanical or digital governors in the U.S. fleet is driven by many factors, including the cybersecurity concerns associated with extended and opaque supply chains for electronic components.

Large units providing a variety of ancillary services are the likeliest candidates to have digital governors; in fact, ISO/RTOs might require a plant owner to have a digital governor to participate in ancillary service markets. Two downsides mentioned by interviewees from the switch to digital governors are the loss of manual control over unit operation and potential increased vulnerability to cyberattacks. Mitigating cybersecurity risks associated to a switch to digital governors requires other investments in network architecture. For units providing black start, it might be especially important to maintain the option of manual control, which is another consideration preventing the switch to digital governors.

For old mechanical governors, several vendors continue to provide support and are able to reverse engineer parts as needed. This ability to continue using mechanical governors even if the original manufacturers no longer exist offers valuable flexibility for plant owners as they evaluate the pros and cons of a switch to digital governors in their specific case.

Mechanical components are robust, and the hydropower industry takes pride in finding ways to extend their life; in contrast, electronic components have high rates of obsolescence.

Extinct supply chain issues due to a manufacturer going out of business are more salient for electronic components than mechanical components because there are typically more options to refurbish or reverse-engineer mechanical components. As examples, refurbishing old governor oil pumps is a flourishing business and small machine shops can reverse engineer components such as valves for which the original supplier no longer exists.

For electronic components, replacements are more frequently driven by obsolescence (software no longer supported) instead of probability of failure. For instance, for PLCs, 15 years was mentioned by several interviewees as the typical replacement cycle.

Spare part strategies have been in place for a long time, but they are being reconsidered/expanded to address current longer lead times to procure replacements.

Consumables such as small bearings, seals, and bushings for transformers are typical items in the spare parts programs of most hydropower owners. Keeping a supply of extra coils for winding repairs is also common. Some of the plant owners interviewed are also maintaining spares for critical, large-ticket items such as transformers and wicket gates. The procurement of spare parts is increasing, relative to previous practices, for components having lead times that would result in months to years of downtime should the component fail.

The ability to share spare parts across plants and manage O&M costs is one of the reasons to choose a single supplier to provide small, less customized components across multiple plants in a fleet. For spare parts to be useful when needed, they require maintenance. For instance, windings need to be stored in a moisture-controlled environment to avoid deterioration and a spare transformer needs similar maintenance as one in service.

Both hydropower plant owners and OEMs expressed increasing awareness/interest in tracing where materials and electronic components come from.

In the current environment (2021) of global supply chain disruptions, with long delays and escalating costs for ocean shipping, some plant owners are willing to pay a premium for domestic components. However, ordering a component from a domestic supplier does not mean that it has 100% domestic content. The purchaser typically has limited visibility into where the manufacturing of subcomponents takes place or raw materials come from. Components that contain microchips are usually manufactured in Asia (Taiwan, South Korea, China, Malaysia) and can delay an order significantly in the current market environment.

Cybersecurity concerns are another reason for increasing visibility into multi-tier supply chains. For instance, Executive Order (E.O.) 13920 "Securing the United States Bulk-Power System" (published in May 2020, expired in January 2021) prohibited acquisition of bulk-power system electric equipment designed, developed, manufactured, or supplied by a foreign adversary if the transaction posed undue risk to grid resilience and national security. The list of electric equipment covered by the E.O. included many components present in a hydropower plant ranging from generation turbines to industrial control systems and protective relays. Even though this E.O. has expired, plant owners are interested in identifying a set of suppliers with whom cybersecurity concerns would be minimized.

Concerns regarding hydropower workforce availability and level of training are widely shared across the industry.

Workforce concerns extend from personnel needed for on-site operations to manufacturing and construction. The types of positions for which hiring is difficult include skilled trades, such as machinists and welders, but also engineers. It is especially difficult to attract and retain construction workers for work at remote sites. Keyser and Tegen (2020) estimate that 13,000 workers would be needed by 2040 to offset the attrition of the current workforce, whose average age is older than that of the overall U.S. workforce. Scenarios with significant growth in fleet modernization and new construction would result in larger workforce needs.

