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Hydropower Supply Chain Gap Analysis

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Disclaimer

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List of Acronyms

BAA	Buy American Act
BABA	Build America, Buy America Act
BIL	Bipartisan Infrastructure Law
CapEx	capital expenditures
CEATI	Center for Energy Advancement through Technical Innovation
CTC	continuously transposed conduction
DOE	U.S. Department of Energy
EV	electric vehicle
FAR	Federal Acquisition Regulation
FERC	Federal Energy Regulatory Commission
FTA	Free Trade Agreement
GE	General Electric
GOES	grain-oriented electrical steel
GW	gigawatt
IDIQ	indefinite delivery, indefinite quantity
IRA	Inflation Reduction Act
ITC	investment tax credit
kV	kilovolt
kW	kilowatt
LPT	large power transformer
LPTA	Lowest Price Technically Acceptable
MATOC	Multiple Award Task Order Contract
MVA	megavolt-ampere
MW	megawatt

NAF	North American Forgemasters
NAICS	North American Industry Classification System
NEC	National Electric Coil
NHA	National Hydropower Association
NOES	non-oriented electrical steel
NPD	non-powered dam
NREL	National Renewable Energy Laboratory
ORNL	Oak Ridge National Laboratory
PSH	pumped storage hydropower
PTC	production tax credit
QA/QC	quality assurance/quality control
SATOC	Single Award Task Order Contract
USGS	U.S. Geological Survey
WPTO	Water Power Technologies Office

Executive Summary

In response to Executive Order 14017 on America's Supply Chains, the U.S. Department of Energy (DOE) conducted supply chain "deep dives" for renewable energy technologies, including hydropower and large power transformers, a critical part of a hydropower installation. Since the deep dives were published, the Water Power Technologies Office (WPTO) has focused on improving our understanding of the hydropower supply chain and developing strategies for addressing supply chain challenges. Because the challenges outlined in the deep dives are most acute for large (greater than 100 megawatts [MW]) hydropower systems, this report focuses on large systems, but it is expected that the recommendations will improve the supply chain for all hydropower systems. Finally, since the federal government owns almost 50% of the nameplate capacity for conventional hydropower systems with 40% (18 gigawatts) of these units being at least 100 MW, the federal fleet is used to prime the development of the supply chain for the rest of industry.

In 2023, DOE's Secretary of Energy asked WPTO to engage the hydropower community for input on strategies to secure and encourage domestic manufacturing. WPTO has established three focus areas:

- Define the market for rehabilitations and new construction of the hydropower fleet.
- Provide insights for policies, incentives, loan programs, and technology investments to encourage domestic content.
- Define the existing and required domestic hydropower manufacturing capabilities and workforce.

This report summarizes WPTO's efforts in the listed focus areas and complements the earlier work by further exploring the identified challenges and conducting a detailed gap analysis of the domestic hydropower supply chain. Specific, actionable recommendations are made to address gaps.

Supply Chain

The hydropower supply chain is divided into three sectors: upstream, midstream, and downstream, as shown in Figure ES-1. The subsector outlined in orange indicates limited domestic capacity, those in yellow represent some capacity, and those in green denote sufficient capacity. Subsectors with intense foreign competition are denoted with a dollar sign. This analysis focuses on the yellow and orange areas, as they have limited domestic capacity.

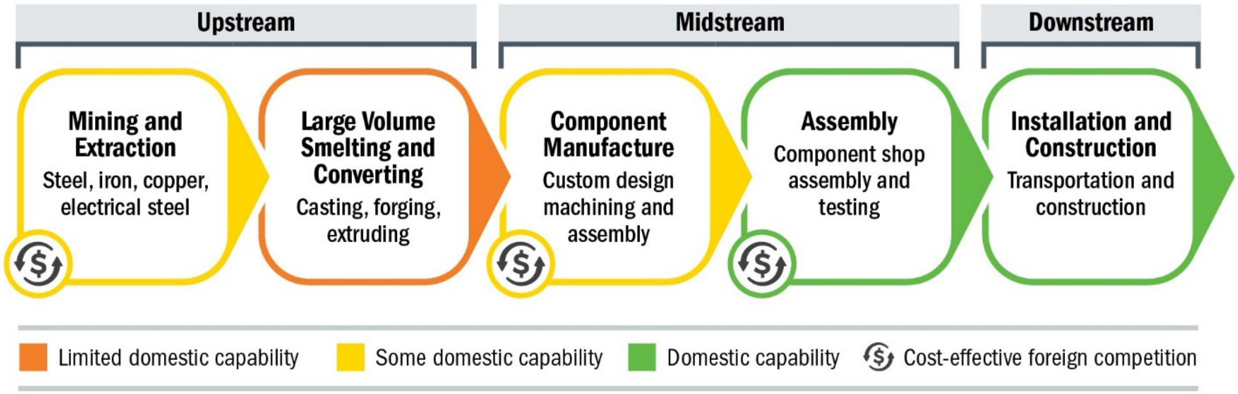

Figure ES-1. High-level domestic hydropower supply chain.

Illustration by Tara Smith, NREL, modified from Uría-Martínez (2022)

Upstream supply chain components include raw material extraction, concentration, and processing into engineered materials. While the United States has strong iron mining and steel production capabilities, it has limited to no mining of the trace metals (e.g., manganese) used in steel, and it imports more than 40% of its copper (United States Geological Survey [USGS] 2024). Similarly, there are only two domestic facilities with forging capabilities for large hydropower shafts (50–75 tons) and a single domestic foundry that can cast large turbine runners (greater than 10 tons).

The first stage in the midstream supply chain is composed of the manufacture and assembly of hydropower components such as hydrogenerators and turbines. Although some U.S. companies manufacture components, the international competition is intense, and acquiring components for 100-MW or larger systems is difficult (with only one foundry capable of producing castings greater than 10 tons) or impossible (with no domestic manufacturers for hydrogenerators greater than 20 MW) to procure domestically.

Gap Analysis

Five major gaps in the domestic hydropower supply chain have been identified:

1. **Unpredictable and variable demand signals:** The development of a domestic hydropower supply chain is hampered by an unpredictable and highly variable demand for materials and components. In general, hydropower systems have exceptionally long lives (e.g., 30–50 years), so replacements and refurbishment schedules have cycles that are years or decades.

2. **Severely limited or nonexistent domestic suppliers for hydropower materials and components:**
    - Single domestic facility for windings >100 MW for large hydrogenerators.
    - Single domestic facility for large forgings (50–75 tons) for large hydropower shafts.

  - Single domestic foundry with casting capabilities >10 tons for large turbine runners.
  - Single domestic facility for <20-MW hydrogenerator manufacture.
  - No domestic facilities for >20-MW hydrogenerator manufacture.
  - Single domestic supplier of grain-oriented electrical steel (GOES) for U.S. transformer manufacturers.
  - Two domestic suppliers of non-oriented electrical steel (NOES) for U.S. hydrogenerator manufacturers.

3. **Federal contracting procedures and domestic content laws:**

   - There are several procurement regulations and/or general practices that inhibit the development of the domestic hydropower supply chain, including bonding requirements, specifying precontract design work, all-inclusive contracts, and focusing exclusively on the initial capital outlay rather than the total project life cycle cost.
   - Both the Buy American Act (BAA) and Build America, Buy America Act (BABA) are designed to assist critical supply chains by specifying domestic content for federal purchases (BAA) and purchases using federal funds (BABA).

4. **Foreign competition, foreign subsidies, and ineffective trade policies:** Discussions with companies in the hydropower industry highlighted inequitable competition from foreign companies and ineffective trade policies as other issues in the hydropower supply chain. Several companies noted that other countries subsidize their steel industries, and China develops “pods” of manufacturing capability to shorten the supply chain to make it more cost-effective.

5. **Shortage of skilled workers:** Hydropower manufacturing and upstream support industries suffer from a significant lack of workers with requisite expertise. As these industries have been offshored over the last 40 years, skilled workers have retired or moved to other industries.

Recommendations

To address the identified gaps, DOE/WPTO should consider the following recommendations:

1. **Lead with the federal fleet** to prime the development of an aggregated, consistent demand signal with our largest producers by examining federal procurement processes and developing best practices for refurbishment of the domestic fleet. Improve federal procurement processes to include multi-entity or multi-project long-term contracts and ensure that small businesses can compete for federal contracts. Develop best practices for refurbishments to ensure a predictable, steady demand.

Over the next 20–25 years, refurbishment of the federal fleet alone could result in

  - 20,700 tons of crowns (i.e., cast steel)
  - 17,300 tons of shafts (i.e., forged steel)
  - 57,400 tons of runner blades and bands (i.e., cast and/or forged)
  - $20 billion in equipment costs alone.

2. **Develop domestic supply chain and end-user datasets** to increase awareness of current and expanding capabilities of the domestic supply chain and installed hydropower fleet. WPTO is funding development of two databases at Oak Ridge National Laboratory: (1) a comprehensive database of suppliers in the hydropower supply chain and (2) an expansion of the HydroSource tool to provide unit and component-level information on the existing domestic fleet.

3. **Work with other low-carbon technologies** to create a significant, steady, and predictable demand signal for common materials.

    - Demand for other low-carbon technologies is expected to be significantly higher than hydropower to meet the Biden-Harris administration's decarbonization goals (The White House 2023). Some of these technologies have impactful provisions within the Inflation Reduction Act (e.g., Section 45X) to spur domestic development.
    - WPTO is creating a plan to work with other DOE programs to develop supply chains for materials common to both programs, including large castings and forgings (wind, nuclear) and windings, transformers, and GOES (wind, grid).

4. **Continue workforce development**, including:

    - Continuing collegiate competitions like the Hydropower Collegiate Competition and Marine Energy Collegiate Competition.
    - Act on recommendations from the Hydropower Workforce Report (Daw et al. 2022).

To develop a domestic, secure supply chain for hydropower, we must address wide-ranging issues, including those that are unique to hydropower (e.g., unpredictable demand) and those that are shared by other clean energy technologies (e.g., workforce deficiencies). By focusing on a significant asset of the domestic hydropower supply chain like the high percentage of federal ownership and leveraging the commonalities of other clean energy technologies, DOE/WPTO can help build a robust domestic supply chain for this vital industry.

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1 Introduction

In 2022, the U.S. Department of Energy (DOE) conducted supply chain “deep dives” for renewable energy technologies, including hydropower (Uría-Martínez 2022). The deep dive identified several challenges in the current hydropower supply chain. In addition, Nguyen et al. (2022) conducted an analogous deep dive assessment on large power transformers (LPTs, where “large” is defined as greater than 100 megawatts [MW]), a critical component of hydropower installations, and concluded that the LPTs as well as several upstream components and materials also have domestic supply chain challenges. The high-level findings of the reports are listed below:

- Turbine: Large steel castings (>10 tons) for turbine components cannot be procured from U.S. foundries.
- Hydrogenerator: Stator windings for units ≥ 100 MW are very difficult to procure domestically.
- Turbine: Ongoing consolidation in the turbine manufacturing industry has resulted in decreased supplier diversity, especially in the large (>100 MW) turbine segment.
- Transformer: LPTs (≥100 MW) are difficult to procure domestically.
- Grain-oriented electrical steel (GOES): Difficult to procure domestically.
- Electronic components: Supply chains are extended and opaque, and the components have high rates of obsolescence.
- Multiple components: Long lead times to procure new or replacement components.
- Workforce: Concerns regarding hydropower workforce availability and level of training.

These reports were initial high-level supply chain assessments focused on identifying the biggest issues and opportunities. Both reports recommended further investigation of their findings. In the 2 years since the deep dives were published, the Water Power Technologies Office (WPTO) has focused on improving our understanding of the hydropower supply chain and developing strategies to address these challenges. Because the challenges outlined above are most acute for large hydropower systems, this report concentrates on 100-MW and larger hydropower systems, but midsize systems are briefly discussed as well.

Early in 2023, DOE’s Secretary of Energy asked WPTO to engage the hydropower community to seek input on strategies to secure and encourage domestic manufacturing. WPTO has established three focus areas for engagement as summarized below:

- Define the market for planned rehabilitations and new construction of the domestic fleet.

- Provide insights for policies, incentives, loan programs, and technology investments to encourage domestic content.
- Define the existing and required domestic hydropower manufacturing capabilities and workforce.

This report summarizes these efforts and complements the earlier work by further exploring the identified challenges and conducting a detailed gap analysis of the domestic hydropower supply chain. The analysis herein includes evaluating current domestic assets at the component level and developing a methodology to forecast specific sized component and material demands for refurbishments. From this analysis, we then make actionable recommendations for closing the gaps.

Section 2 of the report summarizes recent (i.e., since 2021) legislation impacting hydropower deployment and/or its supply chain. It then describes the efforts of WPTO to assess and improve the hydropower supply chain since the publication of the deep dive assessments. In Section 3, we update the earlier supply chain and market studies, identifying specific capabilities by company and location. Section 4 outlines the hydropower demand signal for both new builds to meet clean energy goals as well as refurbishments and upgrades of the current domestic fleet. Section 5 is a detailed gap analysis, and Section 6 provides actionable recommendations for closing the gaps. Section 7 concludes the report by linking the recommendations to the identified gaps and discussing future efforts.

2 Hydropower Supply Chain Background

This section links the 2022 deep dives and the analysis in this report. It summarizes recent legislation impacting the hydropower industry and its supply chain as well as WPTO efforts and the subsequent learnings since the reports were published. At a high level, these initiatives include the *U.S. Hydropower Market Report: 2023 Edition* (Uría-Martínez and Johnson 2023), industry outreach through surveys and roundtables, and a study on hydropower investment (Stark et al. 2024).

2.1 Federal Laws and Policies Affecting Hydropower

Several federal laws contain provisions affecting the hydropower industry and supply chain, namely the Buy American Act (BAA), the Inflation Reduction Act (IRA) of 2022, and the Infrastructure Investment and Jobs Act, also known as the Bipartisan Infrastructure Law (BIL). In general, these laws aim to increase clean energy generation, improve critical supply chains, and increase American manufacturing through the use of minimum domestic content thresholds, tax credits, and capital assistance. Highlights of the provisions of these laws specific to hydropower are outlined below.[1]

2.1.1 Domestic Content

Two key policies govern the domestic content requirements for both federal acquisition and the use of federal funds in infrastructure projects: BAA and the Build America, Buy America Act (BABA). The intent of these laws is to increase the domestic content of goods procured under federal agency projects and/or infrastructure projects using federal funds. BAA is focused only on contracts with federal agencies while BABA applies to federally funded infrastructure projects requiring iron, steel, manufactured products, and construction materials.

BAA restricts the purchase of construction material by federal agencies by requiring federal agencies to use “domestic construction materials” in the construction, alteration, or repair of any public building or public work in the United States. To qualify as “domestic construction material,” the material must be manufactured in the United States. Additionally, it must meet the domestic content threshold, which is set at 65% as of publication, and is scheduled to increase to 75% in 2029. For construction material consisting primarily of iron and steel, the percentage of domestic iron and steel cost must exceed 95%. BAA restrictions are applicable unless certain exceptions apply, for example, when domestic construction material is unavailable, the application of the BAA restriction to a particular construction material is inconsistent with public interest, or costs are unreasonable. Further, BAA does not apply to construction contracts that are

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[1] This report focuses on these laws as they apply to the U.S. Department of Energy and does not go into detail on many of the nuances in the laws.

subject to the Trade Agreements Act. As of the date of publication of this report, the Trade Agreements Act applies to contracts whose value is greater than $6,708,000.[2]

The federal fleet comprises many of the largest turbines (>100 MW) in the United States for which castings and forgings are severely limited or, in some cases, not available. Exceptions to the requirements may adversely affect domestic acquisitions for the federal fleet, notably material unavailability, unreasonable costs, and exceeding the applicable contract value for construction materials. Further investigation is warranted into how BAA has the potential to reshore domestic hydropower manufacturing and shape domestic cost competitiveness with foreign manufactures.

BABA is part of the BIL and implements a requirement to “buy American” for domestic sources of iron, steel, manufactured products, and construction materials for nonfederal infrastructure projects using federal financial assistance. For iron and steel used in the project, all manufacturing processes, from the initial melting stage through the application of coatings, must occur in the United States. Manufactured products used in the project must be manufactured in the United States, and the cost of the components of the manufactured product that are mined, produced, or manufactured in the United States must be greater than 55% of the total cost of all components of the manufactured product. For construction materials, all manufacturing processes for the construction material must occur in the United States.

BABA includes three potential waivers:

1. Domestic content is inconsistent with public interest (a “public interest waiver”).
2. Required types of iron, steel, manufactured products or construction material are not produced in the U.S. in sufficient and reasonably available quantities of a satisfactory quality (a “non-availability waiver”).
3. Inclusion of domestic iron, steel, manufactured products, or construction materials will increase the cost of the overall project by more than 25% (an “unreasonable cost waiver”).

