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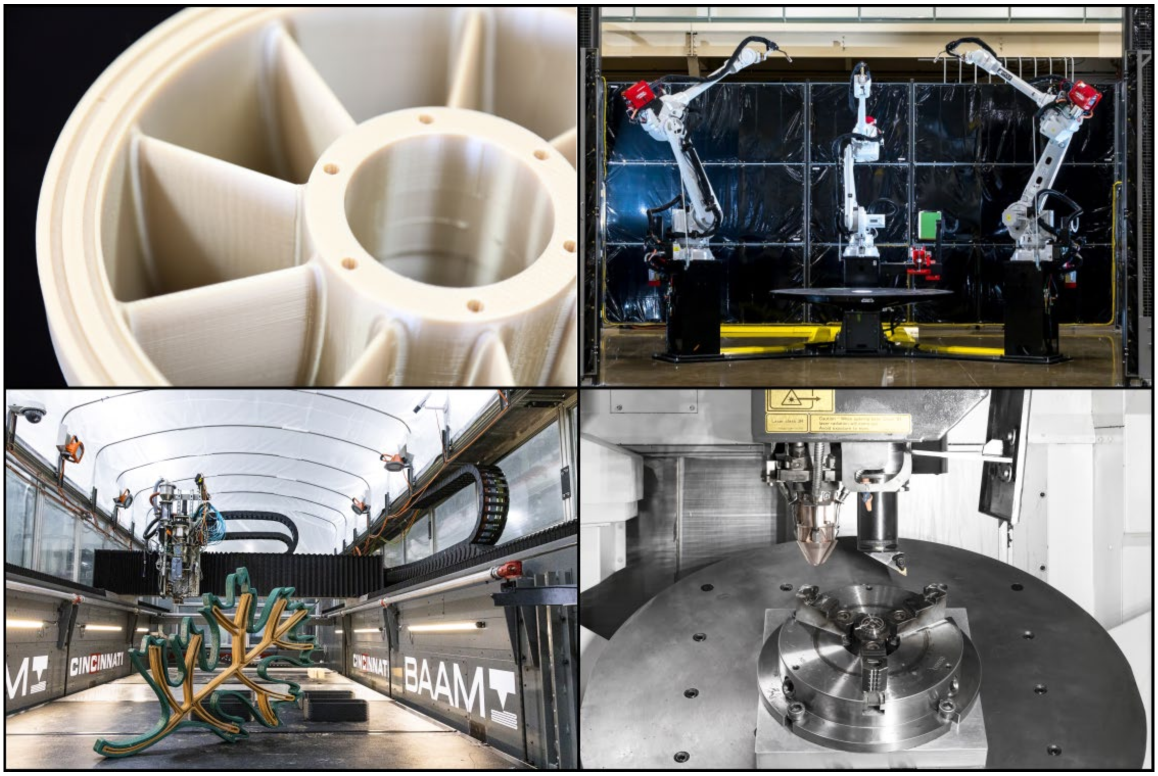
Advanced Manufacturing and Materials for Hydropower: Challenges and Opportunities



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Top left: Fixed guide vanes of a hydropower turbine system additively manufactured at Oak Ridge National Laboratory's (ORNL's) Manufacturing Demonstration Facility. *Photo by Genevieve Martin, ORNL/DOE*.

Top right: MedUSA at ORNL's Manufacturing Demonstration Facility. This is a large-scale hybrid system with three robotic arms for directed energy deposition (DED) metal additive manufacturing. *Photo by Carlos Jones, ORNL/DOE*.

Bottom left: Big-area additive manufacturing at ORNL's Manufacturing Demonstration Facility. This is a large-volume, multimaterial additive manufacturing system provided by Cincinnati Incorporated. *Photo by Carlos Jones, ORNL/DOE*.

Bottom right: Okuma MU-8000V Hybrid machine at ORNL's Manufacturing Demonstration Facility. The hybrid process combines powder-blown DED with milling and turning processes. *Photo by Carlos Jones, ORNL/DOE*.

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Environmental Sciences Division

ADVANCED MANUFACTURING AND MATERIALS FOR HYDROPOWER: CHALLENGES AND OPPORTUNITIES

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ABBREVIATIONS

ANL	Argonne National Laboratory
AM	additive manufacturing
AMM	advanced manufacturing and materials
AMMTO	Advanced Materials and Manufacturing Technologies Office
BAAM	big-area additive manufacturing
CNC	computer numerical control
DED	directed energy deposition
DOE	US Department of Energy
EAL	environmentally acceptable lubricant
EFAS	electric field–assisted sintering
FRPC	fiber-reinforced polymer composite
GTAW	gas tungsten arc welding
INL	Idaho National Laboratory
LCOE	levelized cost of energy
LENS	laser-engineered net shaping
MDF	Manufacturing Demonstration Facility
NPD	non-powered dam
NREL	National Renewable Energy Laboratory
O&M	operations and maintenance
ORNL	Oak Ridge National Laboratory
PBF	powder bed fusion
PNNL	Pacific Northwest National Laboratory
PSH	pumped storage hydropower
SBIR	Small Business Innovation Research
SLIC	Superhydrophobic Lubricant Infused Composite
SNL	Sandia National Laboratories
TRL	technology readiness level
WAAM	wire arc additive manufacturing
WPTO	Water Power Technologies Office

EXECUTIVE SUMMARY

Hydropower is a well-established industry that has been largely contributing to the global generation of clean and renewable energy for more than a century. In the United States in 2021, it accounted for 30% of all renewable energy generation and 6.1% of the total energy portfolio.[1] Hydropower technology and designs have been optimized throughout the years, but manufacturing of hydropower components still relies heavily on traditional methods and materials. Changes in global energy production systems and international supply chain issues are inspiring the manufacturing sector to reconsider their processes. Similarly, the hydropower industry is facing manufacturing challenges stemming from well-known maintenance issues, environmental impact mitigations, and changes in operations. These challenges, along with continued innovation in new hydropower and pumped storage development and modernization of the fleet, present an opportunity for advanced manufacturing and materials (AMM) to provide immense value to the hydropower industry.

In support of the US Department of Energy's (DOE's) Water Power Technologies Office (WPTO), this report aims to characterize the current and emerging manufacturing-related challenges in US hydropower and to identify the high-impact opportunities in AMM that could address these challenges. The results highlighted in this report were collected through literature review, individual stakeholder interviews, and an in-person workshop organized at DOE's Oak Ridge National Laboratory Manufacturing Demonstration Facility that brought together hydropower industry stakeholders, advanced manufacturing R&D, and the government.

Figure ES-1. Summary of AMM for hydropower challenges and example opportunities.

As illustrated in Figure ES-1, the challenges were categorized by those attributed to maintenance of the existing fleet and those for new hydropower development. Aging of the existing hydropower fleet is sparking the need for upgrades and more frequent repairs and replacements of components, such as legacy

[1] https://www.eia.gov/tools/faqs/faq.php?id=427&t=4 (accessed February 22, 2023).

parts that might no longer be procurable. These maintenance activities are technically challenging and extremely costly, especially for large projects, mostly because of revenues lost during required shutdowns. New hydropower projects, such as non-powered dam retrofits for hydropower production, powering conduits/canals, small new stream reach facilities, closed-loop pumped storage hydropower, and environmental mitigation measures, will require technologies and designs that lower costs and improve performance. Future hydropower trends, such as increasing flexibility to enable integration of variable renewables, will likely introduce additional challenges for both the existing fleet and new developments. Additionally, recent global supply chain disruptions affect the manufacturing sector at large, including hydropower. Recent analyses (Uría-Martínez et al. 2022) demonstrate that procurement and/or manufacturing of large metal components, which are essential to the hydropower industry, are currently impossible in the United States, and reliance on international suppliers places the fleet at risk.

State-of-the-art AMM opportunities that were identified as applicable to hydropower include the following:

Additive Manufacturing

Constructing parts layer by layer enables unconventional geometries and material configurations for hydropower components. Additive technologies provide many benefits, including design optimization and the ability to potentially manufacture parts on site, thus increasing accessibility to necessary parts. Embedded sensors, aeration, and cooling channels are some potential hydropower applications.

Novel Machining and Casting Processes

Hydropower facilities rely on large metal components (e.g., turbine blades and wicket gates) with unique geometries and material properties. These components require large casting processes (>10 tons) that are currently mainly performed outside of the United States. Combining additive and subtractive techniques into a hybrid process can enable faster production and higher-quality parts by avoiding supply chain bottlenecks and reducing manual interaction.

Innovative Materials

To enable new value propositions for hydropower, the industry needs lower cost and/or higher performance alternatives for plant components. For example, functionally graded materials could help optimize the surface and bulk properties of runners, and fiber-reinforced polymer composites could help reduce conveyance costs for new facilities.

Novel Coating Processes

Coatings can help mitigate many of the common failure modes for hydropower systems, including biofouling, corrosion, and cavitation. New coatings and application processes can reduce toxicity and improve durability of conventional alternatives.

These technologies provide a variety of value propositions compared with conventional alternatives, including:

- Reducing operations and maintenance costs
- Reducing lead time and capital cost
- Increasing the design space
- Reshoring and increased availability
- Informed decision-making
- Validation and certification for commercial adopters
- Increasing worker safety and satisfaction
- Environmental improvement and risk reduction
- Improving component or system performance

Existing AMM capabilities were mapped to the identified hydropower challenges with the goal of stimulating future ideas, investment prioritization, and collaboration. For example, the existing hydropower fleet could benefit from advanced techniques and materials that enable in situ repairs and replacements, decreasing time and costs for maintenance, refurbishment, and overhaul projects. In contrast, AMM might enable new advanced designs and the adoption of innovative materials with real-time monitoring and control, opening new frontiers for small hydropower, conduit, and pumped storage facilities. Future R&D support and collaboration will be needed across industry, academia, and government to foster commercialization and deployment.

The in-person workshop also identified several key needs that extend beyond R&D investment. These include **workforce development, data collection and dissemination, industry advisory groups, standards development, and expanded testing capabilities**. Many of these needs target the challenges related to first adoption that are ubiquitous for innovations in hydropower, and others address having the expertise and data needed for informed decision-making. Findings from this report, the workshop, and engagement with industry and other stakeholders will help drive and inform future investments made by DOE and WPTO to support advanced manufacturing and hydropower.

INTRODUCTION

This report is sponsored by the US Department of Energy (DOE) Water Power Technologies Office (WPTO). The purpose of this report is to identify high-impact opportunities in advanced manufacturing and materials (AMM) that address critical challenges for hydropower in the United States. This report includes extensive feedback from stakeholders in the hydropower and advanced manufacturing industries, mostly collected through targeted interviews and during an in-person workshop organized at the Oak Ridge National Laboratory (ORNL) Manufacturing Demonstration Facility (MDF). The MDF is one of the DOE Advanced Materials and Manufacturing Technologies Office (AMMTO) Consortia[1] that bring together stakeholders to address process and technological challenges. The main takeaways are incorporated throughout the report, and a full workshop summary is provided in Appendix A. The findings of this report may support future programmatic initiatives by WPTO aimed at supporting hydropower manufacturing innovation through the establishment of R&D collaborations among industry, academia, and government. This report is specifically targeted at the hydropower community, as well as the advanced manufacturing industry and researchers to encourage more direct collaboration for jointly addressing the manufacturing challenges and stimulate hydropower innovation.

1.1 BACKGROUND

Hydropower, or hydroelectric power, is a renewable source of energy that generates power by converting the potential energy stored within a water head—the elevation difference between two water bodies. This elevation difference is typically created by a dam or diversion structure to alter the natural flow of a river or by harnessing the geography of a specific site (i.e., natural change in elevation of a river). Water is a fuel that "is not reduced or eliminated in the process," so hydropower energy relies on "the endless, constantly recharging system of the water cycle."[2] The potential energy is transformed into mechanical energy first through highly efficient hydraulic turbines and then by being converted into electricity through generators. Pumped storage hydropower (PSH) is a type of hydroelectric energy storage consisting of two water reservoirs at different elevations. In PSH systems, the upper reservoir is recharged by pumping water from the lower reservoir during low energy demand (i.e., using electricity when the cost is low), and then energy is generated by discharging from the upper reservoir through hydraulic turbines to meet the grid's demand (i.e., generate electricity when the price is higher). PSH acts similarly to a natural battery in that it can store power and then release it when needed. According to the *2021 Hydropower Market Report* (Uría-Martínez, Johnson, and Shan 2021), PSH accounts for 93% of all utility-scale energy storage in the United States. The United States currently has 43 PSH plants and has the potential to add enough new PSH plants to more than double its current PSH capacity.