Large, multinational companies also mentioned that bringing trained workforce from other global locations is a solution of limited applicability due to complex, expensive visa processes. With few new workers entering the U.S. hydropower industry, there is strong competition for the existing talent pool leading to substantial mobility of workers across companies within the industry.

Several interviewees mentioned a decline in the quality of installation work (e.g., installations of stator windings) that is indicative of insufficient training and experience. Quality of work also varies significantly across different crews managed by the same contractor.

Some plant owners mentioned a decreasing trend in the number of bids they get from contractors.

For some components with few suppliers (e.g., large turbines and large generators), plant owners know they can only expect a very limited set of bids. For smaller components or installations, the transaction costs involved in information gathering and bid proposal preparation contribute to small numbers of submissions. First, the lack of a centralized system capturing new requests for bids makes it time-consuming for companies to learn about them, especially if they are companies that serve many industries rather than just hydropower (e.g., machine shops and domestic casting operations). Second, the acquisition systems of large utilities and federal entities can be complex and pose significant barriers to entry for small companies. Additionally, in the last 18 months, some companies experienced reductions in staff due to COVID-19 and might have less resources to conduct the extensive searches needed to have a comprehensive view of upcoming hydropower-related projects and to prepare bid proposals.

The current environment of escalating commodity prices, including crucial ones for the hydropower industry such as steel and copper, and global supply chain bottlenecks may also inhibit some companies from bidding. For instance, suppliers that typically offer fixed-price bids to their customers are not comfortable doing so now given the significant price uncertainty that exists in the current markets.

Turbine-generator OEMs mentioned they have spare capacity at their manufacturing facilities. However, potential bottlenecks in a scenario of significant growth in U.S. demand for hydropower components could arise for some of the inputs those manufacturing facilities need (large castings, large windings, and workforce) to scale up their output.

Growth in U.S. demand can emerge from multiple scenarios with slightly different implications for where the bottlenecks could appear.

- Increased investments in refurbishments and upgrades connected to the hundreds of facilities being relicensed within the next decade. This scenario implies modest needs for construction work, but it would require components for the wide range of turbine-generator unit sizes to be potentially refurbished/upgraded; thus, it would create work for many different turbine OEMs.
- Significant growth in NPD retrofits would require substantial construction workforce. Unit sizes would typically not be very large (in terms of power rating) making it possible for more than the largest three

manufacturers (Andritz, GE Renewable Energy, and Voith) to submit bids for turbines and generators required for NPD retrofits (e.g., Canyon Hydro, Mavel, Natel Energy).[9]

- New PSH construction would require substantial construction workforce. Unit sizes are typically large so the number of suppliers for turbines and generators is limited (mostly the top 3 global manufacturers plus Toshiba and Hitachi Mitsubishi) and the issues associated with procurement of large castings and windings could be more salient.

Combinations of the scenarios mentioned would lead to more probable/more acute bottlenecks.

Scenarios involving significant growth in new construction would also require increased use of specialized machinery, such as advanced excavation and tunneling equipment. Interviewees did not foresee a high risk of bottlenecks in those items. Construction companies typically own rather than rent the necessary machinery.

Additional components that are not hydropower-specific are nonetheless critical to hydropower plant operations and some of them have risky supply chains.

Large step-up transformers that increase the voltage of the electricity coming out of generators have long lead times (1–2 years) and very few options for domestic sourcing. In some cases, these transformers are connected to multiple units making them even more critical. Other components mentioned by interviewees as critical for operation of the entire plant and not hydropower-specific are powerhouse dewatering systems and bypass structures. Flooding of a powerhouse will result in entire plant outage. For this reason, the dewatering system is designed with redundant pumps and multiple alarm points. The pumps are not hydropower-specific.

4 Supply Chain Opportunities

This section describes some of the opportunities to address supply chain vulnerabilities and challenges discussed in the previous section. Table 3 summarizes the main opportunity threads for addressing vulnerabilities associated to various hydropower plant components.