Table 1 provides a comparison of BAA and BABA.

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[2] Certain free trade agreements (FTAs) have a higher threshold (currently $13,296,489) for construction contracts. This higher threshold applies to the Bahrain FTA, Mexico under the United States-Mexico-Canada Agreement, and Oman FTA.

Table 1. Comparison of BAA and BABA

Parameter	BAA	BABA
Applicability	Federal agencies	A nonfederal entity using federal financial assistance
Funding source	Federal procurement	Federal financial assistance
Projects	Supply or supply portion of a services contract (exceeding micro-purchase threshold) Contract for construction, alteration, or repair of any public building or public work in the United States	Public infrastructure[3]
Materials	Supplies or construction materials (i.e., articles, materials, or supplies that a contractor or subcontractor brings to the construction site to be incorporated into the project)[4]	Manufactured products Iron and steel Construction materials
Minimum domestic content	Supplies and construction materials that are not iron and steel 2022 – 60% 2024 – 65% 2029 – 75% Supplies and construction materials that are iron and steel 95%	Iron and steel – all manufacturing processes, from the initial melting stage through the application of coatings, occurred in the U.S. Construction materials – all manufacturing processes occurred in the U.S. Manufactured materials – all products are manufactured in the U.S., and the cost of components that are mined, produced or manufactured in the U.S. is greater than 55% of the total cost of all components.
Waivers	Unavailability Impracticable or inconsistent with public interest Unreasonable costs	Not in public interest Non-availability Unreasonable (>25% increase) in overall project costs

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[3] Public infrastructure, at a minimum, includes the domestic structures, facilities, and equipment for roads, highways, and bridges; public transportation; dams, ports, harbors, and other maritime facilities; intercity passenger and freight railroads; freight and intermodal facilities; airports; water systems, including drinking water and wastewater systems; electrical transmission facilities and systems; utilities; broadband infrastructure; buildings and real property; and structures, facilities, and equipment that generate, transport, and distribute energy including electric vehicle (EV) charging. These projects are considered illustrative and not exhaustive (Young 2023).

[4] Materials purchased directly by the government are supplies, not construction materials.

Parameter	BAA	BABA
Other	Supplies contracts > $174,000 or construction contracts < $6.708 million[5]; if project is equal to or exceeds this amount, then materials from any country designated under the Trade Agreements Act compete on equal terms	

2.1.2 Other Provisions

The U.S. hydropower sector also stands to benefit from the other provisions of BIL and the IRA. Both contain numerous incentives for new clean energy generation and American manufacturing. This section provides a high-level look at some of the most important provisions. For a more detailed analysis, see the *U.S. Hydropower Market Report: 2023 Edition* (Uría-Martínez and Johnson 2023).

The BIL has allocated over $750 million for three hydropower-specific incentive programs covering production, efficiency improvements, and maintaining and enhancing hydroelectricity (Grid Deployment Office n.d.).

Hydroelectric Production Incentives. BIL section 40331 (revising Energy Policy Act of 2005 Section 242) authorizes $125 million in incentive payments for electricity generated and sold from domestic dams and other infrastructure that adds or expands hydroelectric power-generating capabilities or is constructed in an area with inadequate service. Further requirements include that the facility is owned or solely operated by a nonfederal entity and began producing hydroelectric energy on or after Oct. 1, 2005, and that either is at an existing dam or conduit that was completed before Nov. 15, 2021, or has a capacity not greater than 20 MW and has already received construction authorization from the Federal Energy Regulatory Commission (FERC) and is in an area where there is inadequate electric service. No one facility can receive more than $1 million in a calendar year. Eligible facilities must be put into operation by Sept. 30, 2027 (42 U.S. Code §15881).

In October 2023, DOE announced that 66 hydropower facilities throughout the country would receive more than $36 million in incentive payments for electricity generated and sold in calendar years 2021 and 2022. In March 2024, DOE opened the application window for electricity generated and sold in calendar year 2023.

Due to the long development periods for hydropower projects, including additions, it is unlikely that any new projects will be funded within this provision. All projects would

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[5] The threshold varies among FTAs. See FAR 25.402(b) for details.

need to be “shovel-ready” (i.e., very close to construction) to qualify, as they must be put into operation by September 2027 (42 U.S. Code §15881).

Hydroelectric Efficiency Improvement Incentives. BIL section 40332 (revising Energy Policy Act of 2005 Section 243) authorizes $75 million to enable the implementation of capital improvements to achieve efficiency improvements of at least 3% at existing domestic hydroelectric facilities or dams. The incentive payments cannot exceed 30% of the capital improvements or $5 million, and an eligible facility can only receive one payment. Similar to the hydroelectric production incentives, this incentive may be difficult to obtain before the funding runs out unless it is already under development.

On Feb. 2, 2024, DOE announced the selection of 46 hydroelectric projects across 19 states to receive up to $71.5 million in hydroelectric efficiency improvement incentive payments. The 46 selected projects are in California, Colorado, Connecticut, Georgia, Idaho, Maine, Massachusetts, New Hampshire, New York, North Carolina, Oklahoma, Oregon, Pennsylvania, Rhode Island, Tennessee, Vermont, Virginia, Washington, and West Virginia (Grid Deployment Office n.d.).

Maintaining and Enhancing Hydroelectricity Incentives. BIL section 40333 (adding Section 247 to Energy Policy Act of 2005) authorizes $554 million to enhance existing hydropower facilities for capital improvements directly related to grid resiliency, dam safety, and environmental improvements. Improvements to grid resiliency include providing ancillary services integration of variable resources, such as wind and solar, and managing accumulated reservoir sediment. Dam safety improvements include the maintenance or upgrade of appurtenant structures, dam stability repair, as well as upgrades floodgates or natural infrastructure restoration. Environmental improvements include improvements in environmental conditions, such as fish passage, water quality and recreation. The incentive payments cannot exceed 30% of the capital improvements or $5 million, and an eligible facility can only receive one payment in a fiscal year. Qualified facilities must be licensed by FERC or be a hydroelectric project constructed, operated, or maintained pursuant to a permit or valid existing right-of-way granted prior to June 10, 1920, or a license granted pursuant to the Federal Power Act (16 U.S.C. 791a et seq.), or have a FERC-issued exemption. The facility must also comply with all applicable federal, Tribal, and state requirements, or the facility would be brought into compliance as a result of the proposed capital improvements.

DOE is currently reviewing applications for these incentives and anticipates announcing those selected for negotiations in the late summer/fall of 2024. DOE plans to announce another solicitation for this program in the 2024 calendar year.

Tax Credits. Internal Revenue Code Sections 45, 45Y, 48 and 48E (as enacted or modified by the IRA, August 2022) are production tax credits (PTCs) and investment tax credits (ITCs) to support investments in clean energy, including hydropower, through 2032. Pumped storage hydropower (PSH) investments are only eligible for the ITC. The tax credits in IRA have two important provisions for hydropower:

- The PTC established parity for hydropower relative to other renewables.
- Credit recipients that are tax-exempt entities can select an elective-pay option.

The PTC credit is $0.0275 per kilowatt-hour in 2023, adjusted annually for inflation. The ITC is 30% of eligible investment costs if the taxpayer can show that the project meets wage and apprenticeship requirements. Tax credit adders are available if the project satisfies certain domestic content thresholds or is in an energy community.[6]

On May 16, 2024, the IRS issued Notice 2024-41 (https://www.irs.gov/pub/irs-drop/n-24-41.pdf) which provides updated guidance regarding the domestic content bonus credit under Internal Revenue Code Sections 45,45Y, 48 and 48E. This new guidance provides a safe harbor classification for hydropower and pumped hydropower storage facilities as outlined in Table 2.

Table 2. Guidance for Categorizing Applicable Project Components for Hydropower Facilities or Pumped Storage Hydropower Facilities

Applicable Project Component	Categorization
Steel or iron rebar for the reservoirs, upper and/or lower	Steel/Iron
Steel or iron rebar, plating and piping in water conveyance (penstock piping)	Steel/Iron
Steel or iron rebar in powerhouse and foundation, spiral case, discharge ring, and draft tube	Steel/Iron
Steel or iron rebar in canals	Steel/Iron
Powerhouse structure, gates, stoplogs, screens, and embedded structure parts, foundation plates and anchors	Steel/Iron
Turbine/pump runner (which includes the following manufactured product components, if applicable: spiral/scroll case, vanes, bottom ring, wicket gates, runner, draft tube, shaft, head cover, bearings, and flow control and isolation mechanisms)	Manufactured Product
Motor/generator (which includes the following manufactured product components, if applicable: stator, rotor, windings, poles, generator shaft, thrust bearings, ventilation and cooling system, and exciter)	Manufactured Product
Generator step-up transformer (which includes the following manufactured product components, if applicable: containment/main tank, cooling system, de-energized tap changer, load tap changer, bushings/insulators)	Manufactured Product

WPTO intends to validate the efficacy of these incentive programs. It is continuing with ongoing dialog with the Office of Policy, Loan Programs Office, and Grid Deployment Office to understand the applicability of BABA broadly to IRA, Title 17 (Section 1706) The Energy Infrastructure Reinvestment Program, and BIL. Further investigation into

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[6] Energy communities under IRA include brownfield sites, coal communities and areas with specified compositions of employment and local tax revenue related to fossil fuels. For additional information, see https://energycommunities.gov/energy-community-tax-credit-bonus/.

how these acts have the potential to reshore domestic hydropower manufacturing and shape domestic cost competitiveness with foreign manufactures is warranted.

In addition to the provisions outlined above, there are several incentives within IRA, tailored for other renewable energy development (e.g., wind energy) that could have a positive impact on hydropower due to supply chain synergies. Sections 45X (Advanced Manufacturing Production Tax Credit) and 48C (Advanced Energy Project Credit) of the IRA are good examples of incentives not specifically designed for hydropower but that could result in positive impacts to the supply chain. Section 45X provides tax credits for domestic manufacturing of solar, wind, energy storage, inverter, and critical materials from 2023 to 2032. This provision is not dependent on the source of funding (i.e., federal funds), so more companies can take advantage of these credits. These credits can also be increased through some workforce development efforts such as apprenticeships. Section 48C provides $10 billion for investment tax credits (up to 30%) for advanced energy projects in clean energy manufacturing and recycling, greenhouse gas emissions, and critical materials. In March 2024, $4 billion in investment tax credits were awarded to more than 100 projects under Round 1; Round 2 funding expects applications in the summer of 2024. It is likely that new manufacturing infrastructure developed for the wind industry (e.g., forges and foundries) or other industries because of the credits will also be a domestic source for hydropower facilities.

2.2 Industry Engagement

The National Hydropower Association (NHA), in conjunction with WPTO, conducted roundtables with industry representatives at Waterpower Week in May 2023 and in March 2024 to gain industry insight into existing supply chain issues and to identify and prioritize potential solutions.

In 2023, the industry representatives were divided into three groups—manufacturers, owners/operators, and consultants/developers—and matched with a facilitator. Each group was tasked with developing the three most important supply chain knowledge gaps or challenges and proposing solutions. Information from the breakout groups was then synthesized and discussed with the whole group to identify the most pressing issues and potential solutions, which are summarized below.

- **Need for long-term horizons secured by purchasers, including government:** The 10-year time frame for hydroelectric production incentives within the BIL is a short duration for hydropower, and a minimum of 20 years was suggested to spur greater hydropower development and improvement. There was some discussion about better demand signals coming from other countries with a longer-term horizon of overall needs for their respective current fleets and anticipated new builds that provide more certainty to manufacturers.
- **Escalating quality assurance (QA) and quality control (QC) costs cause operator reconsideration of total project life cycle costs vs. initial component price:** Owners and operators indicated that QA/QC costs are extremely high for foreign procurements, making the total project cost (i.e., QA/QC plus the award cost) approach domestic pricing overall. However,

purchase decisions are made on the initial award price rather than the total project costs. An analysis of the total project costs (i.e., including QA/QC) between potential domestically produced goods and internationally supplied goods should be conducted.

- **Need for aggregated demand signals:** For suppliers to respond or reshore, they need a reliable demand signal and an aggregation of purchases into large contracts to benefit from economies of scale. This suggestion for an aggregate demand signal is developed further in Section 3.

In 2024, a similar process was followed. Specific supply chain needs were broadly identified as predictability, domestic supply chain development, and monitoring and workforce development. In addition to identifying issues, the participants suggested potential remedies.

- **Predictability of the market demand signals and federal fleet contracting procedures:** To ensure that the market demand signals are predictable, consistent, and timely, the roundtable suggested that WPTO:
  - Ensure hydropower is treated the same as other energy generation sources primarily by properly valuing its ancillary benefits.
  - Create better predictability of replacement schedules by building a platform for replacement and refurbishment tracking and analysis. Map this effort to historic plans for implementation.
  - Shorten permitting time frames to encourage certainty of outcomes, so long-lead material procurement can happen in a more planned fashion.

  Improving the federal contracting process would greatly enhance industry’s ability to meet the fleet’s development goals. Because the federal fleet is the largest in the country, this would also help achieve the nation’s climate goals. Specific improvements included:

  - Interagency federal fleet should lead solutions for supply chain challenges such as encouraging/incentivizing domestic production and developing supply chain signals.
  - Develop a long-term capital investment plan and share it with vendors and enable aggregated contracting vehicles, such as a Multiple Award Task Order Contract (MATOC).
  - Offer clear guidance on domestic content and waivers and collaborate with primary and sub-suppliers to de-risk and reduce financial burdens to win awards.
- **Domestic supply chain development and monitoring:** To meet the expected increasing demand for hydropower and PSH to meet climate goals, the roundtable suggested that WPTO should work to ensure at least one supply chain option exists to cover the complete breadth of domestic fleet requirements.

- **Workforce development:** To address the deficit of skilled workers, WPTO should promote the profile of hydropower among young people (high school and college age) and adopt new technologies to entice a new generation of workers.

Both roundtables stressed the need for predictable, aggregated demand signals as well as laws and development plans that accommodate hydropower's unique characteristics (e.g., long development periods and ancillary benefits).

2.3 Market Reports

In October 2023, the fourth edition of the U.S. Hydropower Market Report was released (Uría-Martínez and Johnson 2023). This report combines data from public and commercial sources as well as research findings from other DOE research and development projects to provide a comprehensive picture of hydropower and pumped storage development and overall industry trends. Annual updates are released for each edition of the report.

This edition developed a demand signal based on the December 2022 project development pipeline. Table 3 shows a high-level view of the development pipeline for hydropower projects. As shown in the table, almost 1.2 gigawatts (GW) of new project capacity and 254 MW of capacity additions are in the pipeline.

Table 3. Conventional Hydropower Project Pipeline

Source: (Uría-Martínez and Johnson 2023)

Development Stage	Number of Projects	Total Capacity (MW)	Types of Projects
New Projects			
Pending Preliminary Permit	18	304	Non-powered dam (NPD)
Issued Preliminary Permit	37	339	New stream-reach development; NPD
Pending License	6	6	New stream-reach development
Issued License	48	500	New stream-reach development; NPD
Under Construction	8	14	New stream-reach development
Capacity Additions			
Planning	18	174	Capacity addition
Under Construction	5	80	Capacity addition

The 2022 PSH development pipeline was also estimated to have 96 projects under development and a combined storage power capacity of 91 GW. Several of these facilities have been authorized by FERC, but no new PSH facilities were under construction.

While this represents planned hydropower development, it does not include the federal fleet, current asset refurbishment, or the consideration that many projects in the pipeline are never built. WPTO is thus developing alternative and complementary methods for projecting domestic hydropower demand, which are detailed later in this report.

2.4 Industry Survey

In early 2023, DOE developed a survey to examine the magnitude and duration of the hydropower market for rehabilitations and new construction, which was then administered through the NHA, Northwest Hydroelectric Association, and the Center for Energy Advancement through Technological Innovation (CEATI). The survey also sought input from the hydropower community for ways to encourage domestic content and manufacturing.

The initial response was limited, so it was remarketed, and the results were aggregated, anonymized, and shared by NHA at Clean Currents in October 2023. The survey asked respondents to estimate the number, size, and schedule for refurbishment or replacement of three major systems: complete units, turbine runners, and hydrogenerators. The respondents specified the projects within three future time periods: 0–5 years, 5–10 years, and 10–20 years. While the number of responses was limited (six respondents) and came primarily from the northwest and southeast regions of the United States, the survey did include responses from some of the largest domestic facilities and provided important insights.