Hydropower plays a leading role in the US energy mix, accounting for 30% of US renewable power generation in 2021.[1] Hydropower was first introduced in the United States in the late 1800s; additional hydropower capacity was gradually added through the 1930s and experienced rapid growth from the 1940s through the 1960s. Uria-Martinez, O'Connor, and Johnson (2014) report that this trend reflects the overall electric industry trend for supply changes. During the mid-1960s through the 1980s, overall hydropower growth slowed because of the introduction of new environmental legislation (e.g., the National Environmental Policy Act, Endangered Species Act, and Clean Water Act). At the same time, small hydropower grew thanks to federal investment in R&D and the introduction of avoided cost rates, while PSH grew to help complement the rapid growth of nuclear power. Although the *2014 Hydropower Market Report* covers only the period through 2013 (Uría-Martínez, O'Connor, and Johnson 2014), the overall capacity additions during the 2010s did not significantly change from 2014 to 2019. Along these lines, the *2021 Hydropower Market Report* (Uría-Martínez, Johnson, and Shan 2021) states that a total of

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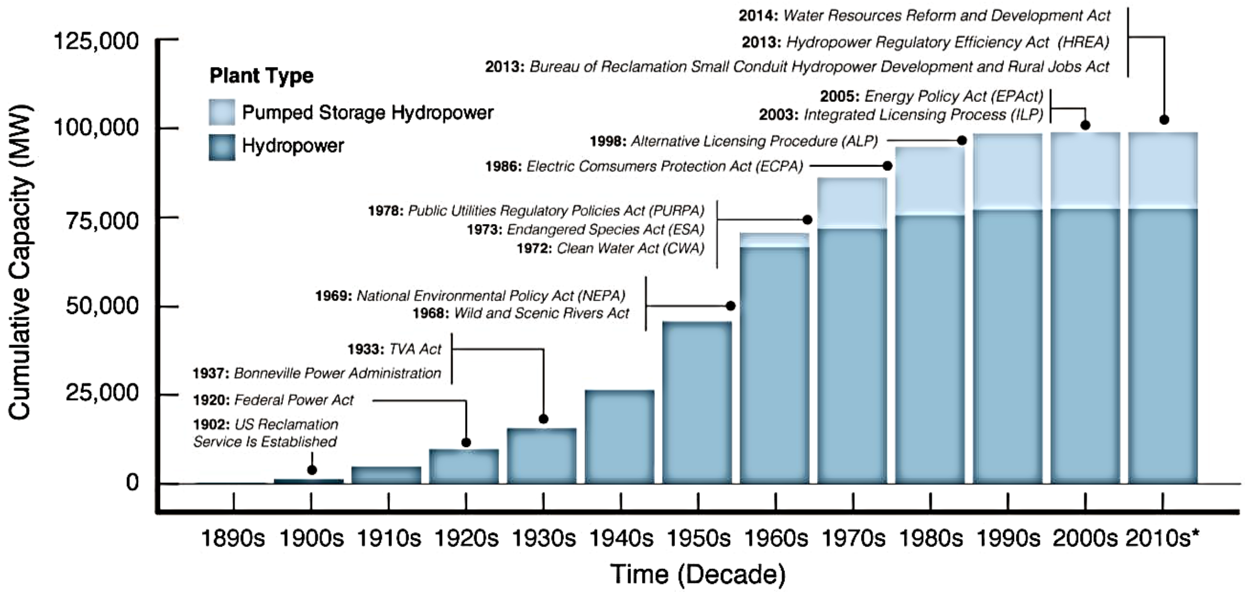
[1] https://www.energy.gov/eere/amo/research-development-consortia.
[2] https://www.energy.gov/eere/water/how-hydropower-works.

1,688 MW of hydropower capacity was added from 2010 to 2019, much of which was additions to existing facilities, and that 1,333 MW of PSH capacity was added during the same period. Figure 1 shows the installation of US hydropower over time, along with various major legislative and institutional milestones relevant to overall trends.



*Data for the 2010s only cover 2010-2013.

Source: NHAAP

Figure 1. Hydropower installation timeline and major legislative and institutional milestones. (Uría-Martínez, O'Connor, and Johnson 2014).

Despite the overall small increases in hydropower and PSH, Uria-Martinez, O'Connor, and Johnson (2014) note recent decades as exhibiting low growth but promising future growth. Overall hydropower growth in future years is likely to be spurred by increased efficiencies in the overall licensing process, including recent regulatory changes to improve the powering of federal dams, canals, and conduits. At the end of 2021, 130 new hydropower projects with a combined additional capacity of 1,500 MW were in the development pipeline (Figure 2). These are projects that have a pending or issued preliminary permit, have a pending or issued license, or are under construction (Johnson and Uría-Martínez 2022). Of the projects in the pipeline, 96% are from powering non-powered dams (NPDs) and expanding existing facilities (Hadjerioua, Wei, and Kao 2012; Hansen et al. 2021). More detailed background information on hydropower manufacturing is provided in Section 2.

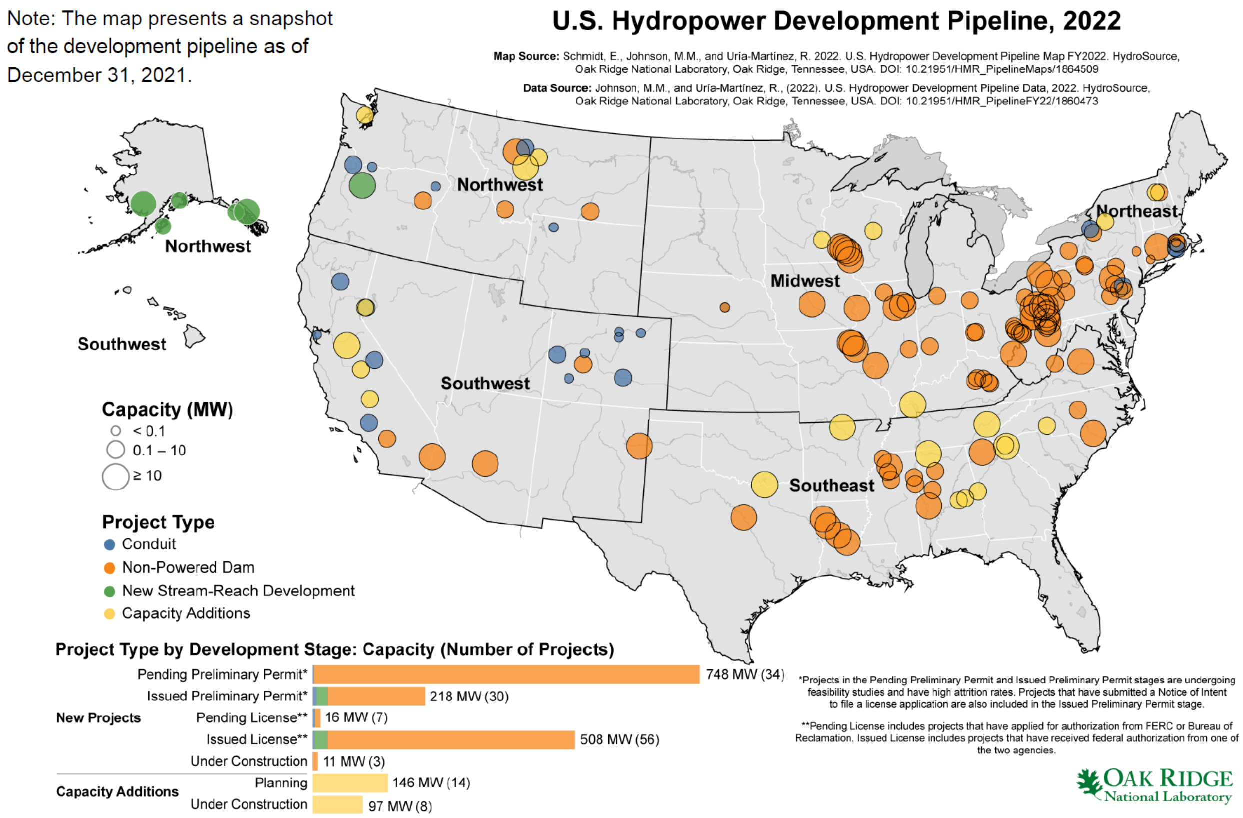


Figure 2. Snapshot of the development pipeline as of December 31, 2021. Original figure from (Johnson and Uría-Martínez 2022).

1.2 MOTIVATION

Hydropower is a clean, reliable energy source with tremendous benefit to the United States, both economically and in terms of grid reliability. Despite hydropower having a long history and being well established, there is still untapped potential and opportunity for growth in the United States. For example, only 3% of the 91,000 dams listed in the National Inventory of Dams[3] are hydropower plants; adding hydroelectric generation capabilities to the remaining NPDs "could add 4.8 GW of reliable, renewable electricity to the grid by 2050," as highlighted by WPTO in its hydropower vision report (US Department of Energy 2016). PSH is the largest contributor to US energy storage at the grid scale, representing about 93% of all commercial storage capacity in the United States (as of 2021), and an additional 35 GW of new PSH is potentially feasible with innovations, including grid and manufacturing innovations. Given the state of hydropower development in the United States, future capacity additions are likely to come through expanding, repairing, or rehabilitating existing hydropower assets, as well as retrofitting NPDs and other water infrastructures (e.g., conduits). In addition, new stream reach development (i.e., pristine sites where hydropower has not yet been developed) is also possible (Kao et al. 2014).

Additionally, existing hydropower facilities require upgrades and maintenance, and all hydropower technological areas have critical supply chain concerns; these challenges can be addressed through advanced manufacturing innovations. DOE published *America's Strategy to Secure the Supply Chain for*

[3] https://nid.sec.usace.army.mil/.

a Robust Clean Energy Transition[4] in response to Executive Order 14017, "America's Supply Chains."[5] The strategy highlights casting and forging supply chains as a major US security concern for hydropower technologies, in addition to wind and nuclear energy. There is a lack of domestic manufacturing for large-scale components in the United States, which causes risk and reliance on other countries, as well as increased costs associated with tariffs, logistics, lead time, and even increased carbon footprint.

To meet the energy deployment goals and ensure energy security and resiliency, enabling a reliable domestic supply chain for hydropower is crucial. In particular, the *Hydropower Supply Chain Deep Dive Assessment* (Uría-Martínez et al. 2022) includes a specific analysis of supply chain issues associated with hydropower. The report demonstrates that steel (carbon or stainless) and copper are the main materials used for the most crucial components, which include turbines, generators, governors, excitors, switchgears, emergency closure systems, and penstocks. Most of these components are custom made; thus, replacements typically require long lead times ranging from months to years. Turbine manufacturers play the role of central hub in the hydropower supply chain by producing turbine runners, generators, and other components through a global set of joint ventures and subcontractors. Existing plants rely on those manufacturers for new components and on machine shops for acquiring existing mechanical components and reverse engineering pieces whose manufacturers no longer exist (i.e., legacy parts).

As shown in (Uría-Martínez et al. 2022), small plants (≤30 MW) are supplied by a diverse set of manufacturers (more than larger units), yet Andritz, GE Renewable Energy, and Voith are still the largest global turbine suppliers, accounting for almost 50% of the installed global turbine nameplate megawatt capacity (in the United States, their share reaches almost 75%). Since 2000, the United States has had a net balance of imports and exports of turbines and related components. However, the industry is currently facing major challenges related to component and workforce supply, specifically the following (as summarized by Uría-Martínez et al. (2022)):

- Large (>10 tons) steel castings and forgings cannot currently be procured for turbine runners and other components from US foundries. Large castings are mostly supplied by steel foundries from Brazil, China, Eastern Europe, and South Korea.
- Windings for large unit generators (>10 MW) are highly difficult to procure domestically. Very few OEMs supply large generators and their components, which typically come from Canada, Mexico, Brazil, and Europe.
- A shortage of material and components for electronics (microchips and digital components—primarily produced in Asia) is affecting multiple hydropower subcomponents. Some plants owners pay a premium for electronic components produced domestically in the United States to avoid global shortages and shipping bottlenecks.
- Concern is rising for workforce availability in hydropower extending from personnel needed for on-site operations to manufacturing and construction.
- Turbine-generator OEMs have expressed concerns regarding increasing bottlenecks for large castings, large windings, and workforce limitation in response to a potential significant growth in US demand for hydropower components. Demand could grow because of the increasing need for refurbishment and upgrades, growth in NPD retrofits, and new PSH construction.

Finally, Uría-Martínez et al. (2022) highlight that unlike mechanical and electrical components, most of the materials and services for the construction of civil works and other structures are met by US companies. However, changes in prices for raw material such as cement and grout could change this.

[4] https://www.energy.gov/policy/securing-americas-clean-energy-supply-chain.
[5] https://www.whitehouse.gov/briefing-room/presidential-actions/2021/02/24/executive-order-on-americas-supply-chains/.

Hydropower and PSH innovation to decrease full life cycle costs, increase existing fleet reliability and performance, and enable a US supply chain for components can be achieved through lower-cost, higher-performance materials, designs, and next-generation manufacturing systems. Musa et al. (2022) identify advanced manufacturing as a crucial opportunity for hydropower innovation and a recommended target area for investment.

The recently published DOE *WPTO Multi-Year Program Plan* (US Department of Energy 2022) identifies the following activity, challenge, approach, intermediate outcome, and long-term outcome related to hydropower growth via manufacturing-related activities (Figure 3).

Figure 3. *WPTO Multi-Year Program Plan* logic model for hydropower growth. Adapted from (US Department of Energy 2022).

In this sense, the findings of this report and the related workshop fit within WPTO's long-term goals (2026 to 2030) to enable "technology developers [to] actively pursue and apply high-impact advanced manufacturing opportunities for hydropower applications" (US Department of Energy 2022). While AMM for hydropower falls within the low-impact hydropower growth activity area within WPTO, this goal applies to both technologies that enable new low-impact hydropower facilities and those that modernize the existing fleet, as highlighted by Figure ES-1 in the Executive Summary.

1.3 METRICS AND DRIVERS FOR HYDROPOWER DEVELOPMENT

Specific metrics must be identified and/or developed to consider the potential opportunity of the innovative ideas developing in hydropower and the potential adoption of novel manufacturing processes and materials. Here, some of the typical metrics used in hydropower research and deployment are briefly discussed. However, several considerations advance hydropower technology deployment, depending on the specific task; therefore, this list is not exhaustive. Conventional metrics include the following:

1. **Levelized cost of energy (LCOE):** LCOE is an estimate of the current year price of electricity, given all assumptions in estimating costs and energy generation (e.g., efficiency, capacity factor, inflation rate, and interest rates) necessary for the project to break even at the end of its lifetime. LCOE is only one of many factors, including net present value and internal rate of return, but is the most commonly used measure of the potential economic viability of a project. Although there are different methods for calculating LCOE, it can be described succinctly as the lifetime costs of the plant, including construction, operation, and maintenance, divided by the lifetime energy production, as illustrated in Figure 4. LCOE is a parameter used to compare the cost of energy generated by different resources/technologies.