Table 3. U.S. Hydropower Supply Chain Key Opportunities

Component/Topic	Opportunity
Turbine	Stimulate growth to reshore capabilities. Investigate AM in hydropower sector.
Generator	Stimulate growth to reshore capabilities.
Electronic components	Increase transparency
Multiple components	Stimulate growth to reshore capabilities.
Workforce	Increase training and early career development

The United States can be a global leader in the development and application of AM for commercial production and can lead in applications of AM in the hydropower sector. Potential applications include metallic turbine components, mechanical governors, and manufactured components of auxiliary support systems.

The United States has a well-developed supply chain for AM with multiple U.S. companies that build AM production equipment and a large base of vendors that produce customized components as Tier 1

[9] Only 1 project out of the 80 NPD retrofits in the development pipeline at the end of 2020 proposes installing a turbine with a power rating greater than 30 MW. Many of the manufacturers in the small turbine market segment produce components for units up to 30 MW.

suppliers. Metal powders for AM are also produced domestically. Additive manufacturing is very well suited to production of complex parts that are not demanded in large volumes, as the processes are designed to eliminate the need to produce single use manufacturing hardware such as molds, fixtures, work holding etc. For these reasons, AM processes may offer a viable option to produce some of the large turbine parts that now require imported steel castings. Application of these capabilities to hydropower manufacturing is an opportunity for U.S. leadership in the global hydropower supply chain.

AM for mid-size components is possible now, but new machine designs will be required to build the largest components, which are also the ones where AM could be potentially most valuable to replace imported castings in the hydropower industry. Additionally, other novel processes are enabling large additive parts such as using AM to produce Hot Isostatic Pressing cans for producing turbine blades or other components. These processes also provide the possibility that the United States could eventually become an exporter of components of these types.

Interviews with manufacturers revealed substantial differences in the degree of AM adoption and types of applications being considered. One large turbine OEM mentioned having used AM for Francis blades and Pelton bucket runners as well as some smaller components. Another large turbine OEM recently announced plans to use AM for producing casting molds. A third large turbine OEM expressed interest in AM as a potential future option for manufacturing larger components. However, this OEM only considers AM for non-essential components at this point because material properties have not been sufficiently tested for applications with components where structural failure could cause catastrophic damage. Of the two OEMs interviewed in the small turbine segment, one uses AM for production of molds for castings and the other has not yet used AM processes in its manufacturing operations.

Another hydropower application for AM is to reverse engineer and print components with extinct supply chains (i.e., no longer produced by the original manufacturer). For instance, the Bureau of Reclamation and ORNL have partnered to evaluate the feasibility, cost, and performance of additively manufactured metal parts for hydropower forebay trash boom moorings, mechanical hydropower governors, and turbine bearing lubrication systems.

Since replacement of imported large castings appears as the highest value opportunity for AM in the U.S. hydropower industry, federal R&D focused on realizing that opportunity should be a priority. Working closely with turbine OEMs in developing capabilities for testing the long-term performance of AM materials and agreeing on the metrics on which these materials must be evaluated will be crucial for these processes to be accepted by the industry and eventually deployed. For this reason, creation of a working group that includes AM researchers from national labs and universities, hydropower equipment OEMs, and plant owners is strongly recommended.

The United States has one of the largest but also one of the oldest hydropower fleets in the world. Increased hydropower rehabilitation and new construction in the United States can spur reshoring of hydropower manufacturing.

With average ages of 64 years for U.S. conventional hydropower and 45 years for U.S. PSH, maintenance and modernization represents a substantial opportunity for U.S. hydropower manufacturing. At the end of 2020, there were plans for refurbishment and upgrades of 62 hydropower plants in the United States to start in 2021–2024. The estimated capital investment from these projects adds up to $4.4 billion. New hydropower construction potential is also a significant opportunity. At the end of 2020, there were 183 new projects in the U.S. conventional hydropower development pipeline with a combined capacity of 863 MW. This represents a very small fraction of the remaining technical potential for non-powered dam and new stream development. For PSH, the development pipeline included 63 projects with combined proposed capacity of 46.7 GW.