Respondents indicated that within the next 5 years, they expect to replace 24 complete hydropower units, totaling more than 450 MW, 12 hydrogenerator systems (440 MW), and 19 turbine runners (928 MW). Expected replacements of complete units decrease to less than 250 MW (total) in both the 5–10-year and 10–20-year time frames. Replacements of turbine runners and generator systems, however, increase significantly in the longer term (10–20 years) with replacements of greater than 18,000 MW for runners and 9,000 MW for generators. In total, over the next 20 years, the respondents expect to replace 50 complete units (705 MW), 129 hydrogenerators (9,516 MW) and 248 turbine runners (19,273 MW). As detailed below in Section 4, these planned replacements are projected to cost $11.1 billion, with just under $8 billion for planned replacements in the federal fleet.

Table 4 shows the anonymized survey responses.

Table 4. Industry Survey Results

Device	Qty	Rating (MW)	Purchase Period	Life Expectancy	State or Region
Complete Unit	24	19	0–5 years	30 years	Southeast (SE)
Complete Unit	18	10	5–10 years	30 years	SE
Complete Unit	2	1.5	5–10 years	30 years	Northwest (NW)
Complete Unit	6	11	10–20 years	50 years	SE
Generator System	1	175	0–5 years	30 years	NW
Generator System	1	40	0–5 years	30 years	NW
Generator System	2	30	0–5 years	30 years	NW
Generator System	1	25	0–5 years	30 years	NW
Generator System	7	20	0–5 years	30 years	SE
Generator System	4	40	5–10 years	30 years	NW
Generator System	3	33	5–10 years	30 years	NW
Generator System	3	20	5–10 Years	30 Years	NW
Generator System	9	12	5–10 years	50 years	Midwest (MW)
Generator System	95	90	10–20 years	30 years	NW
Generator System	3	33	10–20 years	30 years	SE
Turbine Runner	1	175	0–5 years	30 years	NW
Turbine Runner	3	122	0–5 years	30 years	SE
Turbine Runner	1	40	0–5 years	30 years	NW
Turbine Runner	2	31	0–5 years	30 years	SE
Turbine Runner	2	30	0–5 years	30 years	NW
Turbine Runner	2	30	0–5 years	50 years	MW
Turbine Runner	1	25	0–5 years	30 years	NW
Turbine Runner	7	20	0–5 years	30 years	SE
Turbine Runner	5	100	5–10 years	50 years	NW
Turbine Runner	5	68	5–10 years	30 years	SE
Turbine Runner	4	40	5–10 years	30 years	NW
Turbine Runner	3	33	5–10 years	30 years	NW
Turbine Runner	3	20	5–10 years	30 years	NW
Turbine Runner	9	12	5–10 years	50 years	MW
Turbine Runner	18	10	5–10 years	30 years	SE
Turbine Runner	2	1.5	5–10 years	30 years	NW
Turbine Runner	29	120	10–20 years	50 years	NW

Device	Qty	Rating (MW)	Purchase Period	Life Expectancy	State or Region
Turbine Runner	2	100	10–20 years	50 years	NW
Turbine Runner	45	100	10–20 years	50 years	NW
Turbine Runner	95	90	10–20 years	30 years	NW
Turbine Runner	3	33	10–20 years	30 years	SE
Turbine Runner	6	11	10–20 years	50 years	SE

The results of the survey could provide an estimate of overall demand for the federal fleet by generalizing demand across all units. However, due to the long time periods used (e.g., 5 or 10 years) as well as the high-level equipment groupings, it would be difficult to use this method to generate the predictable, consistent demand that the supply chain requires. This uncertainty is likely enhanced because refurbishments are not generally done on a proactive schedule based on design life with a specific budget for high-ticket items. For example, in 2022 the federal fleet was replacing only 65% of the LPTs necessary to keep them within their design life. LPTs are too expensive to be included in typical maintenance funds; thus, separate funding should be allocated proactively to adequately replace these expensive core assets.

While the design life of turbines is 40 years, the average age of the federal fleet is about 65 years, which shows that the units are not being replaced optimally. In fact, Andritz estimates that an upgrade of a 40-year-old turbine can result in an efficiency increase of up to 5% with an even greater increase in energy production (Andritz n.d.). Exacerbating the delays in federal hydropower refurbishments, each agency within the fleet has its own way of operating, including replacement methodology. Finally, the federal fleet has difficulty in implementing upgrades in a timely manner, as they can take 5–10 years to implement after fund procurement. Because of these factors, it is likely that the forecasts above will be pushed out as long as possible; therefore, the schedule above is optimistic.

If refurbishments and replacements were done in a proactive manner based on recommended intervals, rather than pushing them out, then the demand would be more consistent and predictable. These planned refurbishments must also consider other constraints of the agency such as budget and workforce availability. Also, if each agency within the federal fleet used the same procedures, best practices and operational synergies among the agencies could be leveraged to improve refurbishment and replacement projects. It is likely that developing consistent best practices would allow the demand and implementation to be predictable and well-controlled and would improve contracting and implementation time. While adopting new procedures will have many benefits, any change also has risks. In 2009, CEATI International commissioned best practice guides for hydropower replacement and refurbishments; this effort considered both potential benefits and risks (Markovich 2009). It then outlined the process to prepare the business case to ensure the practicality of any new practices developed.

2.5 Hydropower Investment Assessment

WPTO funded an evaluation of the hydropower investment landscape, which is detailed in the report *Hydropower Investment and Public-Private Ecosystem Assessment* (Stark et al. 2024). This report analyzed modernizing the existing fleet, the market for midsized development (i.e., 5–30 MW nameplate rating), and pumped storage. It also evaluated the role of the private sector in defining the current and future states of the market, developed tools for roadshow industry engagement, and suggested methods for WPTO to improve the effectiveness of its expenditures.

2.6 Workforce Development

As with most renewable technologies, the U.S. hydropower workforce is a key concern. To address this concern for the hydropower sector specifically, The National Renewable Energy Laboratory (NREL) published a report in 2022 titled *U.S. Hydropower Workforce: Challenges and Opportunities* (Daw et al. 2022). Highlights from the report include:

- More than 26% of the hydropower workforce will retire within 10 years from the report writing.
- Skilled trades and craft workers were some of the most difficult positions to fill.
- Hydropower could add 300 direct hydropower and almost 9,000 PSH jobs based on the current development pipeline alone (i.e., not including new growth for clean energy).

While working on the present report, we met with industry representatives of many of the supporting industries (e.g., forging and casting) who echoed the concerns catalogued in the hydropower workforce report. These industries have lost significant expertise due to offshoring over the last 30–40 years. Initially, the remaining domestic facilities were able to hire experienced employees, but soon there were more workers laid off than positions available. The experienced workers retired or moved on to other positions, so now there is a lack of experienced workers for new facilities. Training and apprenticeships were the highest rated suggestion for recruiting in the hydropower industry followed by educational outreach. The representatives also noted that it was difficult to recruit younger workers to “old” manufacturing technologies, especially compared to newer tech jobs. The need for apprenticeships aligns with Executive Order 14119 – *Scaling and Expanding the Use of Registered Apprenticeships in Industries and the Federal Government and Promoting Labor-Management Forums*, which expands the use of apprenticeships and promotes labor-management forums across federal agencies.

Keeping up with attrition will be challenging, even without the expected industry growth, as the United States transitions to a clean energy future. Hydropower currently has the greatest share of energy storage and is a critical component to attain domestic clean energy goals.

3 Domestic Supply Chain

The overall domestic supply chain was evaluated to understand its capacity and to help identify issues or gaps in meeting projected demands. This section provides a high-level look at the entire supply chain and then takes a deep dive into three major components: large turbines, hydrogenerators, and transformers.

3.1 Supply Chain Analysis

As noted earlier, the 2022 *Hydropower: Supply Chain Deep Dive Assessment* (Uría-Martínez 2022) identified large castings and forgings and windings for large turbines and hydrogenerators as components that are very difficult to procure domestically. In addition, Nguyen et al. (2022) conducted an analogous deep dive assessment on LPTs and concluded that several components and the LPTs themselves were also difficult to procure domestically. While the shortage of LPTs is not unique to hydropower, it is a concern and will be discussed below.

Large (>10 tons) castings for components such as turbine runners and forgings for turbine shafts were identified as impossible to procure domestically (Uría-Martínez 2022). Most of these components are imported from Brazil, China, Eastern Europe, and South Korea. The exact amount imported from each country for hydropower cannot be determined, as available trading data do not track large castings and forgings as independent categories (Uría-Martínez and Johnson 2023). Stator windings for units greater than 100 MW are also difficult to procure domestically, and they are generally imported from Brazil, Canada, Europe, and Mexico (Uría-Martínez and Johnson 2023).

The 2023 hydropower market report (Uría-Martínez and Johnson 2023) discussed earlier provided a summary of international hydropower and PSH trade from 1996 to 2022.[7] The analysis showed that over this period, the United States has been a net exporter of hydropower components, with an annual average export value of $62 million and an import value of $60 million in 2022 dollars. However, 2020–2022 showed a significant (>35%) decrease in the in the values of both imports and exports, with the United States having a trade deficit for hydropower and PSH components. For the 2020–2022 period, imports were from Canada (33%), Europe (Germany, Italy, United Kingdom; 32%), Brazil (17%), and China (8%). Almost 50% of exports went to Canada and Indonesia.

Trade data for 2023 are now available (U.S. Department of Commerce n.d.), and they show that the United States was a net importer of hydraulic turbines and turbine parts, with an import value of $47.3 million and an export value of $42.4 million. Canada was

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[7] Trade data were based on Harmonized Tariff Schedule subheadings 841011 (hydraulic turbines with a capacity less than or equal to 1 MW), 841012 (hydraulic turbines with capacity greater than 1 MW but less than or equal to 10 MW), 841013 (hydraulic turbines with capacity greater than 10 MW), and 841090 (hydraulic turbine parts and regulators).

the biggest trading partner for both imports and exports, but aggregated, Europe was the largest source of imports, followed by China and Brazil.

For this effort, we conducted searches for domestic companies in the hydropower supply chain using member lists of the NHA and the International Hydropower Association, attendees at HydroVision International 2023, and other published reports (e.g., *U.S. Hydropower Market Report: 2023 Edition*). This publicly available information is summarized throughout the report. In addition, we contacted industry representatives to understand their capabilities and issues with domestic sourcing. All conversations with industry representatives are reported at a high level to ensure anonymity. The identification of companies in the domestic supply chain focused primarily on the hard-to-procure components and their subcomponents but is only an initial summary and should not be considered exhaustive. Oak Ridge National Laboratory (ORNL) is developing a full database of domestic hydropower facilities.

The hydropower supply chain can be divided into three sectors: upstream, midstream, and downstream, as shown in Figure 1. Each sector is further divided into subsectors based on each stage in the manufacturing process. These subsectors include short descriptions or representative products. Orange outlines for subsectors indicate limited domestic capacity, yellow indicates some domestic capacity, and green indicates sufficient capacity. If the subsector has cost-effective international competition, the subsector includes a dollar sign.

One difference in this analysis compared to the 2022 deep dive supply chain study (Uría-Martínez 2022) is that raw materials are considered at greater risk due to the limited domestic supplies of electrical steel as well as trace components of stainless steel (e.g., manganese).

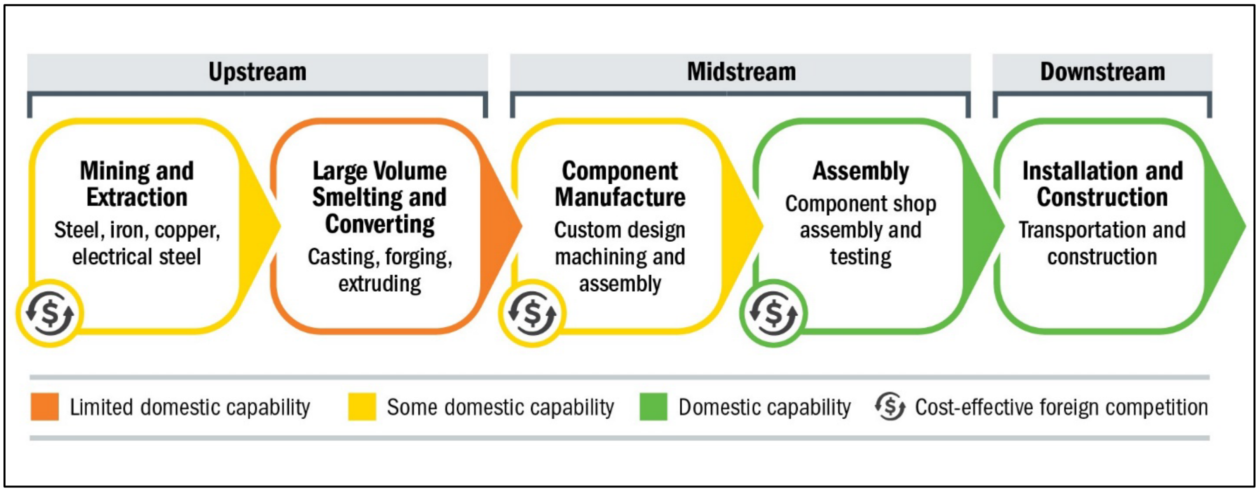

Figure 1. High-level domestic hydropower supply chain.

Illustration by Tara Smith, NREL, modified from Uría-Martínez (2022)

Because this assessment is focused on gaps and methods for addressing the gaps, only Mining and Extraction, Large Volume Smelting and Converting, and Component

Manufacture subsectors (those outlined in orange and yellow) will be addressed, as they have limited domestic capability. Although the assembly and installation subsectors indicate sufficient domestic capability, these areas could quickly become gaps if (1) the hydropower industry significantly expands to meet the Biden-Harris administration's decarbonization goals (The White House 2023) and (2) the availability of a trained workforce continues to decrease. The level of domestic capability of all subsectors could change with the expected growth of other clean energy technologies due to competition for materials and workers. Thus, it is critical that all segments and dependencies of the supply chain be analyzed and weaknesses addressed to ensure the stability of the domestic supply chain.

3.1.1 Upstream

Upstream components include raw material extraction and initial processing into commodity materials such as steel, followed by metal processing via smelting and other conversion processes. Raw materials used in hydropower installations include iron, copper, and trace components for various steel grades such as chromium, manganese, and silicon. Even within commodity materials such as steel, there are various formulations and grades including stainless and electrical steel (e.g., GOES). Many of these raw and processed materials (e.g., copper, stainless steel) are available from recycling operations. In fact, copper recovered from scrap accounted for 33% of the domestic copper supply (USGS 2024).

Hydropower components such as runners and shafts are constructed from specific types of steel, each with a unique composition. Table 5 summarizes these steels, including their ASTM specification and trace material content.

Table 5. Hydropower Component Materials

Steel	Common Name	ASTM Specification	Trace Elements (% by weight)
CF3M	316-L Stainless Austenitic	A351, A743, A744	C: 0–.03 Mn: 0–1.5 Cr: 17–21 Mo: 2–3 Ni: 9–13
CF8M	316 Stainless Austenitic	A351, A743, A744	C: 0–.08 Mn: 0–1.5 Cr: 18–21 Mo: 2–3 Ni: 9–12
CA6NM	400 Series Stainless - Martensitic	A487, A743, A757	C: 0–.06 Mn: 0–1 Cr: 11.5–14 Mo: 0.4–1 Ni: 3.5–4.5 Si: 0–1
F6NM	400 Series Stainless - Martensitic	A182, UNS S41500	C: 0–.05 Mn: 0.5–1 Cr: 11.5–14 Mo: 0.5–1 Ni: 3.5–5.5 Si: 0–0.03 P: 0–0.030

The United States has significant reserves of iron ore and produced an estimated 80 million metric tons of raw steel in 2023 (USGS 2024). This production level is approximately 4% of world production and satisfies 86% of internal finished product demand (USGS 2023). As noted above, hydropower requires specific grades of steel, which in addition to iron and carbon, require the following elements: manganese (Mn), chromium (Cr), molybdenum (Mo), nickel (Ni), silicon (Si), and phosphorous (P). Although the percentage of each of these elements is less than 25%, with most being less than 5%, the specific grades of steel cannot be made without these elements. According to data from the USGS, the United States has no chromium or manganese mining. It imported 74% of its apparent consumption of chromium, and the remaining demand was met by recycling. All its manganese demand is met by imports, as manganese recovery and recycling is negligible. While the United States does produce nickel from a mine, tailings, and as a byproduct of platinum group metals mining, it imports more than 50% of its apparent consumption. Silicon is similar: about 50% of ferrosilicon needed for steels was imported. The United States is a net exporter of molybdenum and has a net import reliance of only 14% for phosphorous.

In addition to steel, hydropower facilities will require copper for the generator, transformer, and other electrical components. Although the United States has 25 copper mines, and in 2023 its refineries produced 3% of global refined copper, it relies on imports for more than 45% of its apparent domestic consumption (USGS 2024). Table 6 summarizes the hydropower raw material capabilities of the United States.