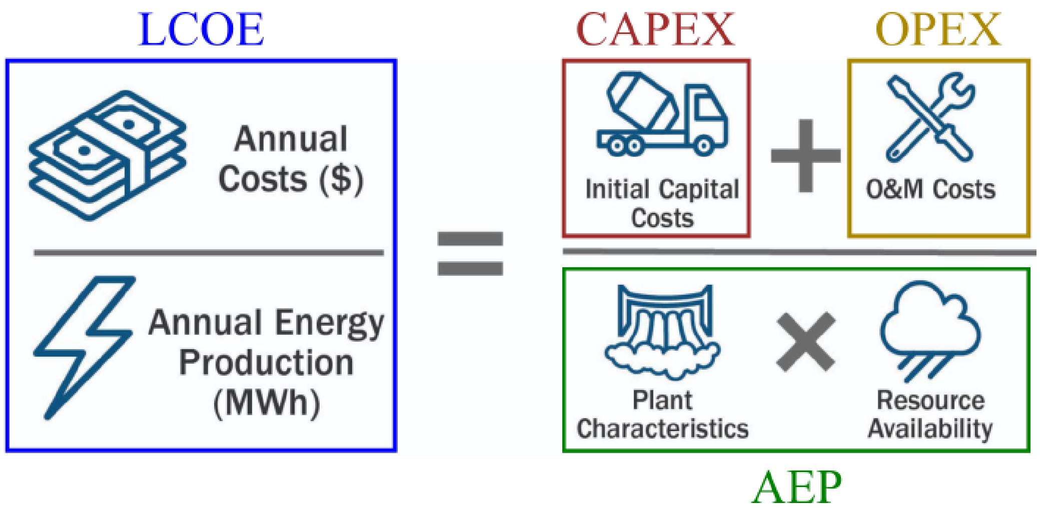


Figure 4. Key components and calculation of LCOE. CAPEX: capital expenditures; OPEX: operations and maintenance expenditures; AEP: annual energy production. Adapted from DOE's I AM Hydro Prize.[6]

LCOE provides a comprehensive, yet accessible, tool for evaluating the role of any innovation in hydropower and can thus be extended to advanced manufacturing. At a high level, the effects of advanced manufacturing on LCOE would be reflected in the items on the right side of Figure 4, reducing the numerator, thus the capital expenditures and the operations and maintenance (O&M) expenditures, and increasing the denominator, thus by improving the plant efficiency and increasing the annual energy production.

2. **Construction and maintenance time:** Time in manufacturing typically translates to costs, either directly or in terms of loss of revenue. The construction of a dam and all the associated civil structures is often the most time-consuming aspect of a hydropower project, generally requiring initial construction of a cofferdam, site excavations, and actual building of the dam. The construction time for conventional hydropower facilities can vary significantly from a year to more than a decade depending primarily on project size and complexity. The typical construction time for small-scale hydropower plants is less than 4 years. Conversely, maintenance operations and/or replacement often require the power generation to be temporarily shut down, thus causing significant loss of revenue. Maintenance checks can be less than an hour, whereas major maintenance operations could be as long as 6 months to a year, involving one unit or sometimes even the whole power plant. The lead time (i.e., the time between the demand initiation and the supply completion) for a turbine runner (for new developments or upgrades) can sometime reach more than a year.

3. **Project development risk:** Hydropower requires huge investments and long development periods because of site-specific considerations that expose hydropower to uncertainties and risks. These risk factors, if not managed, lead to schedule and cost overruns that cause delays in the availability of power, which can increase LCOE and, in extreme cases, lead to project failures (Shaktawat and Vadhera 2021). To evaluate new hydropower projects and techniques and pursue sustainable development of hydropower, these risks must be assessed and minimized throughout the life cycle of the projects.

4. **Scalability and applicability:** Scalability and applicability of new techniques are features that might significantly increase the number of potential solutions for resolving various problems in systems design and operation while also creating space for new solutions. Key to this is the scalability of the

[6] https://americanmadechallenges.org/challenges/iamhydro/index.html.

designs and the manufacturing processes involved in implementing the techniques. Scalable solutions are needed for a range of capacities and a variety of use cases to achieve implementation and economic and environmental benefits.

5. **Market size:** This refers to the total number or value of potential buyers or application areas for a product or innovation. Knowing the potential market size before launching a new technique or product line of business is paramount to evaluate whether the investment is worthwhile.

6. **Environmental sustainability:** Hydropower growth significantly slowed after the introduction of important environmental legislature from 1960 to 1980. These legislations made sure that environmental impacts were accounted for during the design of any new hydropower plant with the goal of protecting local ecosystems. Environmental sustainability has since become a crucial metric to evaluate any innovation.

7. **Technology readiness level (TRL):** This parameter is used to estimate the maturity level of a particular technology and can help management make decisions about the development and transitioning of technology. TRL is based on a scale from 1 to 9, with 9 being the most mature technology (Figure 5). Several advantages can be obtained from TRL metrics, such as providing a common understanding of technology status and risk management, to make decisions concerning technology funding and transition of technology. TRL could describe the ability of a specific technology to be accepted by stakeholders, which includes the design efficacy as demonstrated through modeling, simulation, testing and validation, and the overall readiness to commercialization.

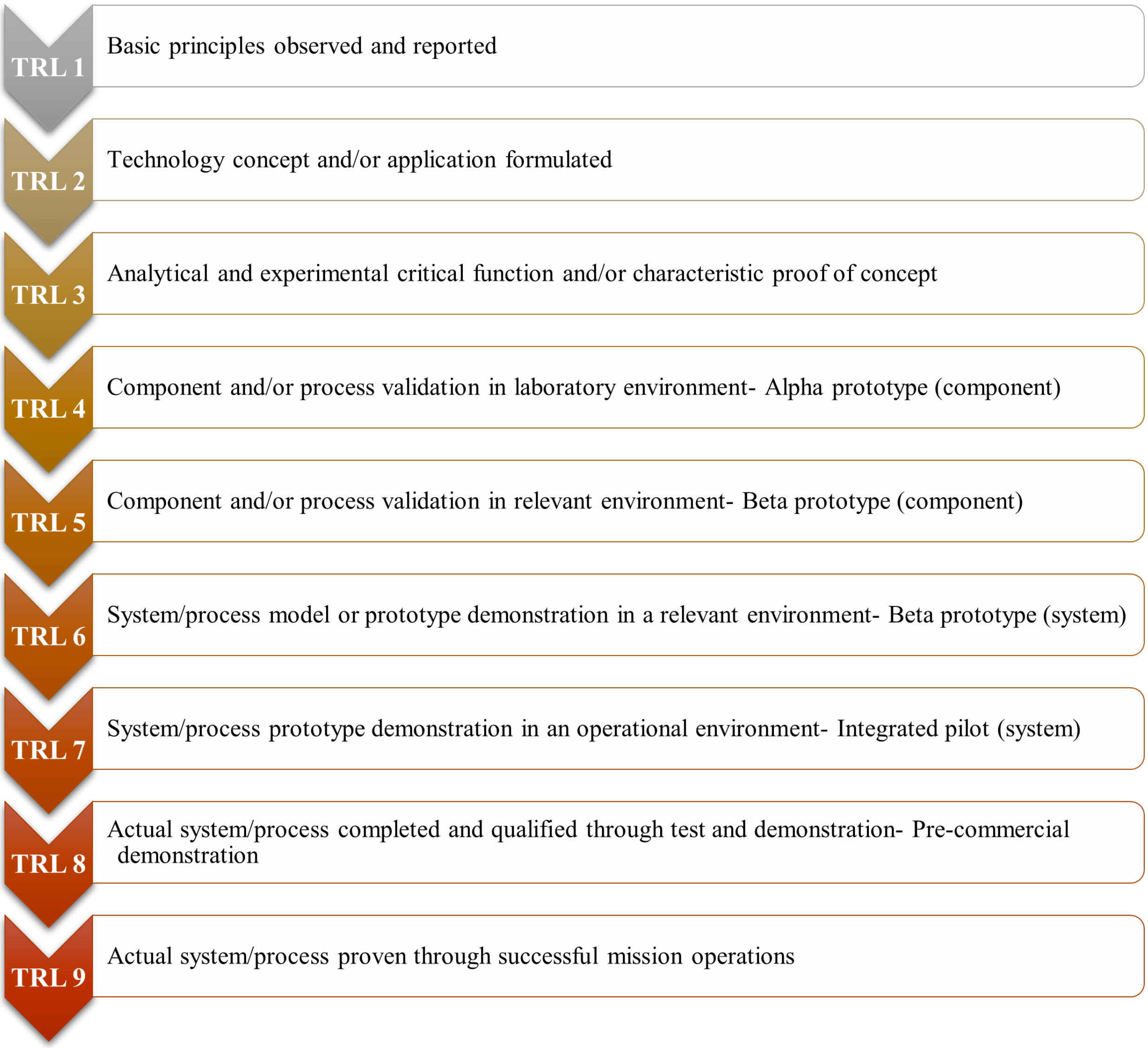


Figure 5. TRLs. Original figure from (Musa et al. 2022).

AMM innovations can target multiple aspects of the LCOE equation for hydropower, as well as other key metrics beyond LCOE such as time, risk, supply chain, and sustainability. Specific objectives to targeting these metrics for enabling and adopting AMM for hydropower include the following:

- *Manufacturability and scalability of materials and processes*, including scale-up of novel materials, coatings to perform in real-world environments, the capability to manufacture complex geometries for hydropower, and the capability to scale up next-generation manufacturing systems and components. This requires modeling and simulation, in situ monitoring during manufacturing, and prototyping and full-scale testing. As an example, one way to achieve scalability can be through standard or modular design concepts, such as those described by Smith et al. (2017) and Witt et al. (2017). This can also include design for manufacturability, transport, and ease of assembly in the United States, targeting capital and construction costs.
- *Strengthening the US supply chain* for specific large-scale metal components for hydropower, referring to the capability to manufacture and procure a specific technology, given the physical design constraints and supply chain constraints (Kurup et al. 2018; Uría-Martínez et al. 2022). This includes

elements of the previous point, requiring decreasing labor and production time to be competitive, and reshoring/creating US jobs. It also includes more modular designs for logistics and transport for specific components, as well as capabilities for on-site fabrication. The time and cost to manufacture and procure equipment carry implications for overall deployment success. Enabling US supply chains for large metallic components is not unique to hydropower or even renewables, such as wind energy, and it crucially affects US energy and security broadly (e.g., nuclear and defense; see, for example, (US Department of Defense 2022)). Therefore, the hydropower industry likely cannot resolve challenges in this area independently and may require a coordinated effort from industry, government, and academia. [7]

- *Quality control and tools for risk mitigation* and increasing certainty in components and decreasing technology failure. In the context of manufacturing, this includes in situ monitoring during manufacturing and digitalization in manufacturing to enable "born-qualified components." This could also include considering O&M upfront through improved material selection and monitoring during manufacturing and operation. Embedded sensors and other tools enable structural health monitoring, where operators continuously assess the life of the components leading to decreased downtime and unplanned maintenance, as well as improved overall performance.
- *Decreasing labor and production or cycle time* for manufacturing and materials processes. This targets capital costs and could include topology optimization (designing optimized structures for specific design parameters, such as available materials and cost, or enabling complex designs) and new systems that rapidly enable production capability.

1.4 STAKEHOLDERS AND PARTNERSHIPS

To accelerate the development of advanced manufacturing R&D and technologies for hydropower in the United States, government, industry, and academia must create effective partnerships to provide capabilities, resources, and knowledge toward common goals. Figure 6 conceptually describes the "triple-helix" strategy for partnering among these stakeholder groups. AMM technologies, which include materials and systems, must be moved from lower TRLs, or more fundamental R&D at universities and national and private labs, to a higher TRL for industry (small, medium, and large enterprises) to adopt.

DOE promotes strategic investment in the transition to a cleaner, domestic, more secure energy future by funding high-risk, high-impact research and technologies that industry cannot commercialize on its own. One way DOE enables this change is by leveraging national laboratory capabilities and investments into user facilities to support partnerships and research collaborations with universities and industry. Furthermore, DOE is invested in stakeholder engagement. To inform this report, a workshop was organized at ORNL's MDF in August 2022. The workshop brought together the main contributors of hydropower manufacturing research, development, and deployment from industry, academia, and government (key takeaways are reported in Section 4, and a summary is included in Appendix A). This report summarizes the current technology needs and opportunities, which will evolve over time as the triple-helix partnerships advance.

To address manufacturing needs and the supply chain issue, DOE's AMMTO has supported the development of R&D consortia[1] that bring together manufacturers, businesses, researchers, and the government. The consortia use federal funding to address high-priority R&D projects in the areas of clean energy manufacturing, industrial efficiency, and decarbonization. ORNL's MDF is a key part of the consortia and is supported and managed by AMMTO.

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[7] https://www.whitehouse.gov/briefing-room/presidential-actions/2021/02/24/executive-order-on-americas-supply-chains/.

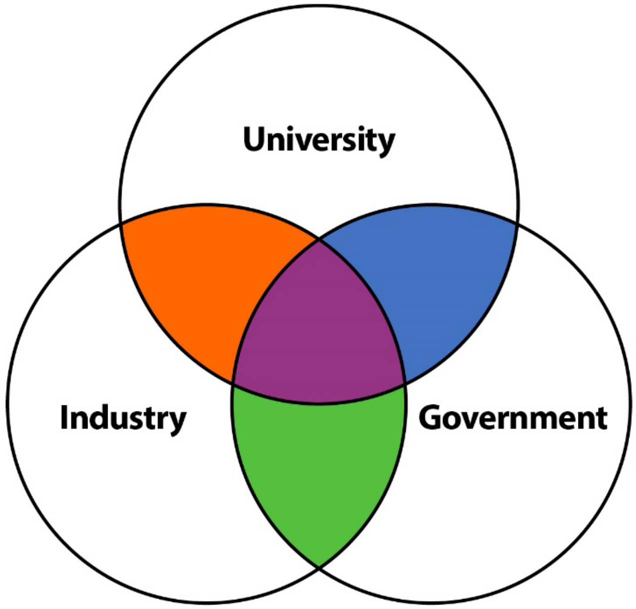

Figure 6. Triple-helix strategic interactions.

1.5 SCOPE AND OBJECTIVE OF THIS REPORT

This report is intended to cover the full breadth of manufacturing related to the hydropower industry. Its findings were ascertained through literature review, hydropower and advanced manufacturing expertise, and stakeholder engagement. This report provides the hydropower industry and manufacturing stakeholders with information relevant to each industry to help inform future advancements related to hydropower manufacturing. The results of this report directly support WPTO's objectives to develop an R&D strategic planning for follow-on activities.

The rest of this report is organized into the following sections:

- Section 2 provides an overview of current manufacturing processes and materials in hydropower and discusses current and emerging challenges related to hydropower manufacturing.
- Section 3 presents current and future state-of-the-art developments in advanced manufacturing and their potential for hydropower applications.
- Section 4 summarizes potential opportunities that advanced manufacturing technologies can offer to help address current and emerging hydropower challenges, as informed by the key takeaways from the Advanced Manufacturing for Hydropower Workshop and engagement activities conducted in support of this report's development.
- Section 5 provides conclusions and potential next steps related to hydropower manufacturing R&D promoted by WPTO.