Policies and incentives that facilitate the modernization of the existing fleet, powering of NPDs, and new PSH builds would provide a powerful demand signal to hydropower suppliers that could lead both to expansion of U.S. manufacturing capacity as well as foreign direct investment in the U.S. supply chain. Two of the hydropower equipment manufacturers interviewed that currently have no U.S. manufacturing facilities expressed interest in establishing a manufacturing presence in the United States.

Almost half of the existing U.S. hydropower capacity is owned and operated by federal agencies. Thus, federal procurement rules can be leveraged to increase the domestic content of manufactured components tied to contracts for refurbishment and upgrade of the federal hydropower fleet in accordance with trade agreements.

The textbox below summarizes the provisions of the Buy American Act that are most relevant for the hydropower supply chain. It also outlines recently proposed changes to its implementation.

Buy American Act: current implementation and proposed changes

The Buy American Act restricts imports by federal agencies for use in the construction, alteration, or repair of any public work in the United States. Unless "domestic construction material" is unavailable, its use impracticable, or its cost unreasonable, it should be chosen over "foreign construction material".*

The Buy American Act restrictions do not apply to contracts for construction materials whose value is above $7,032,000 (48 CFR §25.202). For contracts above that threshold, construction material coming from any country in the Trade Agreements Act competes in equal terms with domestic construction material.**

Section 8 of the E.O. 14005, signed in January 2021, requested the Federal Acquisition Regulation (FAR) Council to consider changes to the implementation of the Buy American Act. The proposed changes were published in the Federal Register on July 30. The public comment period for the proposed changes closed on October 28, 2021. The proposed changes include:

- Increase in the domestic content threshold from 55% to 60% starting in 2022, to 65% starting in 2024, and to 75% starting in 2029.
- New enhanced price preference for critical products and components
  - The proposed price preference for the new critical preference is 20% for large businesses and 30% for small businesses.
  - Determination of which end products and components are critical will be made as part of the quadrennial critical supply chain review instituted in E.O. 14017.
- Post-award domestic content reporting requirement for contractors

*Definitions of "construction material", "domestic construction material", and "foreign construction material" (48 CFR §52.225-9).

Construction material means an article, material, or supply brought to the construction site by a contractor or subcontractor for incorporation into the building or work.

Domestic construction material means: (1) For construction material that does not consist wholly or predominantly of iron or steel or a combination of both: (i) an unmanufactured construction material mined or produced in the United States or (ii) a construction material manufactured in the United States if (A) the cost of its components mined, produced, or manufactured in the United States exceeds 55% of the cost of all its components. Components of foreign origin of the same class or kind for which nonavailability determinations have been made are treated as domestic and components of unknown origin are treated as foreign; or (B) the construction material is a commercially available off-the-shelf (COTS) item; (2) For construction material that consists wholly or predominantly of iron or steel or a combination of both, a construction material manufactured in the United States if the cost of foreign iron and steel constitutes less than 5% of the cost of all components used in such construction material. The cost of foreign iron and steel includes but is not limited to the cost of foreign iron or steel mill products, castings, or forgings utilized in the manufacture of the construction material and a good faith estimate of the cost of all foreign iron and steel components excluding COTS fasteners. Iron or steel components of unknown origin are treated as foreign. If the construction material contains multiple components, the cost of all the materials used in such construction material is calculated in accordance with the definition of "cost of components".

Foreign construction material means a construction material other than a domestic construction material.