Table 6. Domestic Hydropower Raw Material Capability

Source: (USGS 2024)

Raw Material	Estimated 2023 U.S. Mine Production (metric ton contained metal)	% of Global Production	Apparent Reliance on Imports
Major Raw Materials			
Copper	1,100,000	5.0%	46%
Iron	28,000,000	1.9%	Iron ore net exporter, but relies on 13% of finished steel to be imported
Trace Raw Materials			
Chromium	0	0	74% (rest from recycling)
Manganese	0	0	100%
Molybdenum	34,000	13%	Net exporter
Nickel	17,000	<1%	57%
Phosphorous (as phosphate rock)	20,000,000	9.0%	14%
Silicon[1]	310,000	3.5%	50%

[1] Data for silicon is for 2022 because USGS did not estimate silicon production for 2023

DOE's recent *Critical Materials Assessment* (DOE 2023) identified the global supply of nickel as near-critical in the near term (i.e., 2025) and critical in the midterm (2025–2035). While the global supply of copper is not concerning in the near term, the intense demand of electrification will cause copper supply concerns in the midterm. Furthermore, the global supply of rare earth metals, used in motor magnets, is already considered a critical concern, which is expected to significantly increase in the midterm. While none of these materials is unique to hydropower, they should not be ignored. The DOE *Critical Materials Assessment* takes a global view of energy sector material demand and supply risk and does not reflect how important certain materials are to the U.S. energy sector or economy. This is complemented well by the U.S. Critical Minerals List, which is issued by the USGS and focuses on the U.S. economy (Burton 2022).

After the raw materials are purified, they are processed into materials such as stainless steel or copper wire. Electrical steel was one critical material identified in the 2022 deep dive assessment for the electric grid supply chain (Nguyen et al. 2022) and in the *Critical Materials Assessment* (DOE 2023). There are two major types of electrical steel:

GOES and non-oriented electrical steel (NOES). GOES is used for LPTs across the grid, including those in hydropower facilities. NOES is used primarily for electric vehicles (EVs) and generators, including hydrogenerators. As noted in this report, there is only one domestic manufacturer of GOES, Cleveland-Cliffs, which currently produces about 200,000 tons of electrical steel per year, mostly as GOES. U.S. Steel recently acquired a mill in Arkansas for electrical steel (U.S. Steel 2023). However, they will focus on the production of NOES, primarily for the EV market.

Although the Cleveland-Cliffs facilities are very large, having a single domestic supplier of GOES and only two suppliers of NOES are significant weaknesses of the U.S. hydropower industry and likely all renewable technologies' supply chains. Because electrical steel can be readily imported from areas of the world with lower labor costs and/or environmental requirements, domestic steel is at a disadvantage. Similarly, inexpensive GOES from any country can be converted to laminations or transformer cores and then imported to the U.S. market, which further hurts domestic manufacturers. For example, a 2020 U.S. Department of Commerce report noted that the United States imported almost all its transformer cores from Canada and Mexico, although neither country had domestic production of GOES (U.S. Department of Commerce 2020). The manufacturers we spoke to were worried that it might be difficult for Cleveland-Cliffs to continue to produce electrical steel under these conditions, and manufacturers may end up without a domestic source. Since the hydropower base is primarily federally owned, it would be helpful if purchasing requirements such as those for the U.S. Department of Defense (i.e., American-manufactured) were applied to hydropower systems.

POSCO, the large Korean steel manufacturer, recently announced that it was planning to build NOES manufacturing in the United States and increase NOES production in Korea (L. Miller 2023).

Next in the upstream sector is converting the materials into subcomponents, including large (i.e., >10 ton) castings. The *Hydropower: Supply Chain Deep Dive Assessment* (Uría-Martínez 2022) noted the lack of domestic availability for large castings as a significant vulnerability for the domestic hydropower supply chain. In discussions with turbine manufacturers for this analysis, the availability of large forgings (>50–75 tons) for items such as generator shafts is also difficult to source domestically.

We researched several domestic foundries and forges and summarized their capabilities in Table 7. Two foundries capable of large castings were identified. Bradken, located in Tacoma, Washington, has a maximum casting size of 24 tons while Fisher Cast Steel's (West Jefferson, Ohio) maximum is 4.25 tons. Although only Bradken was identified as having casting capability greater than 10 tons, Fisher Cast Steel is used for hydropower facilities of roughly 30 MW or less. As with GOES production, having a single domestic company capable of producing large castings is problematic.

Large, forged components such as hydroelectric shafts can be produced at four forges: Elwood City Forge Group, Eastham Forge Inc., Scot Forge, and North American

Forgemasters (NAF). NAF and Scot Forge can produce forged components that are considerably larger (i.e., >100 tons) than the other forges, but all four can supply forgings of greater than 10 tons. Eastham Forge is planning an upgrade and will increase its maximum forging capability to 20 tons. However, turbines larger than 100 MW require shafts greater than 20 tons; shafts of 50+ tons are common.

Table 7. Summary of Domestic Large Forge and Foundry Companies Used by Hydropower Companies[8]

Company	Forge or Foundry	Location	Max Size (tons)[a]	Materials and Products
Bradken	Foundry	Tacoma, WA	24	Mission-critical steel, stainless steel, duplex, Monel, and nickel base castings
Fisher Cast Steel Inc.	Foundry	West Jefferson, OH	4.25	
Forges				
Elwood City Forge Group[9]	Forge	Ellwood City, PA	35	Carbon, alloy, stainless and tool steels, aluminum, and nickel alloys
Eastham Forge Inc.[10]	Forge	Beaumont, TX	12.5	
North American Forgemasters (NAF)[11]	Forge	Newcastle, PA	135	Hydroelectric shafts
Scot Forge	Forge	Spring Grove, IL	220	Ferrous and nonferrous (carbon, alloy, stainless steel, aluminum, copper, nickel, titanium) Forging plus additive (Forge+) Open die rings, hollows, blanks, spindles, hubs and complex near-net shapes Semi-closed die, complex shapes Seamless rolled rings
Ringmasters[12]	Forge	Wayne, MI	1.5 stainless	Seamless rolled rings

[a] For forging and castings, only the mass capabilities are listed. However, hydropower requires specific materials, complex shapes, and large sizes that may or may not be possible within the mass constraints.

Although this analysis identified large casting and forging capabilities, they are limited to one or two companies. Furthermore, industry partners have noted that the mass of the component is not the only criterion for forges and foundries in the hydropower industry. Complexity of design and shape are also very important and are unique to hydropower.

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[8] Information in the table should not be considered comprehensive; all information is from public sources.
[9] Elwood City and NAF are closely located, and NAF purchases ingots from Elwood.
[10] Will increase to 20-ton forgings after the addition of the planned 7,500-pound hydraulic press.
[11] JV of Scot Forge and Ellwood Group Inc.
[12] JV of Scot Forge and Frisa.

Industry contacts also stated that U.S. foundries and forges have difficulty competing with foreign companies due to cost.

3.1.2 Midstream

The midstream supply chain is composed of the manufacture and assembly of hydropower components such as runners, hydrogenerators, and turbines. The United States has many companies in this segment, shown in Figure 2. As noted earlier, turbines, generators, and transformers have been identified as difficult to procure domestically. Thus, this section will primarily focus on these components.

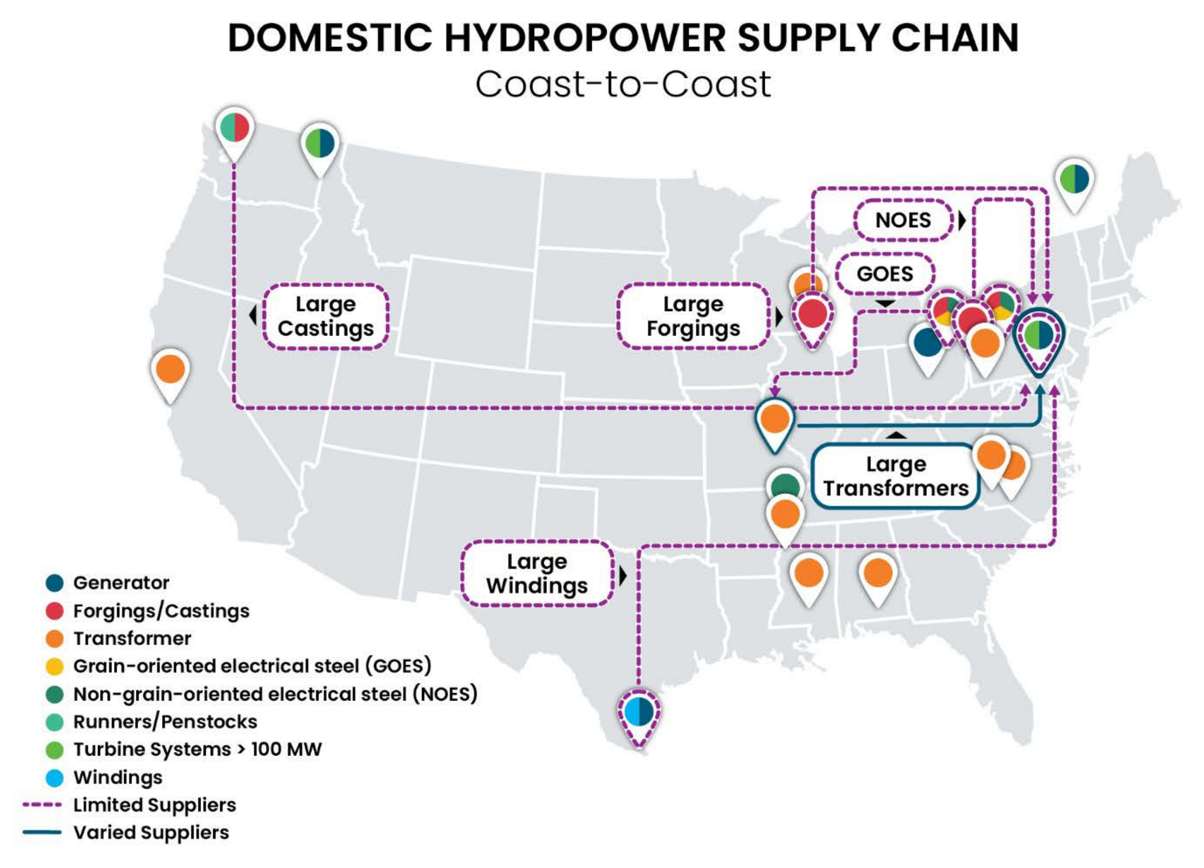

Figure 2. Domestic midstream large hydropower component manufacturers.

Illustration by Tara Smith, NREL

As shown in the figure, there are numerous domestic transformer companies. Hydrogenerator and upstream components such as large-scale foundries and forges are less common. In fact, if we were to domestically source all the major components of a new large PSH facility and associated upstream materials, the supply chain would cross the United States.[13] The significant geographic distribution of the U.S. hydropower supply chain puts the U.S. industry at a disadvantage to those in other countries such as China, where supply chain segments are in closely located manufacturing pods.

Stainless steel can be manufactured from numerous factories across the country, but electrical steel (GOES and NOES) has limited availability. The GOES for transformers is currently manufactured by a single company with factories in Ohio and Pennsylvania. NOES is also manufactured in these facilities and by U.S. Steel, but U.S. Steel focuses on the EV industry.

Starting from the Ohio facility, the GOES for the transformer could go to numerous transformer companies across the country. On the map, it is shown going to a transformer facility in Washington, Missouri. The NOES for the large hydrogenerator would be shipped overseas or to the large turbine system manufacturer, Andritz or Voith[14] who would likely work with a foreign hydrogenerator company. The generator will also require large (up to 1,000-MW) windings, which can only be domestically sourced from a facility in Texas.

The large crown castings would need to be sourced from Washington, where only Bradken can produce castings of up to 200 inches across and up to 24 tons. The runners and turbine shaft would need to come from Scot Forge in Illinois or NAF in Pennsylvania. These would be sent to one of the manufacturers of large (>100 MW) hydropower systems, Voith, ABB, or General Electric (GE). On the map, all the components are shown going to Voith. These components would then be shipped to the PSH facility.

Assessment of the adequacy, capacity, and capability of domestic transportation infrastructure required to move these large elements (e.g., LPTs, generators, turbines) is a concern for hydropower as well as other technologies. This analysis is outside the scope of this report; however, evaluation is recommended.

3.1.3 Downstream

Installation of the components and construction of on-site structures such as dams, buildings, and reservoirs (PSH) make up the downstream segment of the hydropower supply chain. The United States has a significant presence in this segment.

3.2 Turbine Runner Manufacturing

As noted in the 2022 deep dive assessment, the United States has three companies that manufacture a wide range of turbine runner sizes, including those greater than 100

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[13] Equipment for facilities greater than 60 MW cannot be sourced in the United States due to a lack of casting facilities.

[14] Voith is shown in the diagram.

MW: Voith, Andritz, and GE, referred to in the industry as the “Big Three.” Brief descriptions of each company’s domestic capabilities are outlined below.

The Big Three also produce a wide range of pumped storage turbine runners. Pumped storage runners can reverse direction from generation to pump water to a higher elevation for storage. The most widely used reversible turbine runner is a Francis type. Separate pumps and turbines are also schemes being explored in medium to small sizes to allow companies specializing in smaller runners to participate in pumped storage manufacture.

3.2.1 Large Turbines

Voith Hydro, located in York, Pennsylvania, is a full-line supplier of hydropower equipment and services. They supply full water-to-wire systems for a large range of turbine types and sizes, including those greater than 100 MW. They are also a large supplier of hydrogenerators. Their York facility is one of the largest hydropower manufacturing facilities in the world. Voith is owned by Voith Hydro Holding GmbH & Co KG in Germany.

Andritz Group is an Austrian company that owns Andritz Hydro. Andritz Hydro has a manufacturing facility in Spokane, Washington, and is headquartered in Charlotte, North Carolina. They manufacture all types of turbines up to 1,800-m head and 800 MW as well as full hydropower and PSH facilities, including installation and commissioning. Andritz has more than 470 GW of installed hydropower globally with turbines as large as 800 MW (Andritz n.d.).

GE is an American-owned company with its North American manufacturing facility located in Sorel-Tracy, Quebec, Canada. Like the other Big Three companies, GE manufactures a large range of turbine sizes and types and supplies full turnkey hydropower systems. Its hydropower turbines and generators are greater than 25% of the total installed capacity worldwide (General Electric n.d.[a]). In addition to its Canadian location, GE has hydropower manufacturing facilities in Spain, France, Switzerland, India, and China (General Electric n.d.[b]).

3.2.2 Small and Midsized Turbines

In addition to the Big Three, the United States has several domestic turbine manufacturers, including two midsize (~30-MW) domestic turbine manufacturers, Canyon Hydro and American Hydro. While these companies operate in the midsize space, each has potential to manufacture at larger sizes. Canyon Hydro is a 45-year-old company headquartered in Deming, Washington, with a second facility in Sumas, Washington. The Sumas facility uses computer numerical control technology to manufacture runners and other components to extremely tight tolerances.

American Hydro is in York, Pennsylvania, and has extensive computer numerical control capabilities in its 123,000-square-foot manufacturing space. In addition to design and manufacture, it does considerable work in upgrades and rehabilitations.

Table 8 summarizes small and midsized domestic turbine manufacturers.

Table 8. Small and Midsized Domestic Turbine Manufacturers

Company	Manufacturing Location(s)	Capabilities
American Hydro	York, PA	Upgrading and refurbishing Francis turbines, Kaplan turbines, propellers, large pumps, pump-turbines, Seagulls, and conversions of propeller to Kaplan New turbine manufacture Entire new complete equipment package
Canyon Hydro	Deming, WA Sumas, WA	Pelton, Francis, and cross-flow turbines Water-to-wire packages, but only manufacture the turbines and turbine parts
	Springfield, OH[15]	Francis turbines, water-to-wire packages, refurbishment
NuStreem	Mansfield, CT	Kaplan turbine: 75–250 kilowatts (kW)
Natel Energy	Alameda, CA	Designs, engineers, and installs fish-safe turbines Works with other companies for manufacture
Obermeyer	Fort Collins, CO	Designs and manufactures gates and bulkheads that incorporate arrays of compact submersible turbine generator sets. These systems can be installed in existing water control structures.

3.2.3 Foreign Turbine Manufacturers

Several other turbine manufacturers have U.S. locations, but most have only engineering/sales locations with the manufacturing facilities located in Europe, Asia, or Canada. Table 9 provides a summary of these manufacturers, including their U.S. locations, manufacturing locations, and general capabilities.

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[15] Canyon Hydro owns The James Leffel & Co., which is located at the Springfield, Ohio, site.