2. CURRENT AND EMERGING CHALLENGES FOR MODERN HYDROPOWER MANUFACTURING

2.1 STATE OF THE INDUSTRY: OVERVIEW OF CURRENT MANUFACTURING AND MATERIALS

To better understand the challenges and opportunities associated with future hydropower manufacturing, this section offers an overview of current manufacturing processes and conventional materials used in the hydropower industry. As shown in Figure 7, hydropower and PSH facilities are complex integrations of systems and subsystems (i.e., the hydropower technology landscape) that require an interdisciplinary and hierarchical treatment to understand their design, function, and manufacturing. For the context of this report, the suite of hydropower physical equipment is subdivided into four main categories, as inspired by (Musa et al. 2022): (1) *hydraulic powertrain (i.e., turbines and generators);* (2) *pressurized conduits, gates, and valves;* (3) *structures and foundations*; and (4) *electrical interconnection and instrumentation and controls*. A technology is categorized according to its position within an equipment hierarchy specification for a hydropower facility. Each of these major hydropower systems can be disaggregated into components according to one of several hydropower equipment hierarchies (O'Connor et al. 2015). This characterization is not absolute and was chosen to create categories that might share similar manufacturing processes and materials, tests, and modes of failure; a different scope and/or audience might choose to categorize hydropower technologies in a different way.

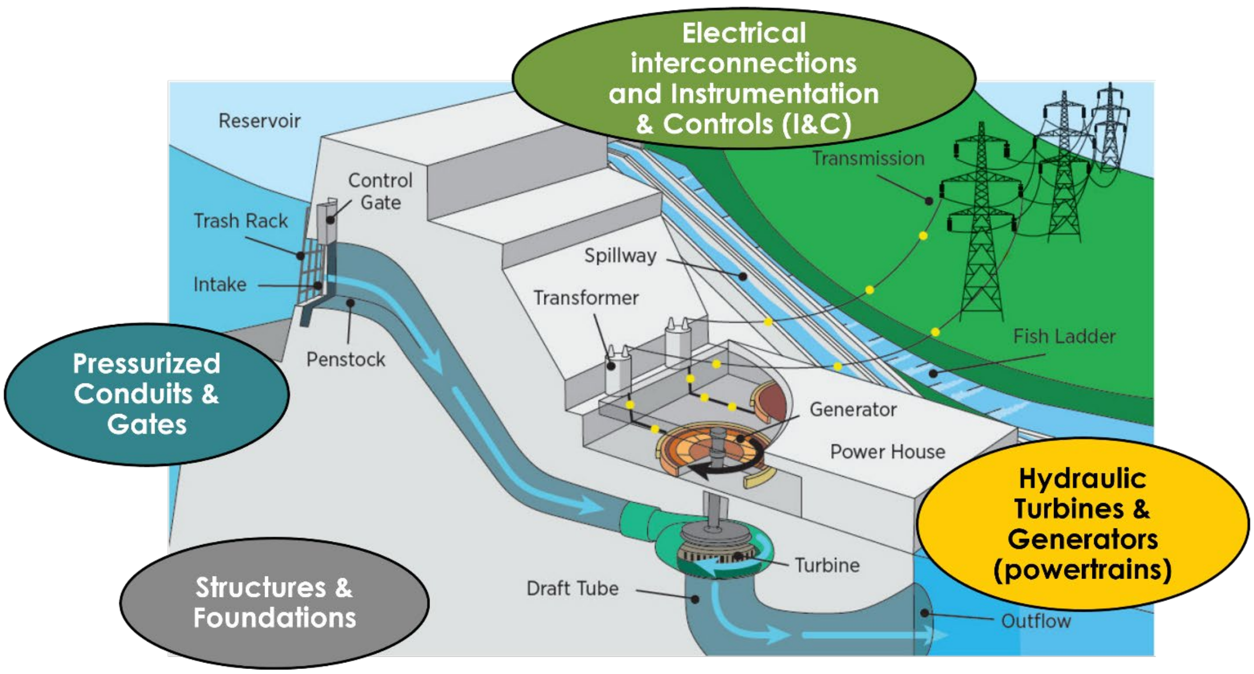

Figure 7. Schematic of a traditional hydropower plant. Source: adapted from https://www.energy.gov/eere/water/types-hydropower-plants.

2.1.1 Manufactured Components of the Powertrain System

Powertrain is the system of mechanical and electrical machines that convert hydraulic potential energy into electricity. In general, baseline powertrain technology includes the following six main components: hydraulic turbine, generator, main shaft, thrust bearing, wicket gates, and governor control system (Figure 8).

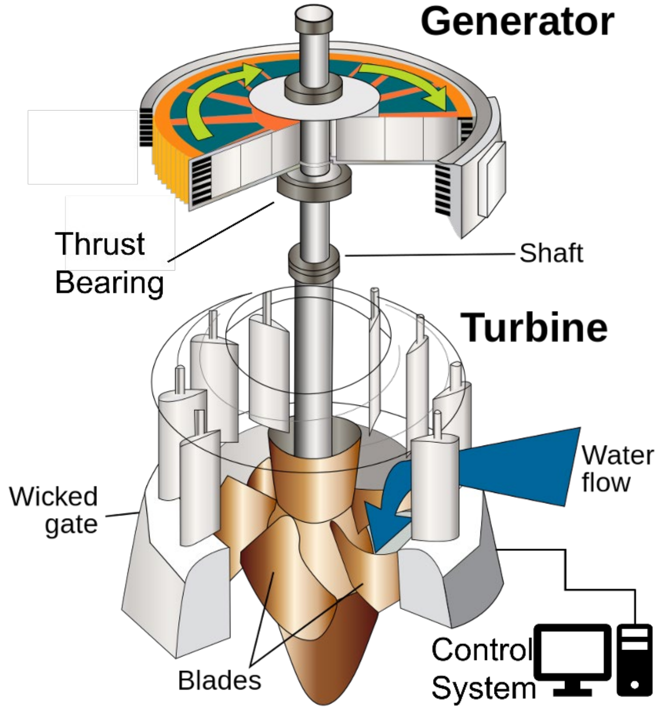

Figure 8. Schematic plot of the powertrain system. Source: adapted from PNGWing.com.

Within the powertrain, the hydraulic turbine and associated flow control components, including needle valves, wicket gates, operating ring, and servomotors, are the major mechanical components in the system that convert the potential energy created by the hydraulic head in reservoirs and rivers into rotational mechanical energy to generate electricity. The water flowing through the penstock impinges on the turbine blades causing the turbine to spin around its main shaft, which directly transfers the rotational energy to the generator. The generator transforms the mechanical energy of the turbine into electricity.

Water turbines are divided into two groups: reaction turbines and impulse turbines. Impulse turbines, such as Pelton turbines, are often used in very high-head (>300 m) applications. The turbine torque is created by water jets impinging on the runner buckets attached to the wheel circumference, which operates in air (i.e., at near-atmospheric pressure); the water jets are controlled by needle valves actuating inside the jet and precisely changing the opening area. Reaction turbines are used in low-head (<30 m) applications (where typically Kaplan turbines are used) and medium-head (30–300 m) applications (where typically Francis turbines are used) (Figure 9). The integrated pump-turbine used for PSH is also part of this category. Reaction turbines are fully submerged, and torque is developed by the water pressure against the blades. Flows to the turbine are controlled by the wicket gates that rotate in unison by the operating ring actuated by the hydraulic servomotors.

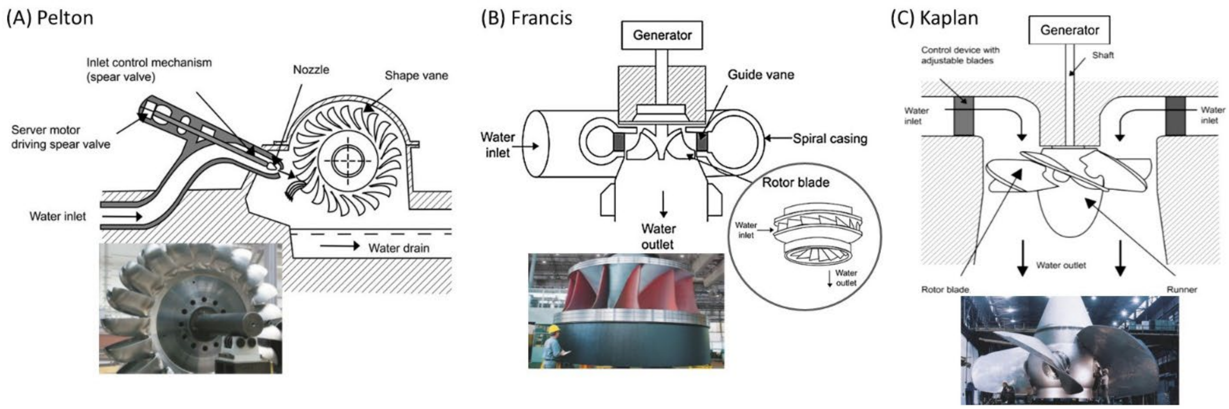

Figure 9. Schematic plots of a (A) Pelton turbine, (B) Francis turbine, and (C) Kaplan turbine. Source: adapted from Wagner and Mathur (2011), with photographs courtesy of Voith Hydro Holding GmbH & Co. KG.

Depending on the hydraulic head, different materials are used for turbine manufacturing (Quaranta and Davies 2022). High-head turbines operate in ranges higher than 300 m and are exposed to high stresses generated by the water pressure and severe fatigue, erosion, and cavitation, all of which lead to potential failure. Therefore, austenitic stainless steel alloys, which have a chromium content of 17% to 20%, are commonly used nowadays to provide atmospheric corrosion and cavitation resistance, which improves the stability of the protective film for a longer life span of the turbine blades. However, turbine designers must balance the performance benefits of stainless steels with the higher costs compared with carbon steels. In some cases, the bulk of the turbine is fabricated with carbon steels and the areas with high probabilities for cavitation/corrosion, such as the blade edge, are plated with stainless steels. Other metals have been used in the past, such as cast iron or bronze for Pelton turbines, but modern turbines tend to use carbon and/or stainless steels to improve operational durability.

On the other hand, low-head turbines operate in the head range lower than 30 m and generally handle slightly smaller stress/pressure issues. Nevertheless, the small power/weight ratio can cause abrasion and fatigue problems because of the heavy weight. Therefore, stainless steel or weathering steels (e.g., Corten steel) are generally used for very low-head turbines. Similar to Pelton turbines, Kaplan turbine blades and internal parts typically used to be cast in iron or bronze but were later cast in carbon steel. Today, casting and fabricating materials include carbon steel or stainless steel. The most commonly used modern material for Kaplan blades is ASTM A487/A743 CA6NM stainless steel, which is lighter but cavitation resistant, fairly easy to cast and manufacture, and can usually be repaired by welding without postheat treatment.

Current methodologies for manufacturing the aforementioned mechanical components still heavily rely on traditional manufacturing technologies for the metal alloys (e.g., stainless steel, steel, and aluminum). The parts in constant contact with the water are typically made with corrosion-resistant materials such as stainless steel and aluminum. This can include castings and forgings for the metal materials, followed by welding, machining, and other finishing processes. For example, hydropower turbines are cast or forged product forms that are machined into the final runner using computer numerical control (CNC) milling machines.

One major challenge for manufacturing new large-scale parts is the lead time associated with procuring the large forgings and castings. Since these are often the first elements required for manufacturing the parts, the remaining steps in the fabrication process follow accordingly. For the past several decades, sourcing these parts often required importing from China, South Korea, Brazil, and Eastern European countries (Uría-Martínez et al. 2022), which is inherently slow and limits the capability for rapid production. Often, larger parts can be built up using plates and other readily available product forms, but this adds a mandatory joining process, typically welding.

Welding can also be time consuming and can introduce undesirable deformation, residual stresses, and discontinuities into parts. Over the past decades, the CNC milling process has made strides in precision and accuracy that significantly improve quality assurance of the components. However, the process is still time intensive and expensive and could benefit from continued improvement on the machine tools and strategies.

In addition to the turbine, the powertrain system also includes the generator, which consists of a rotor, stator windings, and a core. Within the stator winding, mechanical energy is converted into electrical energy by the rotating magnetic field of the rotor past the copper coils of the stator. The rotor typically consists of copper rods mounted together with an insulator to allow desired current flow while preventing unwanted current flow, commonly known as a short circuit. The insulator is one of the most important subcomponents that can withstand voltages without failure and affect reliability. The cross-sectional area and material of the copper conductors, as well as the electrical span of the coils, directly affect the copper losses in the stator. Stator windings are supported by a slotted frame connected to a laminated core, forming a magnetic circuit path for generating voltage from the current flowing through the windings. The core generally consists of a stack of thin sheets of high-permeability steel to reduce core loss. Each lamination is coated with a thin coating of insulating varnish to electrically insulate it from the adjacent laminations and to reduce current leakage in the core.

The technology underlying generators follows the basic principle to generate alternating voltage by the rotating magnetic flux, which is created by direct currents flowing in the rotor. In recent decades, improved materials and enhanced monitoring, evaluation, and design tools have increased reliability and efficiency. Generator shafts are typically made from forgings of materials. Early casting techniques limited the diameter of the shaft to ~36 in. As technology developed, larger diameter and better-quality shafts became possible, allowing for development of integrated thrust runners. Generator rotors were generally designed with a significant margin in operating torque (turbine input power). Therefore, the rotor could be easily reinstalled, and the capacity could be increased without replacement. The design fatigue life of a generator rotor is determined mainly by the material condition and load. Improvements in electrical isolation technology allow for longer life and higher temperature operation with less material (thinner wall) and higher reliability but with the same level of isolation for generators. Early units generally used asphalt or bitumen paint with a mica tape insulation system on the stator windings. Except for mica tape, current technology also uses synthetic epoxy or polyester resins as binders.

2.1.2 Manufactured Components of Pressurized Conduits, Gates, and Valves

All the infrastructures that pass water from the reservoir, over and through the facility, and out into the tailrace downstream of the dam are generally referred to as conveyances. These systems are typically subdivided into those that operate in pressure and those that operate at atmospheric pressure (open-channel flows). This distinction typically leads to a very different choice of materials, with pressurized conduits usually being built with metals and open channels with concrete and rocks (of course exceptions exist). Therefore, for the purpose of this report, open-channel conveyances are discussed with structural components in Section 2.1.3.