**A map showing which countries are compliant with the Trade Agreements Act can be found at https://gsa.federalschedules.com/resources/taa-designated-countries/

The Buy American Act is much more relevant for hydropower than other energy generation technologies because approximately 50% of installed U.S. conventional hydropower capacity is owned by federal agencies (U.S. Army Corps of Engineers, U.S. Bureau of Reclamation, and Tennessee Valley Authority). Pending changes to the Buy American Act regulations summarized in the text box above would be favorable for domestic manufacturers responding to federal requests for bids below the $7,032,000 threshold, but most rehabilitation and upgrade projects in federal hydropower plants are above that threshold. For instance, the median estimated value of the 31 planned turbine or generator refurbishment and upgrade projects in federal plants tracked in the Industrial Info Resources database is $23 million; only three have estimated values below $7,032,000. Some of the key components that can be considered critical (and difficult or impossible to source domestically) are large steel castings and large windings. These components will typically be part of projects with a cost above the $7,032,000 threshold. Therefore, the effect of the proposed changes to the Buy American Act will be very limited in federal hydropower projects unless the changes are accompanied by a raise in the threshold value of the projects to which they apply.

5 Conclusions

The United States has the 4th largest conventional hydropower fleet and the 3rd largest PSH fleet in the world. The existing supply chain adequately supports this large installed base. However, multiple ongoing trends hint at the need to scale up activity. First, the average age of the fleet is 64 years for conventional hydropower and 45 years for PSH and there are billions of dollars of refurbishments and upgrades planned. The 281 conventional hydropower and PSH facilities due for relicensing in the 2020s might lead to a substantial uptick in capital upgrades because relicensing requirements often involve capital investments. Second, the objective of transitioning to a carbon pollution-free grid by 2035 would require substantial growth of all types of renewables as well as long-duration energy storage, including PSH. With the expectation that these trends would lead to an increase in demand for hydropower components in the United States, it is important to evaluate supply chain vulnerabilities and potential bottlenecks that might slow down the desired pace of refurbishments or new development.

The U.S. hydropower supply chain includes manufacturing facilities for two of the three largest global hydropower turbine and generator suppliers. Several other smaller turbine suppliers also manufacture their products in the United States. They do serve primarily the U.S. market but also export turbine components. Turbines and generators are the two most hydropower-specific components. Turbine and generator suppliers support an ecosystem of many other smaller companies that produce subcomponents for their products. Machine shops that can reverse engineer and refurbish components whose original manufacturer no longer exist are a vital part of the existing supply chain and continued reliability of the domestic fleet.

Large steel castings/forgings and generator windings for large units are very difficult or impossible to source domestically and have very long lead times. The difficulty in hiring across the U.S. hydropower industry, already experienced today, would be exacerbated in a scenario of increased activity. Additionally, ongoing global supply chain disruptions have made the vulnerabilities involved in global, multi-tier supply chains more apparent. For instance, small subcomponents involving microchips, which are also mostly imported, can introduce significant project delays.

In scenarios of increased demand for hydropower components in the United States, reshoring manufacturing of critical components should be a high priority to improve supply chain resilience.

Recommended policy actions to address the vulnerabilities and opportunities covered in this report may be found in the Department of Energy 1-year supply chain review policy strategies report, "America's Strategy to Secure the Supply Chain for a Robust Clean Energy Transition." For more information, visit www.energy.gov/policy/supplychains.

Glossary

Additive manufacturing	Process to build an object one layer at a time (3D printed) with the help of computer-aided design. It is the opposite of subtractive manufacturing where the starting point is a solid block from which material is removed until the desired shape is achieved.
Conduit	Hydropower project where hydropower generation capability is added to an existing conduit ("any tunnel, canal, pipeline, aqueduct, flume, ditch, or similar manmade water conveyance that is operated for the distribution of water for agricultural, municipal, or industrial consumption and not primarily for the generation of electricity" 18 CFR 4.30(2))
New stream-reach development	Hydropower project where hydropower generation capability is added to previously undeveloped sites and waterways
Non-powered dam	Hydropower project where hydropower generation capability is added to an existing dam used solely for other purposes (e.g., flood control, navigation)

References

BBA (2019). *Hydro generators: Introduction to stator windings.* Accessed on December 8, 2021: https://www.bba.ca/publications/hydro-generators-introduction-to-stator-windings

Bonnet, M.; Witt, A.; Stewart, K.; Hadjerioua, B.; Mobley, M. (2015). *The Economic Benefits of Multipurpose Reservoirs in the United States Federal Hydropower Fleet*. ORNL/TM-2015/550. Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA.