Table 9. Foreign Turbine Manufacturers With a U.S. Location

Company	Manufacturing Location	Capabilities	U.S. Company	U.S. Location(s)
Gilkes	United Kingdom	Pelton (≤30 MW) Francis and Turgo (≤30 MW) Water-to-wire packages	Gilkes Inc. (USA)	Kemah, TX (large pumps)[a]
Litostroj	Slovenia and Turkey	Pelton: ≤400 MW Francis: ≤350 MW Kaplan: 200 kW–100 MW Low Head: ≤50 MW Pump: ≤350 MW	Litostroj US, LLC	Birmingham, AL
Mavel, a.s.	Czech Republic	Bulb (small) Francis (≤30 MW) Kaplan (≤30 MW) Pelton (≤30 MW) Pit, S-type and micro (<500 kW) Water-to-wire packages	Mavel Americas, Inc.	Boston, MA
Techno Hydro	Guatemala	Pelton: 1–5 MW Francis: 1–5 MW Kaplan: 1–5 MW Water-wire	Techno Hydro	Katy, TX

[a] Some company literature lists Tacoma, Washington, as a location for hydropower, but others do not.

3.3 Transformer Manufacturing

Transformers play significant roles across various functions within the U.S. electrical grid. This report primarily focuses on LPTs with a capacity rating of 100 megavolt-amperes (MVA) or higher. These transformers serve the purpose of increasing voltage to minimize power losses during electricity transmission, as well as decreasing voltage for distribution at lower voltage levels. LPTs are both costly and complex devices, often requiring custom designs and exhibiting extended lead times for production (Nguyen et al. 2022).

In addition to GOES, continuously transposed conduction (CTC) wires are integral materials in transformer manufacturing, contributing to the efficiency, performance, and reliability of these devices. GOES, a specialized type of electrical steel, is crafted to exhibit exceptional magnetic properties when its grain structure is oriented in a specific direction. This unique quality makes GOES ideal for constructing transformer cores, where magnetic fields play a pivotal role. This material reduces energy losses within the transformer and results in higher overall efficiency and enhanced voltage regulation, which is particularly crucial for applications demanding precise energy transfer across various voltage levels. In addition, CTC wire is a specialized copper wire designed for transformer coil winding and is also used for improved efficiency and reliability in transformers. CTC wire minimizes energy losses and mitigates temperature rise, which can be detrimental to transformer performance (Nguyen et al. 2022).

Within the scope of the LPT supply chain, the availability and pricing of LPTs are significantly impacted by the suppliers responsible for providing crucial GOES and CTC raw materials. The areas of vulnerability within this chain are notably concentrated in these two specific material segments. Presently, the United States has only one manufacturer of GOES—while this manufacturer maintains the quality and cost competitiveness offered by imported GOES, it fails to meet domestic demand. Additionally, suppliers of transformer components, such as bushings and tap changers, contribute to potential bottlenecks within the supply chain due to prolonged lead times. An immediate opportunity to enhance the resilience of the LPT supply chain lies in bolstering domestic GOES production capabilities. Notably, the acquisition of Big River Steel by U.S. Steel provides an avenue to upgrade NOES production to produce GOES. This strategy is facilitated by domestic LPT producers, as they can establish a consistent demand for GOES through their diversified sourcing approaches.

Among the major transformer manufacturers with operations in the United States are Delta Star, Hitachi Energy, Hyosung Heavy Industries, Hyundai Power Transformers USA, Niagara Power Transformer, Pennsylvania Transformer Technology, SPX Transformers (now part of General Electric), Virginia Transformers (formerly EFACEC), and WEG Transformers/Electrical Corporation. In addition to their domestic production facilities, several of these companies maintain manufacturing sites in foreign countries (Nguyen et al. 2022). Tables 10–12 show domestic manufacturers for transformers, electrical steel and CTC, and other transformer components, respectively.

Table 10. Major Transformer Manufacturers With Production Facilities in the United States

Company	Manufacturing Location	Capabilities
Delta Star	Lynchburg, VA San Carlos, CA	Up to 200 MVA, 345 kilovolts (kV)
Hitachi Energy (formerly known as Hitachi ABB)	South Boston, VA	Up to 150 MVA, 230 kV
Hyosung Heavy Industries (HICO)	Memphis, TN	Up to 1,000 MVA, 765 kV
Hyundai Power Transformers USA	Montgomery, AL	Up to 100 MVA, 500 kV
Niagara Power Transformer	Buffalo, NY	Up to 100 MVA, 138 kV
Pennsylvania Transformer Technology	Canonsburg, PA	Up to 600 MVA, 345 kV
SPX Transformer Solutions	Waukesha, WI	Up to 1,200 MVA, 345 kV
Virginia Transformer Corp.	Roanoke, VA Rincon, GA	Up to 1,400 MVA, 500 kV
WEG Transformers	Washington, MO	Up to 350 MVA, 400 kV
WEG Electrical Corp.	Duluth, GA	Up to 500 MVA, 550 kV
Siemens Energy (U.S. location)	Various	
Eaton Corp. (U.S. location)	Various	

Table 11. Electrical Steel and CTC Manufacturers in the United States

Company	Manufacturing Location	Capabilities	Notes
Cleveland-Cliffs	Zanesville, OH Butler, PA	GOES, NOES NOES	Formerly known as AK Steel
U.S. Steel - Big River Steel (BRS)	AR	NOES	Focusing on EV market
Sam Dong	Rogersville, TN	CTC copper	
Essex Furukawa	Fort Wayne, IN Franklin, TN	CTC copper	Unclear if CTC can be produced at any of the domestic facilities
REA	Fort Wayne, IN Lafayette, IN Guilford, CT Ashland, VA	CTC copper	Fort Wayne, Indiana, location possesses the capability to produce CTC copper wire

Table 12. Transformer Component Manufacturers in the United States

Company	Manufacturing Location	Capabilities
Hitachi Energy	Alamo, TN	Tap changers, bushings
Quality Switch, Inc.	Newton Falls, OH	Tap changers
SPX Transformer Solutions	Waukesha, WI	Tap changers
PCORE Electric	LeRoy, NY	Bushings
Fostoria Bushings and Insulators Corp.	Fostoria, OH	Bushings
Weidmann	Urbana, OH	Insulating material
Cindus Corp.	Cincinnati, OH	Insulating material
DuPont		Insulating material

3.4 Hydrogenerator Manufacturing

Many industries require generators, and there are numerous domestic generator manufacturers, but hydropower installations require specialized generators that can withstand the weight of the system as well as significant thrust and overspeed (300%–400%) as a result of emergency shutdowns. Some companies focus on manufacturing the hydrogenerator, and others only do refurbishments, which are largely rewinds (i.e., replacing the windings) using the existing rotors and replacement poles and windings. Several hydropower generator and generator part manufacturers were identified in this analysis: Andritz, Voith, Ideal Electric, and National Electric Coil (NEC). As shown in Table 13, it does not appear that any of the companies manufacture large hydrogenerators domestically, although NEC is capable of very large (i.e., 1,000-MW) refurbishments.

Table 13. Domestic Hydrogenerator and Hydrogenerator Part Manufacturers

Company	Manufacturing Location	Capabilities	Notes
Andritz	Spokane, WA	Large-scale turbine systems	Water-to-wire packages
Ideal Electric Co.	Mansfield, OH	Hydrogenerators up to 40 MW	
National Electric Coil (NEC)	Brownsville, TX	Windings for generators up to 1,000 MW	Also has a Columbus, OH, facility that focuses on turbogenerators
Voith	York, PA	Large-scale turbine systems	Offers water-to-wire packages, but only manufactures the turbines, hydrogenerator stators, rotors, and shafts domestically

4 Domestic Hydropower Demand

Demand for hydropower equipment and upstream finished and raw materials has been extremely difficult to predict because of the uncertainty in regulatory processes, lengthy funding timelines, design and build cycles, and other issues. The *Hydropower: Supply Chain Deep Dive Assessment* (Uría-Martínez 2022) used the development pipeline to project future new build, and historical data and other assessments to project refurbishments. In this section, we estimate the current (2022) demand for hydropower and PSH systems by describing the state of the industry and then project (1) the potential growth of the industry based on repair and refurbishment of the existing fleet and (2) the potential growth of the domestic fleet to meet carbon emissions goals.

4.1 Current Domestic Fleet

At the end of 2022, the U.S. conventional hydropower fleet included more than 2,200 hydropower plants with a total generating capacity of more than 80 GW (Uría-Martínez and Johnson 2023). These installations produced 28.7% of all renewable electricity and 6.2% of all electricity in 2022. The U.S. PSH fleet consists of more than 40 plants with a combined generation capacity of 22 GW and an estimated energy storage capacity of 553 gigawatt-hours. These facilities account for the majority of utility-scale power storage capacity (70%) and essentially all (96%) of utility-scale energy storage capacity (Uría-Martínez and Johnson 2023).

Figure 3 and Figure 4 provide a high-level summary of the regionality of the hydropower and PSH fleets, respectively. Figure 3 shows the total installed hydropower in the 16 states with installed hydropower of 1 GW or greater. As shown on the map, Washington, California, and Oregon are the states with the most hydropower capacity: Washington and California have greater than 21 GW and 10 GW, respectively. Collectively, these three states have roughly 50% of the total domestic capacity.

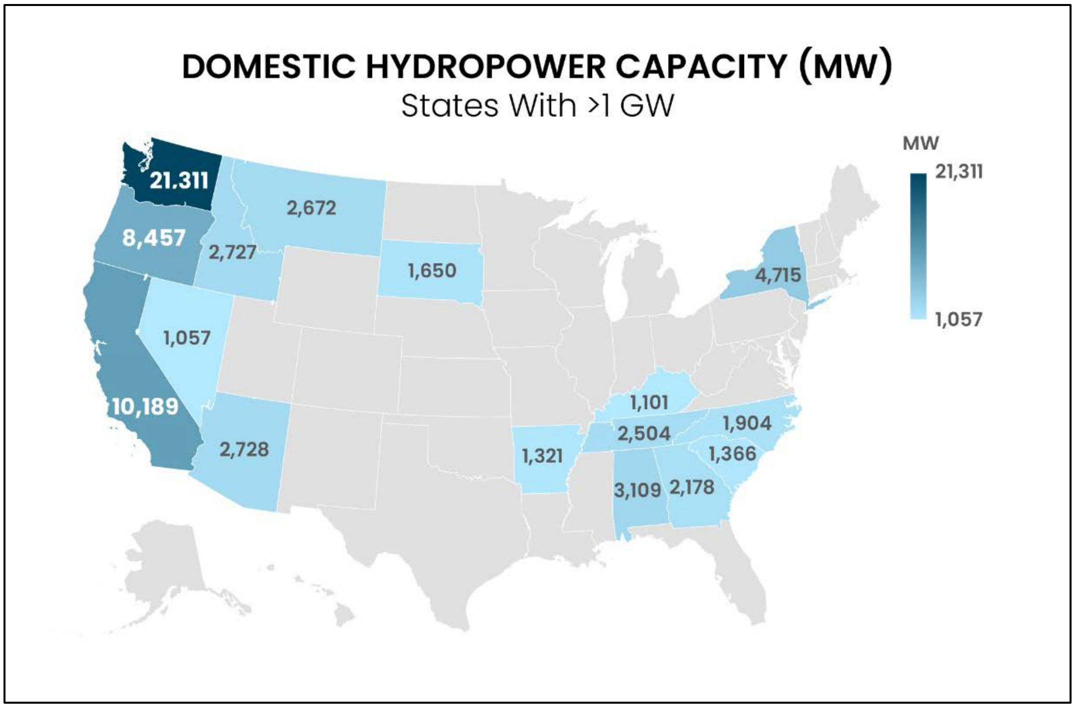


Figure 3. States with more than 1 GW of hydropower capacity (capacities on map shown in megawatts).

Illustration by Tara Smith, NREL

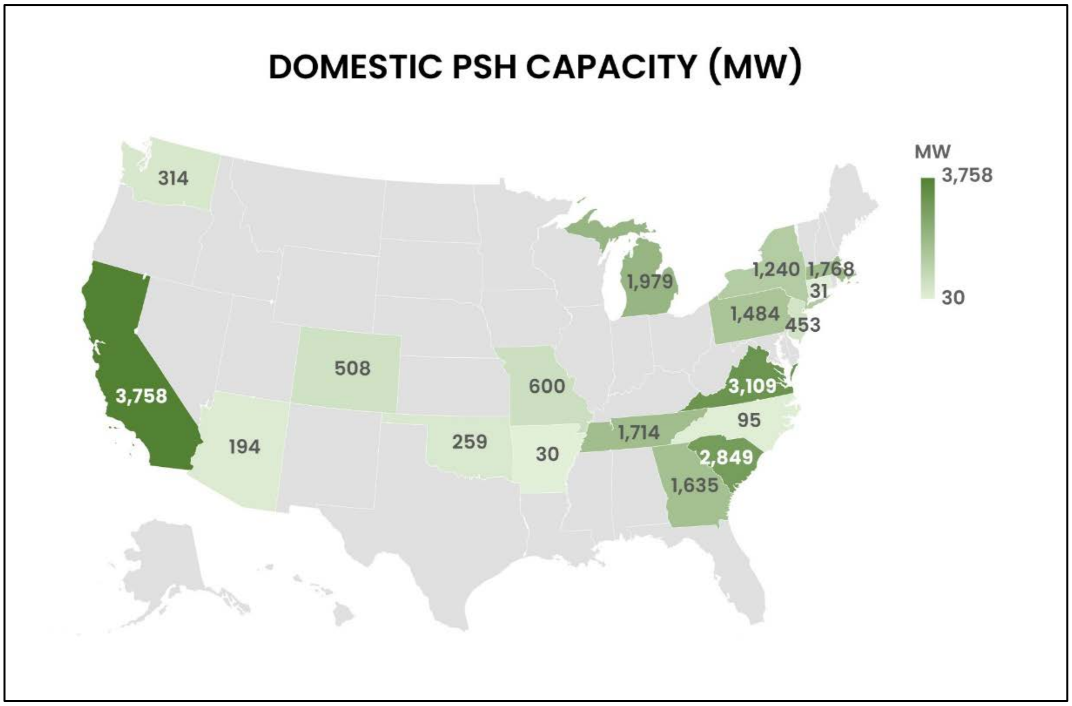


Figure 4. Domestic PSH capacity (capacities on map shown in megawatts).

Illustration by Tara Smith, NREL

PSH capacity (Figure 4) is distributed across 18 states, with 44% of capacity concentrated in the top three (California, Virginia, and South Carolina). NREL conducted analysis based on geographic information system data of the domestic closed-loop PSH potential, identifying 35 terawatt-hours of storage capacity (10-hour duration) across almost 15,000 sites in the 50 states and Puerto Rico (Rosenlieb, Heimiller, and Cohen 2022). Non-powered dams also have significant untapped capacity; less than 3% of domestic dams have power production (Urìa-Martinez and Johnson 2023).

One of the unique aspects of the domestic hydropower resource is that roughly half of the hydropower assets (48.5%) and 16% of the pumped storage assets are owned by the federal government (Uría-Martínez and Johnson 2023). Furthermore, 62% of the hydropower units and almost 50% of the hydropower capacity greater than 100 MW are owned by the U.S. government (ORNL n.d.). As shown later in the report, this high level of ownership presents unique opportunities and associated challenges as we look to expand and enhance this valuable domestic resource.

4.2 New Demand

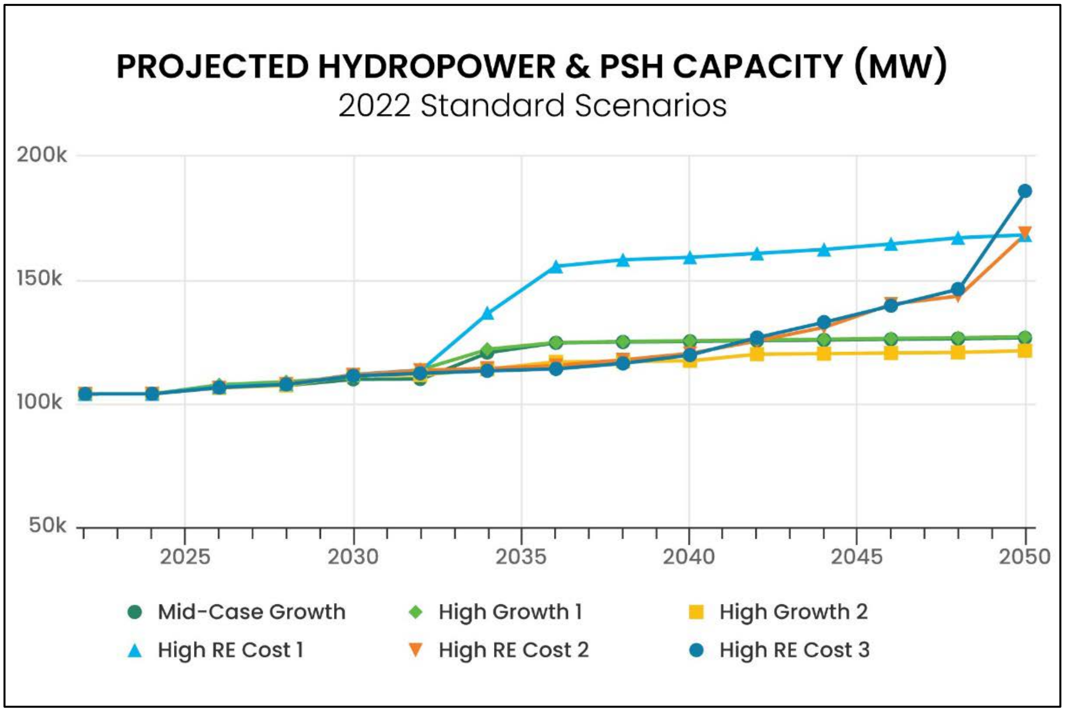
While the current domestic fleet has significant demand for replacement and refurbishment, the transition to a clean energy economy will require additional hydropower and PSH resources. Several groups have made projections for future renewable grid energy and storage demands (International Energy Agency 2023; NREL n.d.). These projections vary significantly depending on their regional scope and overall vision (e.g., achieve net zero), among other factors.