Most of the conveyances operating in pressure are typically associated with the generation section of the facility or with controlled water outlets. These conveyances comprise pressurized conduits and pipes, valves, and gates (Figure 10). Every component in this category must sustain elevated pressure levels and thus guarantee high levels of strength, resistance, and water tightness. In particular, the conveyance systems related to generation, thus the components that convey water into and out of the powertrain, include three main components: the penstock, the turbine housing, and draft tube. The penstock connects the intake at the reservoir and delivers water to the turbine and represents the upstream conveyance component. Typically, entrances are protected with trash racks and have control gates installed in front of the uptake channel. For reaction turbines using long penstocks, a shutoff valve is located immediately upstream of the turbine. The water then passes through the scroll case into the turbine runner and exits through the draft tube, outflowing to the tailrace or the downstream river section. An isolation gate is typically located at the outflow location. For impulse turbines, again with long penstocks, a shutoff valve is located immediately upstream of the nozzles; water jets exit through nozzles at high-velocity and impinge on the turbine blades (or buckets) at atmospheric pressure. Since the turbine is at atmospheric pressure, outlet gates are not necessary for isolation.

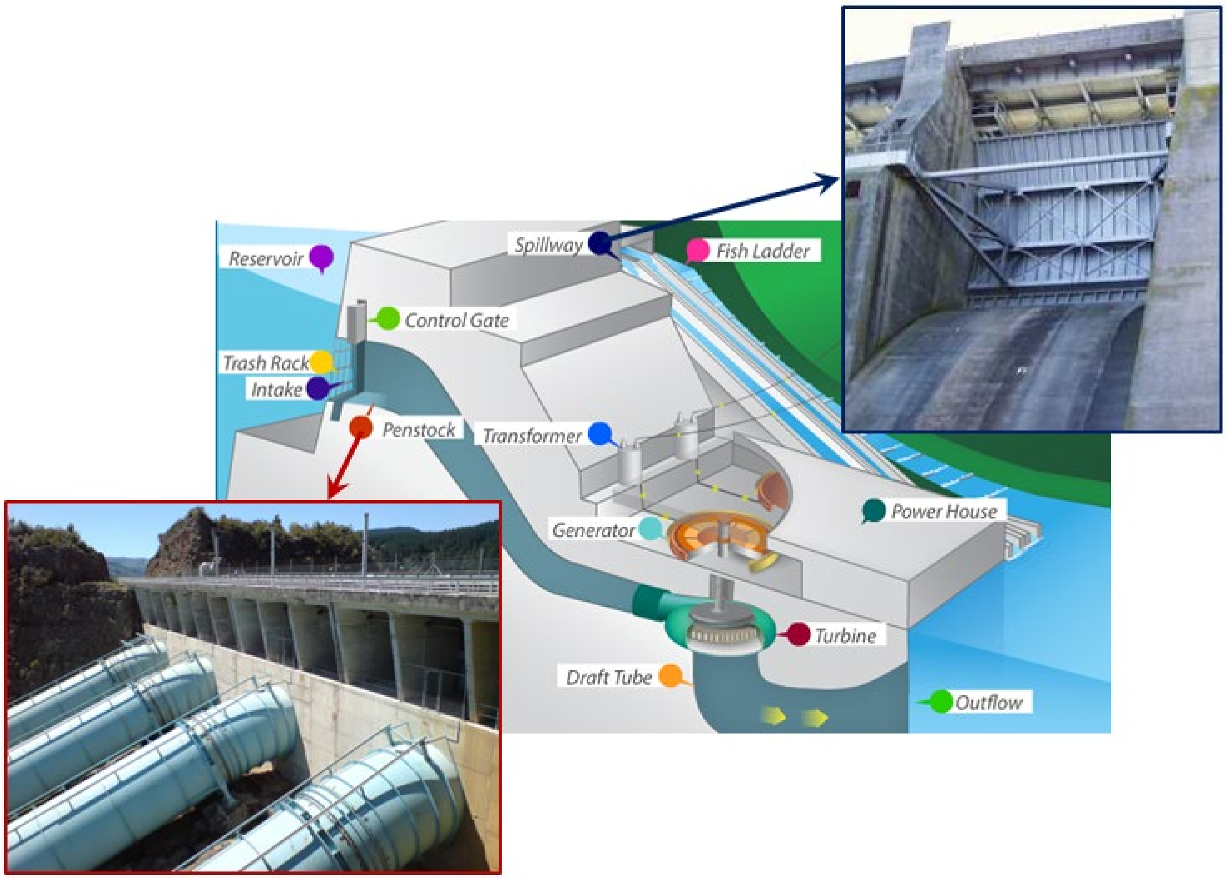

Figure 10. Schematic plot of the hydropower system with components of penstock, spillway, and gate. Source: adapted from DOE.[8]

In any configuration, conveyance system components deal with very high pressure or high water velocity, which is why metal is typically employed, specifically, structural steel. Corrosion-resistant materials are typically cost prohibitive for these parts. These parts are generally made from flat plate stock, which is cut to size and then rolled or formed into the desired (usually round) shape. Parts are typically connected together using bolts, rivets, or welds. These components are typically supported by separate supports or are cast in place using concrete. For economic purposes in long water conveyances, it is common to change material types and wall thicknesses as the pressures increase along the length.

[8] https://www.energy.gov/podcasts/direct-current-energygov-podcast/episode-7-water-wattage.

Over time, traditionally constructed steel penstocks can fail because of excessive material loss from corrosion and erosion. Additionally, deflections and movements can cause unwanted deformations, especially at joint connections and support locations. The hardware used to connect the conveyance parts to each other and to their supports can also fail. However, joints are typically the strong points. Water hammer (i.e., the pressure surge occurring in pressurized conduit when flow is abruptly stopped) and thermal expansion/contraction result in supports being saddled but allowing for movements in line with flow. This said, excessive damage from any of these causes can lead to leakage and undesirable water flow characteristics through the conveyance structure. In extreme cases, leakage can cause additional unintended damage to the surrounding civil structures. However, all these issues might be solved by continuous monitoring and repair of components, which are discussed in detail in Section 2.2.

2.1.3 Manufactured Components of Structures and Foundations

The structures and foundations of hydropower facilities are designed to maintain and support the structural elements, such as the dam structure, powerhouse, foundation sections, and some other larger functional components such as the spillway, tailrace channels, fish passage systems, and energy dissipation aprons.

The dam is the primary component of hydropower structures and foundations. Its main purpose is to hold water and provide hydropower, water supply, recreation, navigation, and flood control. However, dam manufacturing is an extremely complex process that requires a significant amount of labor, materials, and resources. According to their uses, structural types, and materials used, dams can be constructed in many ways. The primary construction designs are gravity (concrete and roller-compacted concrete), embankment (earth- or rock-filled), buttress (concrete), and arch (concrete and roller-compacted concrete); see Figure 11. Conventional materials for dam construction are concrete, steel, rock, and earth. For the construction process, the river is typically diverted away the construction area using cofferdams and several additionally built tunnels, which is one of the most expensive and time-consuming steps of foundation construction. After the dam reaches the desired height, the tunnel used to divert the river is removed, allowing the river to fill the reservoir until it reaches the equilibrium height according to the river discharge. Traditionally, foundations and civil construction are heavily labor intensive and are one of the longest stages of new facility development (DeNeale et al. 2020), and their construction methods have been slow to change (Smith et al. 2017).

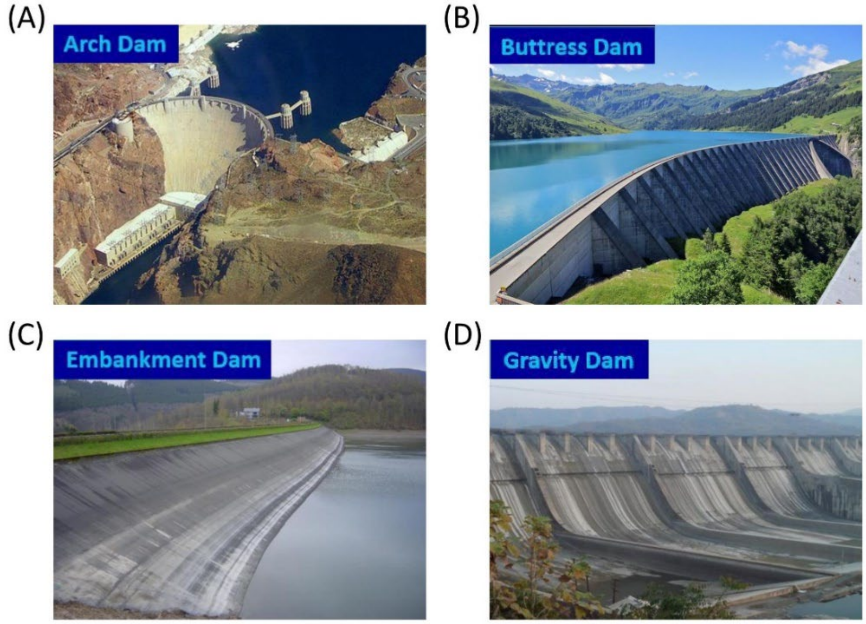

Figure 11. Different types of dams: (A) arch, (b) buttress, (c) embankment, and (D) gravity.

Another important component for hydropower structures is the powerhouse, which contains the powertrain equipment; the stator/rotor/shaft assembly; and the hydropower control equipment, control rooms, automation, control, protection, voltage switchgear, and main gallery with crane equipment for lifting and replacing large equipment. Powerhouses typically consist of several floors, mainly because of the vertical extent over which the powertrain equipment spans and connects to the main dam near the lower levels and houses the turbine and runner assembly. Powerhouses are generally constructed of steel-reinforced concrete with significant structural treatment to support the heavy loads. Structural steel beams comprise the support for interior crane assemblies. As with dams, the manufacturing process also relies on labor and traditional construction machines.

Other crucial structures are part of conveyance systems for generation, flood control, environmental flows, and the passage of all the other constituents forming the river environment, including fish and sediments.

For flow control, the passage of water can occur over the structure (open-channel flow) or through it (closed-conduit flow). This passage can be defined as either controlled or uncontrolled flow, depending on the presence of gates. Uncontrolled water passage occurs based on the reservoir achieving a target water surface elevation, at which time the water begins to passively flow over a spillway. Alternatively, the water flow can be controlled over a spillway via use of gates located at the crest. Water can also be passed through the dam by means of a closed conduit. Water from the reservoir enters though structures such as glory holes or similar types of uncontrolled entrances or through a gated or valve-controlled outlet structure. Passed through the dam, the water exits though the downstream tailrace channel into the river.

Energy dissipation mechanisms are required downstream of a facility to prevent erosion and scouring of the downstream apron and riverbanks. Spillways and downstream aprons are designed to impose hydraulic conditions in the flow that act to dissipate energy of the moving water within the tailrace. Other approaches include dissipation of water energy through the use of sluicing ramps that direct water up into the air in a controlled manner. These types of water passages are exposed to seasonal fluctuations in temperature (e.g., freeze-thaw cycles and UV exposure) that act to deteriorate concrete spillways, aprons, and stilling basins. In addition, the passage of floods at times involves buildup and passage of debris (e.g., fallen wood, ground debris, and trash) that can also affect longevity and contribute to the deterioration of surfaces.

Fish passages are conveyances created to allow fish to migrate both upstream and downstream of the dam, supporting the preservation of ecosystems and thus enhancing the environmental footprint of the hydropower plant. Similarly, sediment conduits and gates are used to enable sediments to bypass the dam and ensure the natural sediment transport continuity, at the same time reducing sedimentation in the reservoir and prolonging the life span of reservoir. Traditionally, both fish passages and sediment conduits use concrete, steel, and rock for the structure, which are similar to the dam materials.

2.1.4 Manufactured Components for Electrical Interconnections and Instrumentation Controls

Electrical interconnections are the equipment and process of connecting hydropower-based generation to the power grid. For hydropower, the three main routes used to connect to the grid are power electronic converters (rectifiers, inverters, and cycloconverters), directly connected induction generators, and directly connected synchronous generators. Instrumentation controls system refers to the equipment that monitors and manages different variables in a system. These technologies are crucial for safe and efficient operation of the hydropower facility because they identify and address changes in normal operating conditions. Sensors that monitor water flow, water pressure, current, voltage, frequency, and temperature are some of the monitoring equipment used for hydropower. Control equipment such as relays, governors, and other devices are used to send commands that cause predetermined actions throughout a system.

The governor is the major controller of the hydraulic turbine, which includes speed-sensing elements, governor control actuators, hydraulic pressure supply systems, and turbine control servomotors. It varies the water flow through the turbine to control its speed, frequency, or power output to support the larger grid demands. The governor is responsible for two critical functions in a hydropower facility. First, it controls the speed of the turbine-generator unit during startup and shutdown and automatically increases or decreases turbine output when the unit is online to respond to grid-frequency fluctuations (i.e., grid responsiveness). Second, it protects the power facility’s civil and mechanical structures by controlling the opening and closing times of the wicket gate to limit under-pressure and over-pressure. The three primary governor types are mechanical, analog, and digital. They perform the same primary functions and have similar sensitivity to speed and frequency changes.

Although mechanical governors are the dominant type of governors in service at hydropower plants, they are no longer manufactured because of their high cost. Analog governors have more functionality than mechanical governors but still have more hardware components than a modern digital governor. Therefore, digital governors, with their lower cost and versatility through software programmability, are the default governors for new installations or replacements.

Several primary failures can be identified, including filter and throttle damage; chocking of oil parts and throttles; leakage of oil through pipeline joints, flanges, and valves; automatic rod setting disturbance; misalignment of feedback wire rope pulleys; and defects on pump motors. To eliminate these failures, periodic maintenance is necessary for the governor system.

Some key materials for the electrical interconnection and instrumentation controls are copper, steel, and aluminum alloys. Most importantly, integrated circuits and semiconductors such as microelectronic devices are major components for the electronic instrumentation control devices, which rely heavily on semiconductor fabrication, foundry, and integrated circuit designs. Furthermore, semiconductors are viewed as a future opportunity to further maximize energy efficiency. Semiconductors can transmit electricity at a modulated rate to convert energy harnessed by hydropower with minimal loss of energy in the process, acting like efficient rectifiers to smooth the electric current.