Bureau of Reclamation. (1992). *Hydrogenerator Design Manual*. Accessed on December 8, 2021: https://www.usbr.gov/tsc/techreferences/mands/mands-pdfs/HydroGen.pdf

Burnett (1997). *Siemens' $1.5 Billion Buys Westinghouse*. Orlando Sentinel, November 15, 1997. Accessed on December 8, 2021: https://www.orlandosentinel.com/news/os-xpm-1997-11-15-9711150485-story.html

Canyon Hydro (n.d.). *Major Components of a Hydro System.* Accessed on December 8, 2021: https://www.canyonhydro.com/guide/HydroGuide4.html

Department of Energy (2016). *Hydropower Vision*. DOE/GO-102016-4869. Wind and Water Power Technologies Office, U.S. Department of Energy. Washington, D.C., USA.

EIA (2021). *International Electricity Generation Capacity*. Accessed on January 18, 2022: https://www.eia.gov/international/data/world/electricity/electricity-capacity

Fasol, K. H. (2002). A short history of hydropower control. *IEEE Control systems magazine* (22:4); pp. 68–76.

Formlabs (n.d.) *Additive versus subtractive manufacturing*. Accessed on December 8, 2021: https://formlabs.com/blog/additive-manufacturing-vs-subtractive-manufacturing/

GE Energy (n.d.). *Synchronous Hydro Generators*. Accessed on December 8, 2021: https://www.gepowerconversion.com/sites/gepc/files/product/Hydro%20Generator%20Brochure.pdf

Gore, B.F.; Blackburn, T.R.; Heasler, P.G.; Mara, N.L.; Phan, H.K.; Bardy, D.M.; Hollenbeck, R.E. (2001). *Comparison of Intake Gate Closure Methods at Lower Granite, Little Goose, Lower Monumental, and McNary Dams Using Risk-Based Analysis.* PNNL-13149. Pacific Northwest National Laboratory. Richland, Washington, USA.

Gracia, J.; O'Connor, P.; Markel, L.; Shan, R.; Rizy, D.; Tarditi, A. (2019). *Hydropower Plants as Black Start Resources* ORNL/SPR-2018/1077. Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA.

Hadjerioua, B.; Wei, Y.; Kao, S.C. (2012). *An Assessment of Energy Potential at Non-powered Dams in the United States*. GPO DOE/EE-0711. Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA.

Hunt, J.D.; Byers, E.; Wada, Y.; Parkinson, S.; Gernaat, D.E.H.J.; Langan, S.; van Vuuren, D.P.; Riahi, K. (2020). "Global resource potential of seasonal pumped hydropower storage for energy and water storage." *Nature Communications* 11; pp. 947.

IHA (2021). *Hydropower 2050. Identifying the next 850+ GW towards Net Zero.* Accessed on December 8, 2021: https://www.hydropower.org/publications/hydropower-2050-identifying-the-next-850-gw-towards-2050

IHA (2021b). *2021 Hydropower Status Report*. Accessed on January 18, 2022: https://www.hydropower.org/publications/2021-hydropower-status-report

Johnson, M.M.; Uría-Martínez, R. (2021). *Hydropower Market Report Update*. September 2021 [PowerPoint Slides]. Accessed on January 18, 2022: https://hydrosource.ornl.gov/publication/hydropower-market-report-update-september-2021

Johnson, M.M.; Uría-Martínez, R. (2021b). *U.S. Hydropower Development Pipeline Data, FY2017*. Accessed on January 18, 2022: https://hydrosource.ornl.gov/dataset/us-hydropower-development-pipeline-data-2017.

Johnson, M.M.; Uría-Martínez, R. (2021c). *U.S. Hydropower Development Pipeline Data, FY2018*. Accessed on January 18, 2022: https://hydrosource.ornl.gov/dataset/us-hydropower-development-pipeline-data-2018.