NREL developed a comprehensive set of 70 “standard scenarios” for domestic electric power demand and storage through 2050 (NREL n.d.). These scenarios include business-as-usual cases (e.g., no new policies), cases aiming to achieve decarbonization, or near-decarbonization cases. They also look at differing economic conditions such as high natural gas or renewable energy prices and technology considerations like the inclusion of nascent technologies. Many, if not most, of the scenarios show that conventional hydropower grows much more slowly than other renewable energy technologies, but considerable growth is expected in PSH. As noted earlier, PSH and hydropower are critical to meet capacity and energy storage needs in the clean energy portfolio.

For this analysis, several of the scenarios were selected that showed a range of potential growth for both conventional hydropower and PSH. These scenarios are summarized in Table 14 and Figure 5.

Table 14. Projected Growth (2022–2050) in Hydropower Technologies for Selected Standard Scenarios

Case	% Hydropower Growth	% PSH Growth
Mid-Case Growth	7.8%	70.9%
High Growth 1	8.6%	69.9%
High Growth 2	7.6%	49.2%
High Renewable Energy (RE) Cost 1	9.4%	246.3%
High RE Cost 2	8.8%	250.8%
High RE Cost 3	9.1%	324.5%



Mid-Case Growth: Mid-level demand growth, 100% decarbonization by 2035, Nascent technologies
High Growth 1: High demand growth, 100% decarbonization by 2035, Nascent technologies
High Growth 2: High demand growth, 95% decarbonization by 2050, No nascent technologies
High RE Cost 1: High RE cost, 100% decarbonization by 2035, Nascent technologies
High RE Cost 2: High RE cost, 95% decarbonization by 2050, Nascent technologies
High RE Cost 3: High RE cost, 95% decarbonization by 2050, No nascent technologies

Figure 5. Projected hydropower and PSH capacity (MW) from 2022 Standard Scenarios.

Illustration by Tara Smith, NREL

As shown in the figure, the total capacity of hydropower and PSH varies significantly among the various cases. The largest increase in demand is shown when other renewable energy technologies have high costs. In all cases, the growth of PSH far outpaces that of hydropower. For the mid-case growth case, which assumes that the

United States achieves decarbonization by 2035 and that nascent technologies (e.g., carbon capture and storage) are employed, an additional 6.3 GW of hydropower and 15.6 GW of PSH would be required by 2050, with the majority being deployed prior to 2035. If nascent technologies do not mature and if other renewable energy technologies are not cost-effective, perhaps due to shortages of raw materials (e.g., cobalt), then the increased demand could be almost 79 GW, with the majority being in PSH. It should be noted that these demands were based on economic analyses without considering supply chain or permitting constraints. PSH facilities can have a lead time of more than 10 years.

The demand signal from the domestic fleet from 2024 to 2050 was projected using the Standard Scenarios to estimate new capacity. The analysis was based on the cost factors developed by (Oladosu and Sasthav 2022). Only the cost of equipment was used to generate the supply chain demand, as the other capital expenditure (CapEx) components (e.g., structures, land) included in the report are not currently of concern. It is unlikely that the highest hydropower demands will be realized, but for this analysis, the average increased demand for the six scenarios was used to project a demand for new builds.

Major assumptions for the analysis are shown in Table 15.

Table 15. Domestic Hydropower Demand Projection Assumptions

Parameter	Value	Source
Domestic fleet		
Hydropower	80,920 MW	(Uría-Martínez and Johnson 2023)
PSH	22,000 MW	(Uría-Martínez and Johnson 2023)
Increased demand in fleet		
Hydropower	6,900 MW	8.5% increase (avg. of cases evaluated)
PSH	41,140 MW	187% increase (avg. of cases evaluated)
Project CapEx cost factor		
Hydropower	$1,352/kW	
PSH	$898/kW	>100 MW factor (Oladosu and Sasthav 2020)
% of CapEx for equipment		
Hydropower	42.2%	(Oladosu and Sasthav 2020)
PSH	42.6%	(Oladosu and Sasthav 2020)

Using these assumptions, the total demand for hydropower and PSH new equipment to achieve grid decarbonization by 2050 is projected to be $3.9 billion for hydropower and $15.7 billion for PSH. Combining these results in an annual demand signal of $0.8 billion from 2024 to 2050. Assuming the federal fleet would grow proportionally to its existing size results in a demand signal of $4.4 billion (10 GW) or almost $200 million annually. Although the analysis assumed a very aggressive new build, refurbishment and replacement of the existing fleet is the major factor in the projected demand due to the significant existing investment and capacity.

In addition to the growth scenarios, there is a business-as-usual scenario that assumes that only current policies are in effect and that nascent technologies are not developed. For this case, hydropower capacity grows from 80,800 MW in 2022 to 86,100 MW in 2050. During that same period, PSH capacity increases from 23,100 to 27,800 MW. For this case, the capital investment for hydropower equipment would be very similar to that of the average growth cases at $3 billion while the capital investment for PSH would be significantly smaller at $1.8 billion. The Standard Scenarios were updated for 2023 with the same results for hydropower but a much higher expected growth for PSH, increasing to 44,800 MW in 2050, corresponding to a capital investment for PSH equipment of $8.3 billion. The higher growth rate for PSH between the 2022 and 2023 Standard Scenarios is primarily due to the IRA.

4.3 Refurbishment and Replacement Demand

Hydropower systems are complex, capital-intensive systems with exceptionally long lives of 25–50 years or even longer. The average age of the federal fleet is 64 years—many of the units are at or near the end of their lifetime and are likely performing suboptimally. Replacement and refurbishment of these existing units is a critical need and is one method of projecting demand. To replace and rehabilitate systems, which will both extend the life and potentially increase output, extensive economic and technical planning is required.

We have developed a component-level methodology to project the demand for refurbishment and replacement. This methodology is based on unit-level information[16] compiled by ORNL, which allows supply chain projections to be refined based on size, turbine type, and location to include the impact of logistics. For example, Figure 6 and Figure 7 show the locations and ownership (federal or nonfederal) of individual units >100 MW for hydropower and PSH assets, respectively.

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[16] The unit-level data are not currently available to the public, but work is underway to include it in the HydroSource database (https://hydrosource.ornl.gov/).

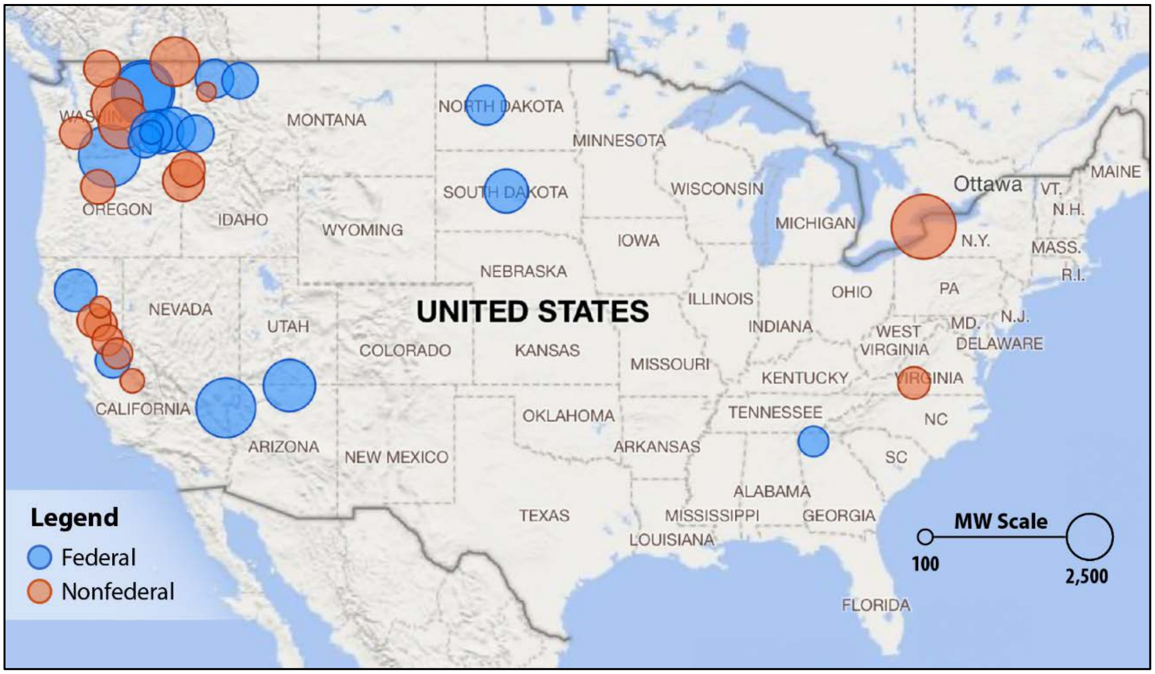

Figure 6. Domestic sites with individual hydropower units (>100 MW),by location and owner. Only units ≥ 100-MW are depicted for each site

Illustration by Tara Smith, NREL

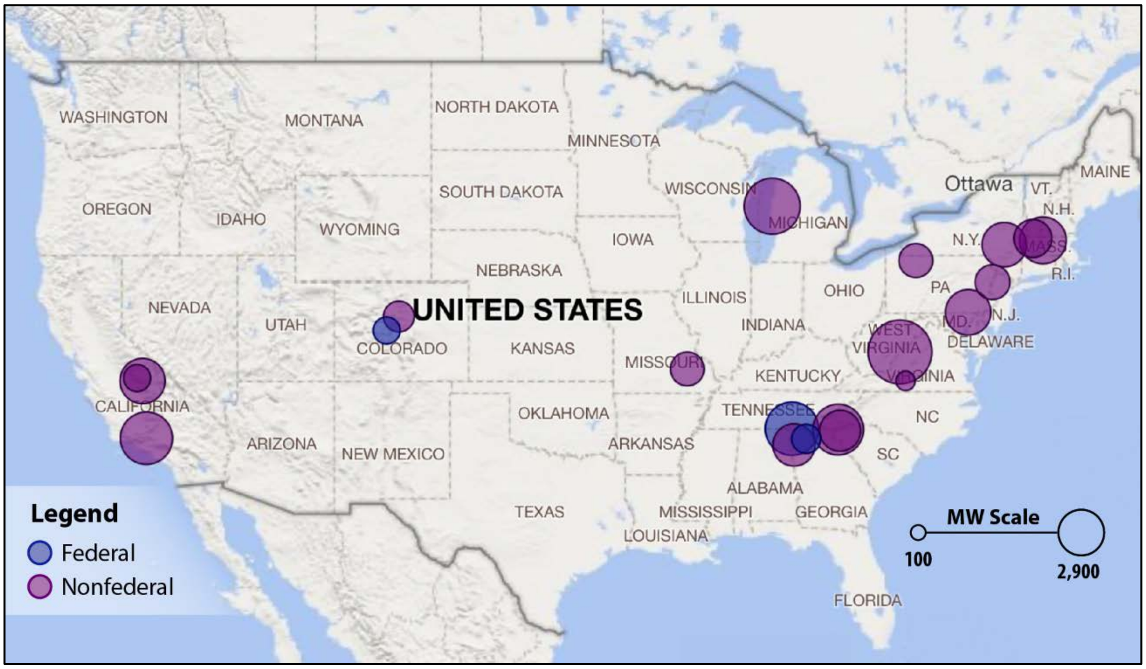

Figure 7. Domestic sites with individual PSH units (>100 MW) by location and owner

Illustration by Tara Smith, NREL

As shown in the figures, the private sector has a greater number of sites with large PSH units, and they are primarily along the Atlantic Coast and in California. The federal government has many large (≥100-MW) hydropower units, and they are primarily on the Pacific coast, especially in the Northwest. The ability to analyze individual units within a hydropower or PSH site is critical in understanding and projecting the replacement and refurbishment demand.

4.3.1 Hydropower Refurbishment Background

Many hydropower facilities, especially those with the ability to stimulate the supply chain, consist of multiple turbine generators within a single facility. These turbine generators depend on control systems that interconnect generation, balance of plant equipment, and water flow control equipment within central control rooms either on the facility or remote to the facility. These systems, many of which date to the early to mid-1900s, have antiquated equipment that has been upgraded as needed to maintain system operation. To determine the best time for replacement, strategies must be developed to account for the interdependency of control system and facility operations during periods of upgrade.

For example, a facility having more than four units cannot simply replace a single unit without understanding the dependencies throughout the system. To accommodate replacements, control systems must be modernized while determining how the modern system will control existing units and have the capability to incorporate modern replacements. The cost of replacement is in the millions to tens of millions of dollars, depending on the size of units. For example, the U.S. Army Corps of Engineers spent more than $320 million to replace 14 units at McNary Dam hydro project on the Columbia River near Umatilla, Oregon (Poindexter 2018).

To determine the specific components to be replaced, the team used the HydroSource Taxonomy developed by ORNL under the Hydropower Advancement Project Performance Assessment Manual that lists specific components necessary for a hydropower facility (Smith et al. 2012). Figure 8 shows the major components of a generic hydropower system.

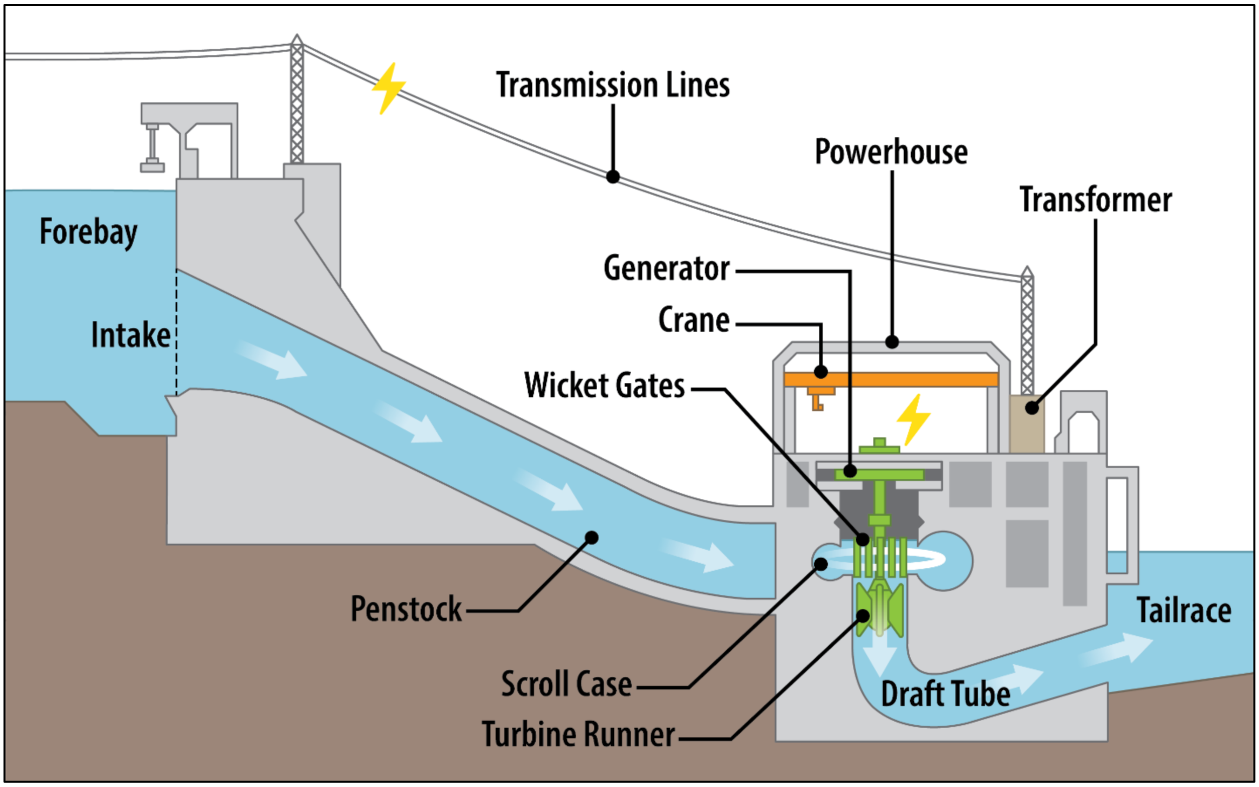

Figure 8. Hydropower components.