2.1.5 Summary of Conventional Materials for Hydropower Manufacturing

Table 1 summarizes the conventional manufacturing processes and materials used for producing most of the components pertaining to the general categories introduced previously.

Table 1. Conventional manufacturing and materials for hydropower

Category	Material	Manufacturing process
Hydraulic turbines and generators	• Steel • Metal alloys (stainless steel and aluminum) • Copper	• Casting • Forging • CNC machining • Extrusion • Rolling • Stamping • Welding
Pressurized conduits and gates	• Steel plate (curved) • Steel bar shapes • Bronze bushing (for gates/ pins) • Friction-reducing lubrication (for trunnion pins and bushings)	• Forging • Welding • Rolling • Forming • Precast • Casting • CNC machining
Structures and foundations	• Concrete • Rock aggregate • Structural steel • High-yield steel-reinforcing bar with surface indentations	• Casting • Welding • Extrusion • Rolling • Cement kiln • Rock crusher
Electrical interconnection and instrumentation controls	• Copper • Steel and aluminum alloys • Integrated circuits • Semiconductors	• Foundry • Extrusion • Stamping • Rolling • Stereolithography (computer chips) • Semiconductor fabrication

2.2 CHALLENGES AND TRENDS FOR THE EXISTING HYDROPOWER FLEET

This section describes some of the technological and material challenges affecting the existing hydropower fleet in the United States (i.e., all the hydropower plants, regardless of their operating status). Overall, most of these challenges stem from the age of the infrastructures and components. Dams in the United States are rapidly reaching their expected lifetime; according to Uría-Martínez et al. (2022), the average age of US conventional hydropower is 64 years, and the average age of US PSH is 45 years. Age is one of the leading factors for dam failure; consequently, many of the existing infrastructures are being scrutinized to decide whether they should be rehabilitated, retrofitted, or removed (Stanford University Uncommon Dialogue 2020). Similarly, equipment and components require routine, scheduled maintenance and sometimes unexpected, unscheduled repair to maintain operability and availability. Unexpected outages can occur because of sudden component failure resulting from accidents, poorly maintained equipment, or unpredicted deterioration of materials. Over time, some equipment might require extensive upgrades and rehabilitation and even replacement because of age or the need for more efficiently operating equipment, such as turbine runners.

Major challenges facing existing hydropower include legacy part replacement, component maintenance and repair, evolving operating conditions, supply chain issues, and data access. In addition, some of the trending challenges affecting new hydropower development, such as climate change and environmental mitigation, might also affect the existing fleet. Advanced manufacturing might offer solutions to some of these challenges; additional information is presented in Section 3.

2.2.1 Components Maintenance, Repair, and Legacy Parts Replacement

One of the most significant challenges is the increasing maintenance and repair for damage to major hydropower components and equipment such as turbine runners, blades, and hubs due to aging of the hydropower fleet. Damages can affect plant efficiency and limit capacity. Based on the North America Electricity Reliability Corporation (NERC)[9] Glossary of Terms, there are different types of outages. *Forced outage* refers to unplanned component failure or other conditions that require the unit to be removed from service immediately, within 6 hours or before the next weekend. *Maintenance outage* refers to the removal of units from service to perform work on specific components that can be deferred beyond the end of the next weekend but not until the next planned outage. *Planned outage* refers to the removal of units from service to perform work on specific components that is scheduled well in advance and has a predetermined start date and duration. According to Uría-Martínez, Johnson, and Shan (2021), and as shown in Figure 12, all the units considered in their study displayed increases in average forced outages from 2009 to 2018; although the trend is slight for medium and large units, the average forced outage hours have almost doubled for small units (≤10 MW). Figure 12 shows that large units (>100 MW) had the longest planned outage (which increased by 41% from 982 in 2009 to 1,382 in 2018) and the shortest forced period. Remarkably, the opposite is true for small units. Whether planned or unplanned, the downtime associated with addressing damage to such integral components can be costly because of the generation loss incurred during the outage. No publicly available data is available to quantify specific revenue losses; however, losses can be roughly calculated by multiplying outage time by an estimate of energy/capacity prices and the probability that the plant will be in service. Probability of service is important because plant owners tend to schedule maintenance outages (at least those within their control) during periods of low demand on plant services.

[9] https://www.nerc.com/Pages/default.aspx.

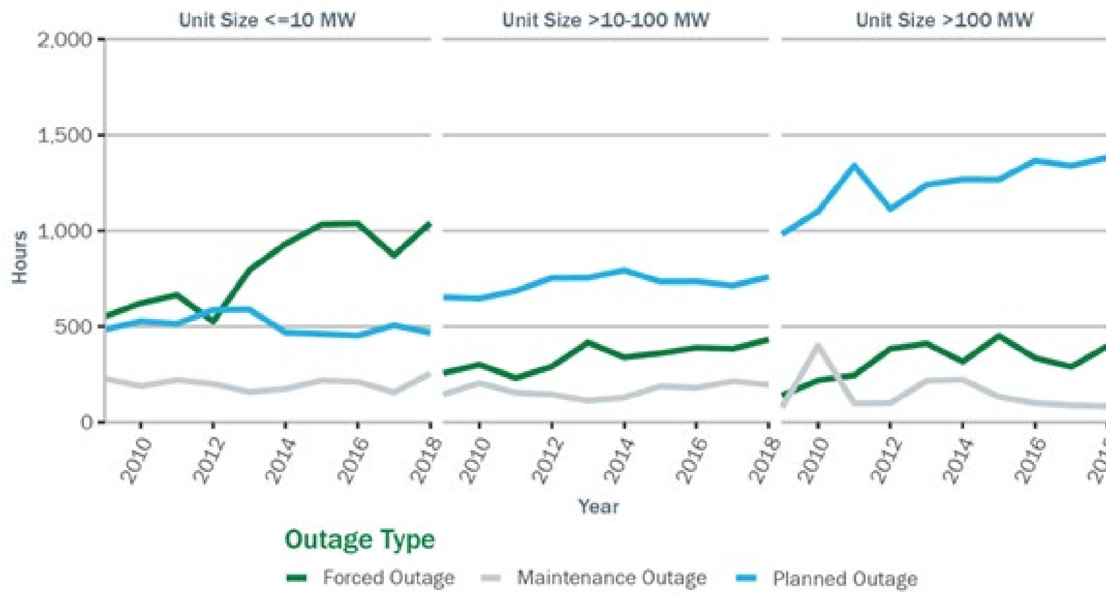

Figure 12. Average hydropower outage hours by outage type and unit size classes. Original figure from (Uría-Martínez, Johnson, and Shan 2021).

Unplanned outages associated with system or component failure can be avoided or minimized to some degree with appropriately scheduled preventive maintenance. Such maintenance is typically scheduled during periods of expected low demand for hydropower, such as during spring and fall months or during operation cycling of units at a facility, and includes inspection and any minor repair or maintenance activities. Predictive maintenance includes monitoring and assessment of performance variables and trends used to inform prediction of failure and is used for planning replacement and upgrades of systems or components. Monitoring systems include sensors for measuring a host of variables, such as temperatures, flows, vibrations, pressures, and leakage, and can be useful for predicting problems based on abnormal or out-of-range conditions. Relationships of parameters can be used to infer conditions and problem areas for systems and components that are difficult or not traditionally instrumented with sensors. Sensors can be added to the surface and exterior of existing components where applicable but might not provide the quality of information necessary for long- and short-term prediction of failure.

Cavitation is a common turbine failure mode affecting a turbine's useful life and results from variable operating conditions as the fluid load varies (Figure 13). Cavitation occurs when bubbles formed in regions of low pressure are transported by the flow in high-pressure regions where they collapse, causing local erosion damage (Kumar and Saini 2010). This often occurs when powertrains are operated outside the optimal operating range. Nonoptimal operating conditions, resulting in increased ramping and cavitation, will likely increase as result of increased hydrological extremes from climate change and the increased need for flexible operations due to other renewable energy resource integration. The most susceptible components to cavitation and thus the most likely to be impacted are turbine blades and guide vanes/wicket gates (Liu, Luo, and Wang 2016). To address this common issue, research has been dedicated to developing a steel alloy with improved resistance to cavitation and to optimized methods to detect the ongoing damage (US Department of the Interior Bureau of Reclamation 2018). Cold spray is another example of active research on cavitation repair conducted by Pacific Northwest National Laboratory (PNNL), which is described in more detail in Section 3.4.4. Sediment erosion is caused by high-flow velocity and impingement of abrasive sediments on the turbine surface and might result in similar wear of turbine components (e.g., blades and guide vanes/wicket gates).

Figure 13. (Left) cavitation on a Kaplan-type turbine near the stainless steel overlay beneath blade tip and (right) cavitation approaching a repair area that used cavitation-resistant stainless steel on a carbon steel blade. Picture courtesy of USACE, Lower Monumental Dam (WA). Photo by Kyle DeSomber, PNNL/DOE.

Fatigue failure is another potential component failure mode caused by the cyclical loading turbines experience and the additional superposition of varying operating conditions on the turbine. This correspondence between the natural frequencies of hydropower plant components and exciting frequencies related to operating conditions can produce high stresses resulting in high fatigue damage rates and significant crack propagation. In addition, flow fluctuations in stationary setpoints and transient events can create high stresses and cause fatigue damage to the runner blades. The joints between the two parts of the hydropower turbine are often weldments and might also undergo high stress concentration, thus causing fatigue failure (Liu, Luo, and Wang 2016).

Current repair methods can lead to high O&M costs, uncertainty associated with detecting the damaged area, and potential distortion and residual stresses induced from the repair. Improved techniques for identifying and locating a failure can improve outage timelines and help minimize lost generation. Turbine runners are typically repaired in place for large turbines or through disassembly and removing the runner for smaller units. The damaged area is excavated to sound metal through air arcing and grinding out the damaged area, repairing the surface with a welding overlay compatible with the runner material, and surface finishing. In some cases, a special layer of weld is added to be compatible with both the turbine runner material and a more cavitation- and erosion-resistant final weld layer. In either case, specific weld procedures, pre/postheating, and strong backs are required to prevent distortion in turbine runners. Routine maintenance is conducted to prevent and limit issues associated with corrosion, erosion, and biofouling of penstocks, piping systems, heat exchangers, and other supporting systems exposed to water.

If not protected, metal surfaces exposed to water can incur corrosion, and if left unchecked, can lead to damage requiring replacement. Biofouling or attachment of invasive species such as bacteria, mussels, and freshwater sponges to conveyance systems can greatly reduce capacity by causing blockages and/or increasing pipe wall surface roughness resulting in head losses in penstocks, thereby reducing generation efficiencies. Current maintenance activities include periodic examination and painting of surfaces to prevent corrosion and monitoring of conveyance systems and subsequent removal of blockages and roughened surfaces associated with biofouling. Maintenance associated with timely and costly removal of biofouling in some systems, such as the generator cooling system, can reach upward of $80,000 per year (Pucherelli 2018), which for a small facility (<10 MW) could be cost prohibitive.

Component damage from electrical and mechanical failures is an inherent challenge for existing powertrain systems that might require repair. The most common failure for a generator is failure of the electrical insulations, which are typically made of nonmetallic materials such as glass, ceramics, and rubber-like polymers. Failure of the insulation is typically a result of abrasion from vibration or contamination. Vibrations, wear, and fatigue are all expected to increase as result of increasing off-design operating conditions in the future.

Finally, a significant challenge that the existing hydropower fleet is facing includes the repair or replacement of legacy parts that no longer exist because the original die casting is no longer available on the market. In many cases, these legacy parts are characterized by geometries that are very specific to their use and must be reverse engineered and custom machined to duplicate. This adds to outage durations as turbine generators must be taken out of service and disassembled to the component level; then reverse engineering and machining of the replacement part occurs. In such cases, opportunities exist for advanced component scanning to reverse engineer the component through additive manufacturing and CNC machining to replace parts inexpensively and quickly (see example in Figure 14). In some cases, portions of a legacy part might require repair only as opposed to complete replacement, but opportunities for replacing worn, broken, or damaged legacy parts should be leveraged to minimize risk to quality control, which could be an issue with repair.

Figure 14. Legacy governor components for the Glen Canyon Dam. (Left) original component and (right) reverse engineered advanced manufacturing component. Photo courtesy of the US Bureau of Reclamation. Picture by David Tordonato, US Bureau of Reclamation.

2.2.2 Evolving Operating Conditions and Data Collection Needs

As noted in the previous section, the existing hydropower fleet will continue to face changes in its normal operating conditions as a result of climate change and the increased deployment of more intermittent renewable energy technologies, such as wind and solar. Climate change is expected to alter water availability and variability, affecting flood and drought frequencies and intensities; this will induce changes in water releases and generation schedules, which will become more variable and transient, and it will place additional strains on equipment and materials. Additionally, as the US electric grid continues to evolve, increases in intermittent renewables might necessitate changes in existing hydropower operating conditions with more frequent starts and stops to meet power demand throughout the day or over certain periods of time. Such changes in the ideal operating conditions of hydropower equipment and the increased frequency of on/off generation could lead to increased wear and fatigue of components, leading to increased failure risk and reduced life (Somani et al. 2021). This trend is already being seen among certain sections of the hydropower fleet and will undoubtedly present challenges as solar and wind use continues to grow. As an example, a turbine generator might operate at, or very near, a rough zone to maximize the amount of spinning reserve available, thereby maximizing available grid services and corresponding economic benefits that can be captured through changes in set points.

Wear and fatigue from off-design and partial-flow operating conditions of turbines can contribute to flow-induced vibrations and cavitation erosion of the turbine hubs and blades and require maintenance and repair. This need stems from the pitting and thinning of material, which lead to overall reduced generation efficiencies and can result in premature catastrophic failure. Even though turbine geometry is designed for mitigating cavitation at optimal operational conditions, many runners will still experience such damage caused by operating outside the intended operating range.

Given that much of the existing hydropower fleet is many decades old and likely not yet equipped to face the trends of energy markets and environmental changes, some systems suffer from a lack of refined data collection relevant to facility operating conditions and system/component conditions. Improved monitoring and sensors can help improve decision-making regarding component replacement, maintenance, and repair needs and avoid costly failures. Similarly, the industry is recognizing how sharing more data regarding operation changes, material, and health monitoring of existing equipment would benefit the hydropower community at large. Both research and technological advancement is fueled by constant data analysis; thus, more data collection and sharing are needed. For example, the Hydropower Fleet Intelligence project,[10] led by ORNL, is creating standardized methods for integrating, assessing, and using disparate data sets and has evaluated the feasibility of using data for predictive maintenance applications.