Johnson, M.M.; Uría-Martínez, R. (2021d). *U.S. Hydropower Development Pipeline Data, FY2021*. Accessed on January 18, 2022: https://hydrosource.ornl.gov/dataset/us-hydropower-development-pipeline-data-2021.

Johnson, M.M.; Uría-Martínez, R. (2020). *U.S. Hydropower Development Pipeline Data, FY2020*. Accessed on January 18, 2022: https://hydrosource.ornl.gov/dataset/us-hydropower-development-pipeline-data-2020.

Johnson, M.M.; Uría-Martínez, R. (2019). *U.S. Hydropower Development Pipeline Data, FY2019*. Accessed on January 18, 2022: https://hydrosource.ornl.gov/dataset/us-hydropower-development-pipeline-data-2019.

Kafle, A.; Lal Shrestha, P.; Chitrakar, S.; Thapa, B.; Thapa, B.S.; Sharma, N. (2020). "A review on casting technology with the prospects on its application for hydro turbines." *Journal of Physics: Conference Series* 1608; pp. 012015.

Kao, S.C.; McManamay, R.A.; Stewart, K.M.; Samu, N.M.; Hadjerioua, B.; DeNeale, S.T.; Yeasmin, D.; Pasha, M.F.; Oubeidillah, A.A.; Smith, B.T. (2014). *New Stream-reach Development: a Comprehensive Assessment of Hydropower Energy Potential in the United States.* GPO DOE/EE-1063. Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA.

Keyser, D.; Tegen, S. (2020). *Workforce Development for U.S. Hydropower: Key Trends and Findings.* NREL/TP-6A20-74313. National Renewable Energy Laboratory, Golden, Colorado, USA.

Schmidt, E.; Johnson, M.M.; Uría-Martínez, R. (2021). *U.S. Hydropower Development Pipeline Map 2021*. HydroSource. Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA.

Schmidt, E.; Johnson, M.M.; Uría-Martínez, R. (2021b). *U.S. Pumped Storage Hydropower Development Pipeline Map 2021*. HydroSource. Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA.

Stocks, M.; Stocks, R.; Lu, B.; Cheng, C.; Blakers, A. (2021). "Global atlas of closed-loop pumped hydro energy storage." *Joule* (5:1); pp. 270–284.

Toshiba (n.d.). *World's First Adjustable-Speed Pumped Storage Generating System*. Accessed on December 8, 2021: https://toshiba-mirai-kagakukan.jp/en/learn/history/ichigoki/1990hatuden/index.htm

Uría-Martínez, R.; Johnson, M.M.; Shan, R. (2021). *U.S. Hydropower Market Report.* DOE/EE-2088. Water Power Technologies Office, U.S. Department of Energy. Washington, D.C., USA.

Uría-Martínez, R.; O'Connor, P.W.; Johnson M. M. (2015). *2014 Hydropower Market Report*. DOE/EE-1195. Wind and Water Power Technologies Office, U.S. Department of Energy. Washington, D.C., USA.

Voith (n.d.). *Precision Heavy Manufacturing in the United States*. Accessed on December 9, 2021: https://voith.com/corp-en/VH_Image-Brochure-Voith-USA_13_vvk_t3384e_en.pdf

Vu, H.D.; Agee, J.C. (1998). *WECC Tutorial on Speed Governors*. Accessed on December 8, 2021: https://www.wecc.org/Reliability/Governor%20Tutorial.pdf

Williams, E. (2014). *Precision Machine Future in Flux*. The Lewiston Tribune, October 3, 2014. Accessed on December 9, 2021: https://lmtribune.com/northwest/precision-machine-future-in-flux/article_0c5508db-aa9b-5267-adfb-e1446d9d2129.html

U.S. DEPARTMENT OF ENERGY

For more information, visit:
energy.gov/policy/supplychains

DOE/OP-0007 ▪ February 2022