Illustration by Besiki Kazaishvili, NREL

Hydropower systems are specific to the turbine type. Most hydropower turbines are Pelton or Kaplan types, which depend on head and flow for operation. When a system is being replaced, equipment that is deeply embedded in the facility, such as intakes, penstock, and draft tubes are mostly reused. However, components such as the scroll case or distributor can be replaced or retrofitted to accommodate modern turbine designs and increase efficiencies. The draft tube may be updated to accommodate new designs as well. Flow control systems, such as wicket gates, are replaced along with their operational equipment. All turbine componentry is likely replaced, and generators can be rewound or replaced. Using the taxonomy at the component level allows us to identify and size componentry that is difficult or impossible to source domestically.

For this analysis, only the largest fabricated cast or forged components were investigated, namely, the hub, blades, shaft, and thrust block. The largest component of a Kaplan runner, based on mass, is the runner hub, which supports the thrust and load of the turbine blades. Water passes the blades, which capture energy and in turn rotate the generator. Kaplan blades are adjustable depending on head and desired power generation, so the runner hub must withstand the forces of operation and the cantilever forces of the blades due to the hydraulic thrust of the passing water. The hub has historically been made from cast steel with machine-finished high-tolerance surfaces. Typical Kaplan units can have anywhere from two to six blades.

Francis runners consist of many fixed blades. Water passes through the blades and is discharged centrally. Francis hubs can be cast in a single assembly or in combined castings, forgings, and weldments. Commonly, the upper crown will be cast with the cone welded to the crown. Next, blades will be shaped and welded between the crown and the lower band. Assuming this construction technique, the upper crown will be the largest cast component on the runner. Figure 9 shows the Francis runner crown, and Figure 10 shows the Kaplan runner hub.

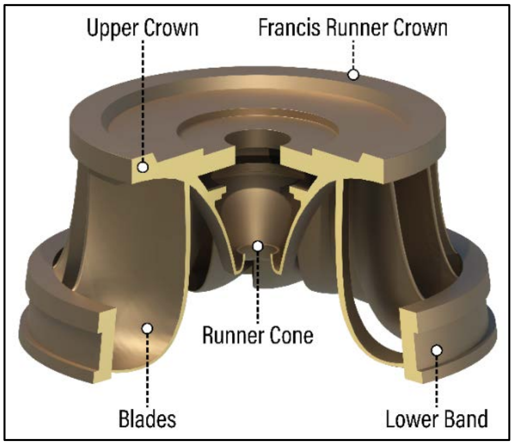

Figure 9. Francis runner crown.

Illustration by Besiki Kazaishvili, NREL

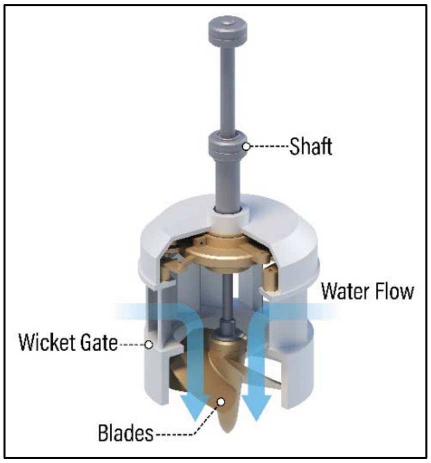

Figure 10. Kaplan runner hub.

Illustration by Besiki Kazaishvili, NREL

The turbine shaft is coupled directly to the runner hub and passes through the headcover, which separates the wetted environment from the dry environment of the powerhouse. Turbine shafts must withstand the torsional forces of starting and stopping, as well as fluctuating hydraulic loads. Depending on the height of a unit, an intermediate shaft will be included between turbine and generator shafts. All shafts will be forged and bolted together.

The final sizable singular component is the thrust assembly. This consists of a thrust block keyed to the generator shaft. The thrust runner is the sliding surface beneath the thrust block. The thrust block supports the entire weight and hydraulic thrust of the hydropower turbine runner and generator system. This item is smaller than the Francis crown or Kaplan hub. Focusing on the hub and crown will highlight individual units where domestic componentry will be difficult or impossible to source.

4.3.2 Refurbishment Demand Methodology

Hydropower turbine power ratings vary from a few hundred kilowatts to the largest case of 805 MW at Grand Coulee Dam. Multiple variables go into the determination of power in a hydropower unit, most notably head and flow. Further, hydropower units spin at synchronous speeds to match and maintain 60-hertz generation. This results in size relationships between the head, flow, and operational speed of units. Through these physical relationships, and knowing volumes and masses of some existing units, estimates for component size were determined across the fleet using the ORNL Existing Hydropower Assets, FY2023 Unit Level Dataset.[17] The detailed demand methodology is described below.[18] All equations are from Hydropower Engineering (Warnick 1984).

Beginning with Bernoulli's equation, simplifying, and converting units, the resultant hydraulic power equation is:

$$P = 11.7 * \ Q * \ \rho * g * h \tag{1}$$

where *P* is power in megawatts, *Q* is flowrate in cubic feet per second, ρ is the density of water, *g* is the gravitational constant, and *h* is head in feet.

From this equation one can see that power is dependent on both the head and flow. By examining this equation more closely, it becomes evident that similar power ratings may be achieved with a higher factor, or dependence, on head or flow. For example, a low-head facility, such as what could be found on the Mississippi River system may have a lower head and a very high flow. This may be equal in power rating to a system having a very high head and low flow, such as a system found in the mountains of California. Because of this contrast in head versus flow, systems with similar power ratings would require very different construction. The flow area to minimize head loss in the low-head example will be large, resulting in a physically large turbine. The flow area for high head will be small; because of driving pressure, the velocities can be very high, resulting in a small turbine runner.

Generators are typically directly coupled with turbine runners. This requires hydropower generation units to operate at a fixed speed that is a multiple of the grid frequency. The

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[17] The unit-level datasets are not currently available to the public, but work is underway to include these in the HydroSource database, (https://hydrosource.ornl.gov/).

[18] Results (e.g., weights and sizes) were validated by comparing with GE data and showed excellent agreement (i.e., within a few percentage points).

fixed speed sets the number of poles in the generator. The specific speed, N_s, is a universal constant that combines flow, power, and rotational speed.

$$N_s = \frac{N\sqrt{P}}{h^{\frac{5}{4}}} \tag{2}$$

where N is wheel speed (rpm), P is power in horsepower, and h is water head in feet.

Next, based on the specific speed of the unit, equations have been derived to estimate the diameter of turbine runner. This effort focused on Francis, Kaplan, and propeller-type runners because other types are rare or, as is the case with the Pelton runner, may be assembled in multiple pieces. Since the Pelton is manufactured in multiple pieces and then assembled, the size and weight of the individual pieces are more easily obtained domestically.

Using the specific speed, the diameter of a Francis or Kaplan turbine runner is calculated as shown below. Propeller runners are calculated using the same equation as the Kaplan runners.

$$D_{Francis} = 104.65 * \sqrt[3]{{N_s}^2} * \frac{\sqrt{h}}{N} \tag{3}$$

$$D_{Kaplan} = (569.5 + 17.4 * N_s)99 * \frac{\sqrt{h}}{N} \tag{4}$$

where $D_{Francis}$ is the diameter of the Francis runner (inches), D_{Kaplan} is the diameter of the Kaplan (or propeller) runner (inches), N is the wheel speed (rpm), N_s is the specific speed, and h is the water head (feet).

Using the ORNL Existing Hydropower Assets, FY2023 Unit Level Dataset, many of the variables are available for individual units. The dataset was used as an input to calculate the specific speed, then the unit diameters were estimated for the specific turbine types. The federal fleet has the most complete data within the database. Of the 657 federal hydropower units present, 467 individual diameters were able to be estimated.

Next, using known weights for specific Kaplan runners and Francis runners, we developed a linear correlation of the total mass of the runner to its diameter. Then, the mass of the largest cast component (i.e., crown [Francis] or hub [Kaplan]) of all other units was calculated assuming:

- The Francis crown/cone is one-third of the runner mass.
- The Kaplan hub is one-quarter of the runner mass.

Of the 467 federal units analyzed, 352 units (75%) would exceed the current maximum domestic casting capability of 25 tons.

Shafts are the largest (i.e., most massive) forged component in a hydropower unit. The shaft mass was calculated by examining the rotational speed and maximum power rating. A linear relationship was formed using some known shaft weights of existing hydropower units. This calculation is less precise than the casting estimate because shaft length is a variable that would impact the overall mass of the shaft.

Shafts presented a much better result in terms of domestic capability. Of the 467 federal units analyzed, 53 (11%) exceeded the probable domestic capacity of 50 tons.

This method was used to estimate the mass of available runners and shafts in the federal fleet, resulting in a total mass of 20,700 tons of crowns, 17,300 tons of shafts (i.e., forged steel) and 57,400 tons of runner blades and bands. As noted above, most of the cast crown and hub components would be larger than the current domestic capacity, which is based on a single facility. While the demand for large, forged components can more easily be met by domestic facilities, more than 10% would be difficult to procure and could only be produced by a handful of facilities, and 2% could not be sourced domestically at all. As noted earlier, however, mass is not the only factor in determining facility capabilities. Hydropower components may have large dimensions, complex designs, or specific metallurgy that could eliminate some facilities and increase the domestic manufacturing gap.

These material demands can be translated into an equipment cost using the methodology described for new builds. However, because we have estimates for the actual size of each federal unit, we can use the capital cost factors from Oladosu and Sasthav (2022) to provide high-level estimates of the capital demands for refurbishment of the federal fleet (Table 16). The analysis assumes that the runners and shaft make up most of the capital cost factor in each turbine size and that the mass of each component is proportional to its cost.

Table 16. Capital Costs for Equipment Replacement in the Federal Fleet

Turbine Size (MW)	CapEx Cost Factor ($/kW)	%CapEx From Equipment	Equipment Replacement Cost Factor ($/kW eq)	Total Demand ($ million)	Total No. Units	Total Capacity (MW)
≥100 MW	$1352	42.2%	$570.5	$10,665	107	18,693
≥30 and <100 MW	$1489	43.0%	$640.3	$8,440	238	13,182
<30 MW	$2654	37.7%	$1000.6	$1,790	132	1,789
			Totals	**$20,895**	**467**	**33,664**

As shown above, this demand equates to $20.9 billion or about $800 million/year (2024–2050). As expected, the demand from refurbishment of the federal fleet is significantly more (i.e., 4.8x) than that from new demand. However, not all the federal fleet will be refurbished in this time frame. Based on planned refurbishments of the federal fleet from the industry survey (Section 2.4), the actual projected demand is $8 billion over the next 20 years, which is 2x greater than potential new installations in the federal fleet (Section 4.2).

5 Gap Analysis

Throughout the analysis, we have identified areas in the domestic hydropower supply chain where domestic material, component or equipment demand could not be met from U.S. suppliers. While this analysis narrowed some of the gaps identified in earlier assessments (e.g., domestic forging and foundry capabilities), other gaps have been uncovered (e.g., complexity of hydropower components). We have grouped these gaps into five categories:

- Unpredictable and variable demand signals.
- Severely limited or nonexistent domestic suppliers for hydropower materials and components.
- Federal contracting procedures and domestic content laws.
- Foreign competition, foreign subsidies, and ineffective trade policies.
- Shortage of skilled workers.

Each of these categories is discussed in greater detail below.

5.1 Unpredictable and Variable Demand Signals

Development of a hydropower domestic industry is hampered by an unpredictable and highly variable demand for materials and components. In general, hydropower systems have exceptionally long lives (e.g., 30–50 years), so replacements and refurbishment schedules have cycles that are years or decades. In addition, when budgets are tight, general system improvements or refurbishments can be pushed out even further. Another complication is that hydropower systems are large and complex and require significant investments over years of development and construction. All these factors cause the demand signal to be erratic and insufficient to allow suppliers to plan and keep shops open.

5.2 Severely Limited or Nonexistent Domestic Suppliers for Hydropower Materials and Components

As noted throughout this report, domestic suppliers for hydropower products and materials are limited (e.g., one or two suppliers) or nonexistent. Bradken is the only identified domestic foundry with casting capabilities of greater than 10 tons for medium to large turbine runners. However, it is unlikely that even Bradken’s capabilities extend to castings for Kaplan or Francis runner blades and hubs (i.e., >220 inches in diameter, ~60 MW) due to a combination of size and complexity. Thus, Kaplan and Francis turbines greater than 60 MW cannot be sourced domestically. In addition to the lack of very large casting capabilities, domestic forging capabilities are also limited. Only NAF and Scot Forge are capable of forging large hydropower shafts (>50 tons). Pelton turbines are more easily supplied domestically because the runners are assembled from smaller components.

Transformers and hydrogenerator manufacturing are similarly restricted. NEC is the only domestic facility capable of producing windings greater than 100 MW for large hydrogenerators, and there are only two domestic suppliers of NOES for the hydrogenator core. The lack of NOES capabilities will become even more problematic in the future due to the high demand expected from the EV sector. In fact, the U.S. Steel plant in Arkansas has announced that it is developing NOES specifically for this sector (Z. Miller 2023).

Finally, Cleveland-Cliffs is the only domestic supplier of GOES for U.S. transformer manufacturers as well as all other LPTs across the grid. Complicating the dearth of manufacturing capabilities is that the facilities are spread out across the country, and manufacturing hydropower turbine systems would require shipping parts and materials across the country several times.

5.3 Federal Contracting Procedures and Domestic Content Laws

Although there are several federal laws designed to assist critical supply chains by enhancing domestic manufacturing, these laws have some limitations, which decrease their efficacy, especially with respect to small businesses. Since the federal government is the largest single owner of hydropower assets, it makes sense to stimulate the development of this domestic supply chain by focusing on the federal fleet. Through discussions with industry representatives, it was noted that there are several procurement regulations and/or general practices that inhibit the development of this domestic industry, including bonding requirements, specifying precontract design work, and focusing exclusively on the initial capital outlay rather than the total project cost, including implementation.

One policy issue is the low capital threshold of TAA of $6,708,000 for hydropower projects, which waives BAA restrictions for many, if not most, projects. For example, based on the work of Oladosu and Sasthav (2022), this would barely cover the equipment costs of an 11-MW hydropower facility.

Federal contracting policies can pose significant hurdles, especially for small businesses. For example, industry contacts have noted that bonding is difficult for small businesses to obtain for federal hydropower projects. Under the Miller Act of 1935, contractors on federal construction projects >$150,000, which includes most hydropower projects, must post two surety bonds as a condition of the contract: a performance bond guaranteeing performance of the work and a payment bond guaranteeing payment of subcontractors and suppliers. The amount of the bonds varies widely and depends on the size of the contract as well as other factors such as credit history or prior experience on similar-sized projects. Surety companies list average percentages of the contract costs of (0.5%–2.5%) for performance bonds and (0.3%–0.8%) for payment bonds (Evergreen Surety n.d.; Viking n.d.; Bond Exchange n.d.). While the bonding requirements can be costly, a more important limitation for small businesses is that it can be impossible to obtain a bond for projects larger than they have experience with or that require more working capital than the company has. While the Surety Bond Program administered through the Small Business Administration was designed to help small businesses obtain bonds for projects up to $9 million for nonfederal contracts and $14 million for federal contracts, most hydropower projects exceed this value (U.S. Small Business Administration 2024).

Small hydropower businesses have also found it difficult to benefit from the Small Business Administration's set-aside procurement rules due to the selection of North American Industry Classification System (NAICS) codes in the contract. Many times, hydropower procurements are classified under the all-encompassing NAICS code 238990 (Other Heavy and Civil Engineering Construction) due to the heavy volume of construction involved with these projects. However, few small businesses would fall under this code, so there is no set-aside. Typical NAICS codes more applicable to small hydropower businesses might be 333611 – Turbine and Turbine Generator Set Manufacturing. In fact, NEC was qualified for small-business set-asides in 2013 under codes 333611 and 335312 – Motor and Generator Manufacturing, but they have never been awarded a contract under these codes. While dividing a large project into different NAICS codes may present administrative and other challenges, it may be warranted for the domestic hydropower industry given the small number of domestic providers of critical components.