Finally, as the grid and hydropower evolve, cybersecurity of large energy generation systems is also becoming increasingly important. Remote cyberattacks on critical infrastructure are becoming more severe and more frequent. Any control system that is not locally isolated from the greater network is vulnerable to these remote cyberattacks, which can include direct communication links or other external factors such as timing and location. Hydropower plants around the United States are critical not only for energy production and energy security but also for national security at large considering the tremendous consequences that a threat to a large hydropower dam would bring. As more electrical interfaces are being made through inverter-based generation, digitalization of assets, and remote operations, additional potential vulnerabilities need to be examined with respect to control systems, communication links, and any potential supply chain concerns.

[10] https://www.ornl.gov/project/hydropower-fleet-intelligence.

2.2.3 Environmental Mitigations

Environmental mitigation is another major trend in the hydropower sector. Hydropower facilities need to meet increasingly higher standards of environmental performance, and technological innovations are needed to meet those standards while reducing costs and optimizing production. In general, environmental mitigation refers to all those designs aimed at minimizing the environmental footprint of hydropower development on natural sites. This could include technology and structures that allow fish migration upstream and downstream of the dam; avoid sediments being trapped in the reservoir, thus allowing their natural continuity in the river; and maintaining an adequate level of water quality. Additive manufacturing could be employed in several of these design solutions. Fish-friendly turbines are being proposed for both old unit replacement/upgrade and new projects development. These turbines are designed to minimize the injury and mortality of fish that might go through the powertrain system while providing high generation efficiency. Aeration from turbine blades, environmentally friendly lubricants, and nonlubricated bushings are other forms of environmental mitigation from powertrains that target improving the water quality downstream of the dam. DOE, the Electric Power Research Institute, and the Hydropower Research Foundation have extensively funded R&D of fish-friendly turbines in recent years, including the Alden turbine[11] and the Voith Minimum Gap Runner[12] (Cook et al. 2000; Hogan, Cada, and Amaral 2014; Electric Power Research Institute 2007a; 2007b; 2008; 2011; Electric Power Research Institute and US Department of Energy 2011). Typically, to reduce fish mortality innovative design solutions include thicker blades with curved and slanted leading edges, as recently demonstrated by Natel Energy with their Restoration Hydro turbine,[13] which can enable >98% of safe passage of salmonoids (Amaral et al. 2020) while maintaining a turbine efficiency greater than 90%. Complex and unconventional shapes and the additional material needed for the thickness of blades such as these represent a variation that might challenge the economics of traditional manufacturing processes and thus be a good candidate for advanced techniques.

In general, the capability to create complex shapes is one of the greatest advantages offered by advanced manufacturing and is thus a great opportunity for environmental mitigation. For instance, fish migration research might unveil that fish attraction and migration could be enhanced by building fish passage structures made in noncanonical shapes that differ from conventional construction standards and that create hydraulic dynamics more amenable to the fish. Sediment passage strategies are also extremely relevant to reducing the impact of dams on river geomorphology. Newer technologies will likely aim at capturing sediments before they reach the reservoir and continuously bypass them downstream of the dam, thus maintaining the natural continuity of sediments within the stream reach. A similar approach was recently proposed by the University of Minnesota, which DOE funded[14] to develop a sediment bypass system that uses siphon flow to capture sediments and pass them above the dam.

2.2.4 Supply Chain Issues

Finally, as introduced in Section 1.2, the disruption of supply chains induces challenges for the manufacturing sector at large and cuts across every area of the whole hydropower technology landscape, with powertrain being the most affected and most consequential. Changes in material and manufactured parts supply can present challenges for replacing or repairing hydropower facility components. Uría-Martínez et al. (2022) presents information on the US hydropower supply chain, noting that the components most crucial to assess for risks "include turbine, generator, governor, excitor, switchgear, emergency closure system, and penstock. The principal materials used to produce them are steel (carbon

[11] https://www.aldenlab.com/.
[12] https://voith.com/corp-en/products-services/hydropower-components/turbines.html.
[13] https://www.natelenergy.com/turbines/.
[14] See https://www.energy.gov/articles/doe-announces-249-million-funding-selections-advance-hydropower-and-water-technologies.

or stainless) and copper. Most of them are custom components whose replacement involves long lead times ranging from months to years." In addition, "the three largest global turbine manufacturers (Andritz, GE Renewable Energy, and Voith) account for almost 50% of global turbine nameplate megawatt (MW) capacity installed." However, turbine and generator supplier diversity is significantly larger for smaller units (30 MW or less) compared with larger units.

Uría-Martínez et al. (2022) summarizes key challenges facing the industry and presents opportunities to address the challenges. Key challenges identified are presented in Section 1.2 of this report.

2.3 CHALLENGES AND TRENDS FOR NEW HYDROPOWER DEVELOPMENT

The development of new hydropower faces several technological challenges sparked by changes in the global energy sector. The introduction of variable and intermittent renewable resources on the grid, such as wind and solar, will impose more flexible hydropower operations and technologies and will require additional energy storage through PSH (US Department of Energy 2016; Rosenlieb, Heimiller, and Cohen 2022; US Department of Energy 2022). According to recent resource assessments and opportunity studies, there is a great untapped potential in adding hydropower generation to NPDs (Hadjerioua, Wei, and Kao 2012; Hansen et al. 2021; Kao et al. 2022). NPD retrofitting, with a US potential of up to 12 GW, represents an attractive opportunity for hydropower development because most of the construction costs and environmental impacts have already occurred during the development of the structure. Similarly, conduit retrofits have an estimated 1.4 GW of potential in the United States and are considered quite feasible, in part because of the simplified licensing process. Furthermore, retrofitting or rehabilitating existing infrastructure, whether powered or not, provides an opportunity to improve the environmental conditions of the site with co-development initiatives such as fish-friendly turbines, fish passage designs, and sediment bypass technologies. All these potential emerging environmental mitigations are great candidates for advanced manufacturing and novel material applications considering that costs are one of the main barriers to their adoption.

2.3.1 Small Hydropower

Recent resource assessments have highlighted that most of the US hydropower potential (84.7 GW) comes from low-head new stream reach developments and NPD retrofits (Hadjerioua, Wei, and Kao 2012; Kao et al. 2014). Specifically, 74% of potential NPD and new stream reach development capacity (>1 MW) comes from head levels below 10 m (Sasthav and Oladosu 2022). This class of development, typically characterized as less than 10 MW and less than 10 m of gross head, is termed *small hydropower*, marking a shift from the historical high-head developments of early hydropower development. Furthermore, these facilities qualify for a Federal Energy Regulatory Commission licensing exemption, potentially expediting their development.

The primary challenge for small hydropower is increasing the value proposition, since new stream reach development can have LCOEs 2–3 times greater the onshore wind, solar, or natural gas plants (Sasthav 2022). Several factors play a role in the value proposition that could be ameliorated through AMM. First, small hydropower lacks the economies of scale related to head, flow, and capacity that benefit the LCOE of larger projects (O'Connor et al. 2015). Since profit margins are tighter on smaller projects, not only must technologies be cheaper and more efficient but also developers must have better data to inform design decisions and avoid cost overruns. Second, the optimal designs of small hydropower can differ significantly from their high-head counterparts, thus requiring new technologies to enable them. For example, most small hydropower potential is located in valley regions with lower terrain slopes, meaning it would require longer conveyances to achieve a given head (DeNeale et al. 2020). Some design concepts leverage in-stream modular technologies without long penstocks to avoid this cost (Witt et al. 2017). Other innovative projects might aim to leverage low-cost materials, such as high-density polyethylene penstocks, to solve this design challenge. Third, new projects will likely face run-of-river operational constraints since smaller plants generally have less storage value and recent licenses reflect increased run-of-river requirements, plus it would be difficult to site new reservoirs in the built environment (Sasthav and Oladosu 2022). Run-of-river constraints eliminate the ability for peaking, or energy arbitrage, and can require greater unit flexibility to maintain high capacity factors. Durable runner materials and variable speed configurations could help unlock this flexibility. Finally, small hydropower plants must be cost-effective while meeting high environmental performance standards. The cost of sediment bypasses, fish screens and passageways, and safety or recreational features tend to have an outsized effect for smaller facilities (Oladosu et al. 2021). This can also be attributed to the economies of scale for the plant, since larger plants are affected less by fixed-cost measures. Technologies such as sediment siphons, modular fishways, and even environmentally acceptable lubricants (EALs) can help reduce the cost to meet the performance standards and reduce the risk of fines during operation.

2.3.2 NPDs, Conduits, and Other Water Infrastructure Retrofits

As indicated in Section 2.3.1, the majority of NPD retrofit potential falls under the small hydropower category. However, retrofitting existing water infrastructures might require different development approaches with respect to new stream reach development, exhibiting specific challenges and opportunities. NPDs are currently considered one of the best opportunities for hydropower development in the United States (US Department of Energy 2016; 2022). More than 91,000 dams are included in the National Inventory of Dams,[3] but only 3% of those have hydropower capabilities (Hansen et al. 2021), as shown in Figure 15. The remaining 97% are water infrastructures serving other purposes, including navigation, flood control, water supply, irrigation, and recreation (Bonnet Acosta et al. 2015). To support hydropower development at NPDs, ORNL has developed an NPD Characteristics Inventory data set (Hansen et al. 2022), two explorer tools,[15] and an assessment of the most promising development opportunities at NPDs in the United States (DeNeale, Hansen, et al. 2022).

[15] https://hydrosource.ornl.gov/tool/npd_tools.

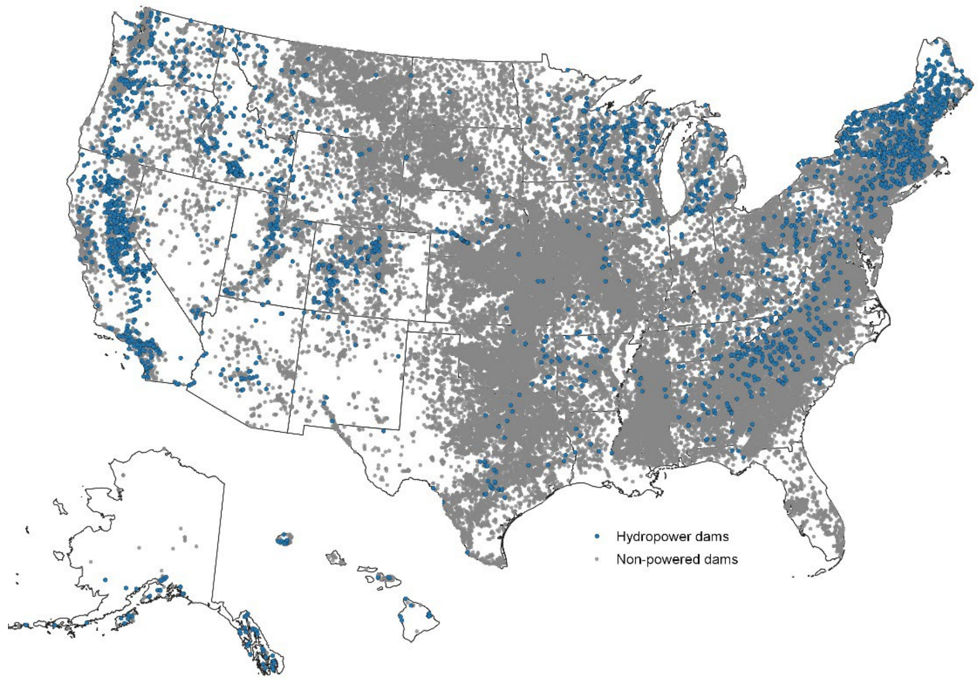

Figure 15. Location of existing hydropower dams (blue dots) and NPDs (gray dots) in the United States. Adapted from (DeNeale, Hansen, et al. 2022).

Other existing water infrastructures that could be exploited for hydropower development include conduits and artificial canals. Kao et al. (2022) has recently estimated a total of 1.41 GW of hydropower potential at conduits in the United States, stemming from the agricultural sector (662 MW), industrial sector (378 MW), and municipal sector (374 MW). This potential would remarkably add to the 530 MW of existing conduit hydropower projects. In the cited study, conduits are defined following the Code of Federal Regulations as "any tunnel, canal, pipeline, aqueduct, flume, ditch, or similar manmade water conveyance that is operated for the distribution of water for agricultural, municipal, or industrial consumption and not primarily for the generation of electricity."[16] Examples include irrigation canals and ditches, pipes in municipal water and wastewater systems, and cooling water discharge pipes at thermoelectric power station stations.

The advantages offered by NPDs and other retrofits are related to the fact that many of the major initial costs and environmental impacts have already been incurred. However, to add generation capabilities to NPDs, developers are challenged to explore unconventional design concepts that can maintain as much as possible the original design of the existing structure to contain the costs and preserve structural safety. One possible way is to develop innovative water conveyances with power generation technologies to be applied to existing structures with minimal civil works. For example, siphons with embedded generation technology installed over NPDs could represent a cost-effective, flexible, and easy-to-install solution that might avoid time-consuming and expensive modifications to the dam structure. This innovation could mitigate the safety risks associated to excavation into and around the dam since the water would move over the structure, thus avoiding structural damage, cofferdams, and so on. In this sense, innovative light materials for conveyances and conduits could also be explored. High-density polyethene, fiberglass, fiber-reinforced polymer, and centrifugally cast fiber-reinforced polymer mortar applications should be explored for penstocks, draft tubes, and other pipeworks for future developments or replacements. As introduced in Section 2.1.2, these parts are commonly made in steel and cast iron, which normally present

[16] Code of Federal Regulations, Title 18, Chapter 1.B.4.D § 4.30 (b) (2).

higher costs than these other materials. According to a recent cost analysis conducted by ORNL, conveyances are among the major costs drivers for NPD retrofits; thus, nonsteel materials for water conveyance and penstocks might be adopted to reduce costs and improve flexibility for maintenance and retrofits (Oladosu, George, and Wells 2021). In fact, reinforced plastic-based material might be easier to install and join, potentially reducing overall civil construction costs. Alternative materials can also be explored for larger, nonpressurized conveyance structures such as spillways, outlets, and fish and boat passages. For example, inflatable rubber structures and pneumatically actuated gates as water control structures have been in use since the 1980s. These technologies are relatively inexpensive and can easily be installed on preexisting water structures to increase dam height and thus increase the nominal hydraulic head or to replace outdated outlets. Such technologies might also be easily deflated to pass high flows, debris, or sediment and is resilient to large debris such as boulder and ice flows.