Another common federal contracting procedure that adversely impacts small businesses is requiring up-front work as a condition to submit bids. One small business relayed that a large federal hydropower contract required more than $150,000 of computational fluid dynamics modeling prior to the bid. The company proposed that this requirement be included in the contract and described in detail how the modeling would be completed with the funding. Because the modeling was a prerequisite to the bid, the company was disqualified. It is likely that if bidding requirements were modified to be based on describing an approach rather than requiring prework, smaller companies could demonstrate their competitiveness with the larger companies. Another method that could improve competitiveness would be to choose another contracting process such as staged contracts where the initial deliverable would be a concept paper describing the approach and the second stage would be an invitation-only proposal (Obama White House 2014). It is important that agencies evaluate the necessity of up-front requirements to ensure that they are truly required and consider modifying the process so that competence can be demonstrated another way. Current processes with expensive up-front requirements can preclude companies from even being evaluated.

Another issue with the federal contracting process for both large and small businesses is its inflexibility, both in the requirements as well as in their execution (e.g., doing it the way it has "always been done"). One significant example of inflexibility is that many federal contracts have "no escalation" clauses. These have proven problematic for industry in the last few years because contractors were not allowed to increase prices, even though the pandemic caused significant increases in raw material costs and delivery times. The long duration of hydropower contracts (e.g., decades) exacerbates the issue in the hydropower industry.

The last issue, making awards based on capital costs alone, is not unique to federal contracting. Many contracts are awarded to the lowest-cost bidder, and, in general, procurement specialists are rewarded for keeping capital expenditures low. However, by focusing on this factor alone, many other direct and indirect costs are ignored over the life of a project.

For example, as noted earlier in the industry roundtable, lower cost can sometimes mean issues with QA/QC. To save costs, companies will contract with individuals located in the country or region that may not be wholly independent from the manufacturer, causing a conflict of interest. In addition, if the supply chain is based on a region of the world that is unstable or prone to labor strikes, the schedule can be delayed, and significant costs incurred. Communication and project integration can also be problematic due to different time zones, customs, or other factors. By not accounting for the entire life cycle of a project, many of the potential issues are ignored, and the projects end up coming in late and at a significant cost.

To combat this and other issues, restrictions on when and how federal civilian agencies can use the Lowest Price Technically Acceptable (LPTA) (i.e., the low-cost bidder) were added as a rule to the Federal Acquisition Regulations (FAR) in 2021. Among other requirements, this rule specifies that LPTA shall only be used when “the agency determined that the lowest price reflects the total cost, including operation and support, of the product(s) or service(s) being acquired” (FAR 15.101). Now, many procurements use a trade-off or best-value approach, which considers all costs. In 2023, there was a 50-50 split of trade-off and LPTA evaluation criteria in public solicitations posted to the System for Award Management (Siken 2023). Given the long duration of hydropower projects and the irregular demand signal, there may be a lag in the number of federal awards using the trade-off methodology, which could explain the concerns voiced in the roundtable. It is likely that the number of contracts using trade-off criteria will continue to increase in federal procurements. In fact, one of the General Services Administration’s goals for 2024 is to continue to decrease LPTA procurements (J. Miller 2023).

5.4 Foreign Competition, Foreign Subsidies, and Ineffective Trade Policies

Discussions with companies in the hydropower industry highlighted subsidized competition from foreign companies and ineffective trade policies as other issues in the hydropower supply chain. Several companies we spoke to pointed out that some countries subsidize their steel and other industries, which enables them to undercut domestic prices. Import codes do not have a uniform category for castings, so these products are often miscategorized or embedded in some other product, leading to challenges in the enforcement of trade regulations. Furthermore, as mentioned by Wadsack et al. (2021), it is difficult for domestic companies to manufacture for export due to unfavorable import duty structures.

In 2021, the government of Great Britain decided to nationalize Sheffield Forgemasters, a large facility that produces complex castings and forgings for critical systems such as the Royal Navy’s nuclear submarine fleet as well as other sectors (Chuter 2021). This government support included plans for capital upgrades and allowed the forge to expand into other areas such as modular nuclear reactors. While the forge was nationalized to protect defense supply chains, this forge may also supply specialized components in the hydropower industry. China is another country that subsidizes its steel and other industries. One industry representative noted that it had lost a hydropower contract to a company in China because the Chinese company had an advanced manufacturing facility. The loss was even more difficult because it was to a state agency on a project financed by municipal bonds.

Industry representatives also noted that one advantage of China's centralized planning and industry support is that it develops pods of manufacturing capability in specific areas to shorten the supply chain to make it more cost-effective. As shown earlier, the geographical spread of the U.S. domestic hydropower supply chain is significant and would incur high transportation costs.

Other representatives indicated that American companies can also be disadvantaged by trade agreements. In 2019, the United States imported more than 95% of transformer cores from Canada and Mexico, and neither has domestic GOES production (U.S. Department of Commerce 2020). Although both countries get most of their GOES from Japan, they also import from China and Russia. It appears that there may be loopholes in these agreements, which may be exploited to undermine the domestic hydropower and upstream industries.

5.5 Shortage of Skilled Workers

Finally, as in most of the renewable energy supply chains, hydropower manufacturing and upstream support industries suffer from a significant lack of expertise in the workforce. As the supporting industries have moved overseas in the last 40 years, skilled workers have retired or retrained for other industries.

6 Recommendations

To address the gaps in the domestic hydropower supply chain, we met with a wide range of industry representatives, including governmental and private sector owners and operators, equipment manufacturers, foundries, and forges to develop four high-level recommendations with specific actions outlined for each. The recommendations are listed below, followed by detailed discussions for each.

1. Lead with the federal fleet to prime the development of an aggregated, consistent demand signal with our largest producers by examining federal procurement processes and developing best practices for refurbishing the domestic fleet.
2. Increase awareness of domestic supply chain by developing databases of domestic manufacturing and installations.
3. Work with other low-carbon technologies to create a significant, steady, and predictable demand signal.
4. Continue workforce development efforts through DOE and other initiatives.

6.1 Lead With the Federal Fleet

6.1.1 Demand Signal

As noted earlier, the federal conventional hydropower fleet is almost 50% of the domestic hydropower fleet; if we focus on this sector, which is controlled by a single entity, we can begin to develop the necessary procedures, systems, and aggregate demand for the private fleet to follow.

The potential demand signal from the federal fleet can be significant through both new facilities and refurbishments. For example, as outlined in Section 4.3, meeting net-zero goals by 2035 or 2050 could demand an additional $4.4 billion (10 GW) over the next 25 years, or almost $200 million (0.4 GW) annually. This demand signal could be significantly higher depending on the rest of the renewable energy market. The demand from refurbishing the current installed federal capacity would result in an even greater demand signal of up to $21 billion.

6.1.2 Examine Federal Procurement Processes

Procurement of federal goods and services are governed by numerous mandatory procedures and processes, but as outlined earlier, there are also many optional or customary procedures (e.g., whole project vs. phased project bids). To encourage the development of a domestic hydropower supply chain through the federal fleet, federal procurement processes should be evaluated to ensure that they are effective in developing the domestic supply chain while procuring the hydropower and PSH equipment and services they need.

Task Ordering Contracts

Industrial representatives noted that the Canadian government contracts for hydropower are designed much differently than in the United States. They group multiple units/sites together and go out for bid for the entire group so that the selected supplier has larger and longer-term contracts. It also reduces the number of bid cycles. An example of these contracts is the Hydro-Québec award of a refurbishment contract for the first six of a possible fourteen 54-MW turbine generator units at the Carillon generating station (Andritz 2020). More recently, Ontario Power Generation awarded a contract to GE Vernova to modernize up to five hydropower plants over the next 15 years (Noon 2024).

The federal government does have contracting vehicles such as indefinite delivery/indefinite quantity (IDIQ) contracts, that could help improve the duration of the contracting procedure and help ensure a more predictable demand signal. IDIQ contracts provide for an indefinite quantity of services for a fixed time. They are used when an agency cannot determine, above a specified minimum, the precise quantities of services that it will require during the contract period. IDIQs help streamline the contracting process and speed service delivery. These contracting vehicles are frequently used for service contracts and architect-engineering services. Minimum and maximum quantity limits are specified in the contract as units of supplies or dollar values for services.

There are two types of IDIQs: MATOCs and Single Award Task Order Contracts (SATOCs). In MATOCs, contracts are awarded to several prequalified companies. When a new task is required, a request for proposal is developed, and all the prequalified companies bid on it; the award can be made for the lowest price or best value. In a SATOC, several companies bid on an initial request for proposal, and a single supplier is selected. The agency will issue task orders to the selected supplier, usually over several years. SATOCs are frequently used by military branches. In general, MATOCs are preferred because they increase competition.

Although the federal government owns a large share of the domestic hydropower resource, there is no overarching agency that controls the units. Furthermore, the controlling agencies such as the U.S. Army Corps of Engineers or the Bureau of Reclamation are broken into multiple districts, each with contracting authority. Thus, even though both are single entities, requirements may vary by district/region, and procurements will likely be less aggregated.

Domestic Content Provisions

Federal agencies conducting product subject to domestic content requirements (e.g., BAA) should perform thorough due diligence to ensure that they are maximizing the use of domestic materials or end products. If not, the underlying causes of the failures should be identified, and specific remedies outlined, taking into account U.S. international obligations. In addition, where products are not available, are agencies using waivers judiciously, as a tool to drive investment in domestic manufacturing.

Increase Involvement of Small Businesses

Small businesses in the domestic hydropower supply chain are currently underutilized. Several customary or discretionary federal procurement processes such as the selection of NAICS codes or the type of contract specified can hinder the ability of small businesses to compete in the federal sector and should be evaluated. As noted earlier (Section 5.3), most if not all hydropower projects are categorized under NAICS code 238990, which few small businesses would fall under, and include significant, expensive prework to qualify to bid. Bonding requirements have also been identified as a hurdle for small businesses in competing for federal contracts. In addition to addressing these issues, the federal procurement processes should be evaluated to identify other barriers to small-business participation in the hydropower sector.

Evaluate Trade Agreement Rules

Trade agreement import regulations are another area that was identified as a potential concern for companies in the hydropower supply chain. These regulations should be reviewed with respect to the hydropower industry to understand if there are loopholes that can be exploited that undermine the industry's domestic supply chain or hinder American manufacturing. Remedies for any identified issues should be developed.

Develop Best Practices for Refurbishing the Domestic Fleet

Most federal units are near or at the end of their expected life and are likely operating suboptimally. The refurbishment or replacement of these units is done at the site or organizational level and is generally based on the availability of funds rather than on a standard procedure that can be planned for. To address this issue, we recommend developing best practices that are based on whole-life cost model methods to optimize replacement schedules. The timing, priorities, procedures, and contracting methods should all be considered when developing best practices. The CEATI *Best Practice Guide for Planning and Executing Hydro Overhaul and Retrofit Projects: The Optimization of Hydro Plant Rehabilitation* (Markovich 2009) is a good starting point for this evaluation.

By systematically planning refurbishments, it is more likely that the funding will be available, units will be maintained near optimal conditions, and the demand signal will be more consistent and predictable, allowing industrial partners to keep shops open.

6.2 Develop Domestic Supply Chain and End-User Datasets

Developing tools to predict demand is another way that WPTO can help both the federal and private fleets. Several tools are under development or are already available, including a database of domestic suppliers along the hydropower supply chain (under development by ORNL), the HydroSource tool (ORNL n.d.) that allows users to see data (e.g., size, turbine type) on individual units (enhancements under development), and the sizing and costing methodologies outlined in this report. WPTO should continue to engage with industry and develop other tools to tackle issues in the domestic supply chain.

6.3 Work With Other Low-Carbon Technologies

While the demand from the hydropower industry is in the billions of dollars annually, it is not sufficient to build out a domestic industry, especially in the material and component sectors. Many of the components and materials used for hydropower systems (e.g., transformers and electrical steel) are also used in other clean energy technologies, such as wind energy, and for upgrading the national grid. In addition, other industries such as ship manufacturing and defense supply chains have commonalities with hydropower.

We have identified low-carbon industries that can be leveraged so that the aggregate demand and the smoothing of federal procurement cycles can address the gaps in their respective supply chains:

- Windings (wind, grid, solar)
- Transformers (wind, grid, solar)
- GOES (wind, grid, solar)
- NOES (wind, grid, electric vehicles)
- Large castings and forgings (wind, nuclear, naval operations).

This list should not be considered exhaustive, and there are other industries such as oil and gas that can be leveraged in many areas, including workforce development. In any case, these sectors are projected to have a higher demand (in megawatts) than hydropower. For example, while the NREL mid-case Standard Scenario forecasts an increase of ~5 GW for hydropower and PSH, it projects a >250-GW increase for land-based wind alone. Furthermore, the demand for GOES in the hydropower sector is dwarfed by that for the grid build-out. Thus, it is incumbent on the federal government to assess clean energy supply chains together to understand and leverage commonalities.

Another significant commonality between the hydropower supply chain and other low-carbon energy technologies is the need for a well-trained domestic workforce. In fact, all low-carbon energy technologies expect workforce gaps and shortfalls. Skilled manufacturing personnel, technicians, scientists, engineers, and others are needed to successfully make the energy transition. By developing training programs at all levels and locations—apprenticeship, community college, trade schools and universities—a skilled workforce can be developed.

6.4 Continue Workforce Development

There are few low-carbon energy technologies that have as significant of a gap in educational programs than hydropower. For many, hydropower is out of sight and therefore out of mind, but for those in the hydropower industry, we often hear “hydropower found me.” But we cannot wait for hydropower to find the next-generation workforce with the lack of hydropower-focused programming. In the hydropower workforce report completed on behalf of WPTO (Daw et al. 2022), nearly 70% of the schools surveyed do not offer hydropower degree programs, although in some schools, hydropower is included as a topic within other energy courses or can be pursued as an area of specialization. Schools expressed interest in expanding their hydropower programs; however, 34% cited lack of funding as the main obstacle. In addition, schools expressed that students were unaware of the importance or relevance of hydropower as a growth industry or hydropower as a career path. This is a huge gap and an even larger opportunity for our future workforce.

In addition to expanding academic programs to address this known gap, there are also a vast array of experiential-type programs that can help raise the awareness of hydropower and its opportunities, including internships/fellowships/apprenticeships, experiential placements, job fairs, primary and secondary school competitions, collegiate competitions, programs that place veterans and other unique workforce segments, and more. Many of these programs incorporate opportunities for the future workforce to “see” and “hear” why hydropower matters and to learn its unique challenges and innovation opportunities. The hydropower industry could also partner with existing youth engagement initiatives in the casting and forging space, such as union training centers and the Steel Founders’ Society of America’s Cast in Steel competition.[19] For the programs that are already in place, efforts are needed to more proactively present these opportunities to the next-generation workforce. And, for those programs that involve clean energy but not yet hydropower, efforts are needed to augment those programs and “teach the teacher,” so they can take on hydropower as a clean energy workforce opportunity.

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[19] https://www.sfsa.org/subject-areas/castinsteel/

7 Conclusions and Future Work

To develop a domestic, secure supply chain for the hydropower sector, we need to address wide-ranging issues, some of which are shared by other domestic clean energy technologies (e.g., workforce deficiencies) and some that are unique to hydropower (e.g., unpredictable demand). As outlined in the report, by focusing on the most unique aspect of the domestic hydropower supply chain—the high percentage of federal ownership—and leveraging the commonalities of other clean energy technologies, we can build a robust domestic supply chain for this vital industry.

Table 17 provides a high-level look at which strategies address the current challenges in the domestic hydropower supply chain.

Table 17. Cross-Reference of Challenges and Strategies for the Domestic Hydropower Supply Chain

	Challenges Addressed				
Strategy	**Unpredictable Demand**	**Limited Suppliers**	**Federal Laws and Contracting**	**Trade Policies**	**Insufficient workforce**
Lead with the federal fleet	X	X	X	X	
Develop domestic supply chain and end-user datasets	X	X			
Work with other low-carbon technologies	X	X	X	X	X
Continue workforce development					X

While not all the strategies can be implemented instantly and some are interdependent, by working on each strategy in parallel and exchanging information among other efforts, these strategies can result in a significant impact in the development of a robust hydropower supply chain. None of these strategies or challenges is independent. For example, we can generate a consistent demand signal, but without a skilled workforce, we cannot meet that demand. In the near term, by examining the federal fleet and looking at methods to improve federal procurement while developing and implementing best practices for fleet overhaul and retrofit in the midterm, we can partner with other clean energy technologies to develop a domestic hydropower supply chain that extends to the private sector as well.

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