In general, standardization, scalability, and modularity play a crucial role in technology advancement and cost reduction. This concept applied to hydropower development was first introduced by Witt et al. (2017), who explained the rationale behind standard module hydropower and provided a series of general specifications for modular designs. The idea behind standard module hydropower is to develop individual modules that target the primary hydropower functionalities (power generation and water control) and sustain the basic river natural functionalities (naturally flowing water, sediment continuity, fish migration, and recreation activities); this translates into the introduction of standardized modular technologies for generation, foundations, water passage, sediment passage, fish passage, and boaters passage. The ultimate goal is to enable the sustainable growth of small hydropower by lowering construction costs while improving environmental compatibility.[17] The idea was recently extended to NPD retrofits by DeNeale, Sasthav, et al. (2022). The opportunities for new manufacturing applications for this new design paradigm are extensive, even if the concept is only partially applied to a site development (i.e., adopting just one of the modular solutions to be applied to an existing project). Modularity and standardization could be applied to any new parts of a dam retrofit, as exemplified by modern Obermeyer Hydro Inc.[18] inflatable ogee gates. However, they are most common for generation technologies, especially for turbine-generator packages that can be preassembled in the factory and delivered on-site on a prefabricated installation interface, thus reducing on-site work. In general, modularity could be pursued for subcomponents of the units, reducing outage time caused by component replacement and potentially integrating with environmental enhancement technologies if needed (e.g., aeration). Turbine-generator packages that are compact, preassembled, and totally submersible already exist; examples include the Amjet turbine[19] that uses variable-speed technology and a permanent magnet generator to eliminate the need for mechanical controls, the Voith StreamDiver[20], and the ANDRITZ HydroMatrix,[21] which are bulb-type turbines that incorporate the generator into a hub on the upstream nose of the unit. Other emerging turbine technologies sponsored and peer reviewed by DOE are available in the *2019 Project Peer Review* report published by WPTO (US Department of Energy 2020) and include the following:

- Restoration Hydro turbine:[13] a new unit designed by Natel Energy to be compact (water-to-wire unit), cost saving (no fish exclusion and minimal civil works), fish friendly (>99% fish passage survival), and efficient (90% demonstrated efficiency)
- Pennsylvania State University turbine:[22] a hydropower turbine prototype designed and developed for low-head, variable flow applications—modular, multibladed, and hubless (allowing flow through the center for ecological enhancement, self-cleaning, and low maintenance) and connected to a direct-rim-drive, variable-speed generator

[17] https://smh.ornl.gov/.
[18] http://www.obermeyerhydro.com/inflatabledams.
[19] http://amjethydro.com/.
[20] https://voith.com/corp-en/hydropower-components/streamdiver.html.
[21] https://www.andritz.com/products-en/hydro/products/hydromatrix.
[22] https://www.energy.gov/sites/prod/files/2019/12/f69/06_EE0006928_PSU_Fontaine_FINAL.pdf.

- Eaton Corporation turbine:[23] a turbine design inspired by the Eaton technology Roots-based compressors and expanders—to be integrated with small modular units and used at NPDs
- Percheron Power turbine:[24] an optimized Archimedes hydrodynamic screw turbine made of composite materials using advanced manufacturing techniques—designed to be assembled in the factory and shipped to reduce equipment and installation costs

The Small Business Innovation Research (SBIR) and Small Business Technology Transfer programs[25] have recently funded two new projects aimed at exploring innovative hydropower technologies:

- Cadens is proposing to develop micro-hydropower turbines for smaller rivers to be integrated in microgrids.
- Polnox Corporation is developing the next generation of EALs[26] for use in hydropower generation.

Using prefabricated structures for powerhouse or other auxiliary structures is an application worth exploring with innovative manufacturing and materials, both for dam retrofitting and new development. Precast concrete sections and on-site 3D concrete printing could also fit this purpose. Large-scale 3D cement printers are being investigated to develop small buildings in significantly short amounts of time, often in response to natural disasters or to build affordable houses. Prefabricated structures or concrete printing are also sought for foundation design. For instance, underwater concrete printing or, in general, technologies for underwater equipment application would massively reduce construction time and costs by reducing the use of cofferdams and other water diversion techniques (DeNeale et al. 2020). Cofferdams are not only one of the highest cost drivers during foundation construction but also introduce significant environmental disruptions by affecting flow patterns and benthic habitats. Innovative materials are being studied to develop geotextiles, reservoir linings, and treatments, in general, to reduce seepage through the core and the soil underneath. Earth stabilizing and soil treatments to minimize seepage, such as advanced grouting techniques, are mostly relevant for new site development. However, as mentioned in the introduction of Section 2.2.3, existing hydraulic structures are aging, and some are starting to exhibit structural safety issues. Therefore, novel materials and manufacturing should be explored for existing structures, not only for future retrofit projects but also for general safety.

2.3.3 Pumped Storage and Flexible Hydropower

The increasing penetration of intermittent renewable energy resources on the market will change the hydropower paradigm and impose more variability in energy production and storage. PSH offers one of the most efficient ways to store excess energy (in the form of hydraulic potential) and currently represents the largest portion of energy storage in the United States: 23 out of 24 GW total (Denholm et al. 2021). A recent study by the National Renewable Energy Laboratory has shown that PSH could provide a potential of 35 TWh of energy storage (3.5 TW of capacity when assuming a 10-h storage duration) across 14,846 sites, with the greatest density of technical potential in regions with higher elevation differences, such the Rocky Mountains, the Cascade Range, and the Alaska Range (Rosenlieb, Heimiller, and Cohen 2022).

Manufacturing advancement is needed to support the growth and improvement of PSH with applications to powertrains, conveyance, and structures. For instance, two types of PSH designs exist based on how reservoirs are connected to the external environment. Plants connected to naturally flowing water are referred to as *open loop*, whereas *closed-loop plants* consist of two independent reservoirs connected to each other (Saulsbury 2020). This latter type is environmentally advantageous because, as an isolated

[23] https://www.energy.gov/sites/prod/files/2017/04/f34/cost-optimization-modular-helical-rotor.pdf.
[24] https://www.energy.gov/sites/prod/files/2019/12/f69/07_EE0007247_Percheron_Straalsun_FINAL.pdf.
[25] https://science.osti.gov/sbir/Awards.
[26] https://www.sbir.gov/node/1524197.

system, it could avoid interaction with aquatic life. Closed-loop PSH could be artificially created even within existing natural systems using membranes as a reservoir; for instance, a polyester-based fabric with flexible PVC coating was proposed as a floating reservoir to be added in natural reservoirs and create closed-loop PSH (Hadjerioua et al. 2019). Similarly, artificial reservoirs floating in the ocean were proposed as an alternative PSH installation combined with floating offshore wind energy (US Department of Energy 2016). Pressurized conduits within conventional and PSH plants might also benefit from innovative materials. For instance, fiberglass-reinforced plastic, centrifugally cast fiberglass-reinforced polymer mortar (e.g., Hobas[27]), and high-density polyethylene (e.g., Whelolite[28]) could be used for penstocks and draft tubes. Energy-absorbing material could help reduce the potential damage induced by water hammer effects, which could arise as consequence of variable operation, inducing transient hydraulic behaviors.

The powertrain equipment for hydropower still has room for improvement and innovation. Some PSH plants use hydraulic machines that can be used as both a turbine and a pump by reversing the rotational direction. These machines are traditionally single speed (i.e., fixed speed), in which the pump/turbine and the motor/generator operate synchronously at the same fixed speed. However, adjustable-speed machines are becoming widely adopted in PSH plants and small hydropower because they can vary their power consumption while pumping and provide more flexibility during generation. Adjustable-speed machines are based on two emerging generator types that use power electronic converters, namely the doubly fed induction machine and converter-fed synchronous machine (Kougias et al. 2019). Ternary and quaternary technologies are other solutions to provide flexible pumped storage where the water is short-circuited from the pump to the turbine, increasing the flexibility of power consumption while pumping. Variable-speed permanent magnet generators were previously explored in a DOE-funded project as an alternative to both pumped storage and low-head hydropower (Kinloch 2015). The wind industry is also proposing superconducting generators that can provide high torque and efficiency in compact electric machines by reaching high magnetic and/or electric lading (Wang et al. 2016). The high efficiency can be achieved because of the superconducting properties that novel materials can exhibit at temperatures that can be reached using commercially available cooling systems. Another innovation gaining interest and funding is magnetic gearing, which transfers power between high-torque, low-speed rotation and low-torque, high-speed rotation, using the modulated interaction of magnetic fields instead of the physical contact of traditional gears (Bird and Williams 2018; Praslicka et al. 2021). Since small hydropower projects often adopt speed-increasing gearboxes to drive generators at a faster speed than the turbine, magnetic gears could become a viable solution by reducing wear and mechanical damages, thus improving durability and reliability.

[27] https://hobaspipe.com/.
[28] https://www.weholite.com/.

3. ADVANCED MANUFACTURING AND RELATED CAPABILITIES FOR HYDROPOWER

As described in Section 2, the hydropower industry has many unique challenges that need to be addressed to maximize its potential within the US energy portfolio. Many of these unique challenges can be improved through continued R&D of advanced manufacturing techniques. These include additive manufacturing (AM), novel machining and casting processes (e.g., hybrid additive and subtractive), innovative materials, and new coatings development.

As presented, the construction of new hydropower facilities might be limited to small hydropower installations, pumped storage facilities, and retrofitting of NPDs. These situations can implement many of the AMM techniques described here to maximize their performance and reduce deployment costs compared with traditional methods. The most beneficial techniques will be those that are dedicated to enabling advanced design and manufacturing of new parts with real-time monitoring and control. In contrast, existing hydropower facilities stand to benefit the most from advanced manufacturing techniques dedicated to effective repair materials and techniques, including in situ monitoring in operation, although upgrade and required overhaul projects can also benefit from newly manufactured components to improve their efficiency and maximize their output potential.

The overarching goal of the advanced manufacturing techniques presented here is to address many of the component-specific technical challenges described in Section 2, as well as the more generalized objectives that are described in Section 1 (e.g., cost, weight, performance, manufacturability, and production time). Notably, the applicability of each of the techniques described here will depend heavily on the specific application. Complementary to all advanced manufacturing techniques to be discussed, will be a digitalization component that includes modeling, simulation, and in situ monitoring to ensure part quality without the need for extensive nondestructive and destructive examination postprocessing. Further R&D should be performed in all of these areas to validate their potential for solving the unique challenges of the hydropower industry.

3.1 ADDITIVE MMANUFACTURING

AM is the process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies.[29] This is typically done by laying down multiple 2D layers on top of one another to build a 3D part. The printing toolpath is automatically generated by software called the slicer. The slicer creates cross-sectional slices of a 3D CAD model at the desired layer height to develop the toolpaths for each of the 2D layers. Each layer provides additional height to the part to build the desired final object geometry in 3D. In general, a thicker layer height will print faster but will have a lower resolution and rougher surface finish.

Diverse AM processes have been developed commercially and are constantly evolving to adapt to more demanding requirements. One specific area of constant development is the increase in build volume, or the dimensions of space in which a print can be produced by a specific machine. This increasing scale can provide some new opportunities for large-scale hydropower parts. Another area of constant development is the increase in build rate, which improves the manufacturing time and cost of additively manufactured parts.

[29] https://www.iso.org/obp/ui/#iso:std:iso-astm:52900:ed-2:v1:en.

Many unique characteristics of AM can lead to advantages over traditional manufacturing:

- Earlier production use of stocked supplies of feed material instead of depending on the lengthy procurement of raw material stock that is common with traditional manufacturing
- Might complement or eventually replace current casting and forging processes, thus potentially reducing reliance on imports from overseas while supporting reshoring US capabilities
- More complex designs, often allowing for lighter, more efficient parts with additional functionality
- More easily achieved special alloys and multimaterial parts
- Reduced waste

However, a few characteristics of AM can present challenges or be disadvantageous relative to traditional manufacturing:

- More expensive feedstock on a weight basis
- Feedstock availability and supply chain
- High susceptibility to process-induced defects, which influence the mechanical properties and performance of fabricated parts
- Reduced mechanical properties (usually due to interlayer weakness) for some processes
- Might be more time consuming for large, simple parts made from readily available raw materials
- Might be more expensive for higher quantity parts, which use tooling for rapid production
- Limited testing data and use case history
- Limited design and testing standards
- Lack of rigorous qualification and certification methodologies specific to AM to ensure that parts meet specifications for critical applications

The specific additive process used depends on the size, material, geometry, and resolution requirements of the part. The following subsections have been separated according to the material of the final parts and describe a few of the processes that are relevant to hydropower.

3.1.1 AM of Metal Parts

The metal-based additive processes described here are well suited to the steel and stainless steel alloys that are common to the hydropower industry. However, many other materials can also be used, including custom alloys and multimaterial parts. When done properly, additively manufactured parts can be made fully dense with very little porosity, which allows them to readily replace many traditionally manufactured parts, including weldments and castings.

Smaller scale metal AM machines typically rely on powder bed fusion (PBF) technology and use metal powder feedstock that is melted by electron beam or laser. Although some custom metal powder systems have up to 0.6 m^3 build volume, most metal powder systems have less than 0.04 m^3 build volume. For example, one of the largest commercially available machines, the Arcam Spectra H,[30] has a cylindrical build space of Ø350 mm × 430 mm tall (volume 0.04 m^3). This process is typically more expensive than directed energy deposition (DED) processes but can accomplish higher resolution parts with internal features that could not be achieved with DED. Figure 16 shows some examples of PBF parts, and Appendix B1 presents a case study that used this process for rapid production of legacy parts on a hydropower facility. Possible future work for hydropower should investigate applications that could

[30] https://www.ge.com/additive/additive-manufacturing/machines/ebm-machines/arcam-ebm-spectra-h.

benefit from having high-resolution internal features such as embedded cooling channels, sensor channels, or lattice-filled structures for making parts lighter.

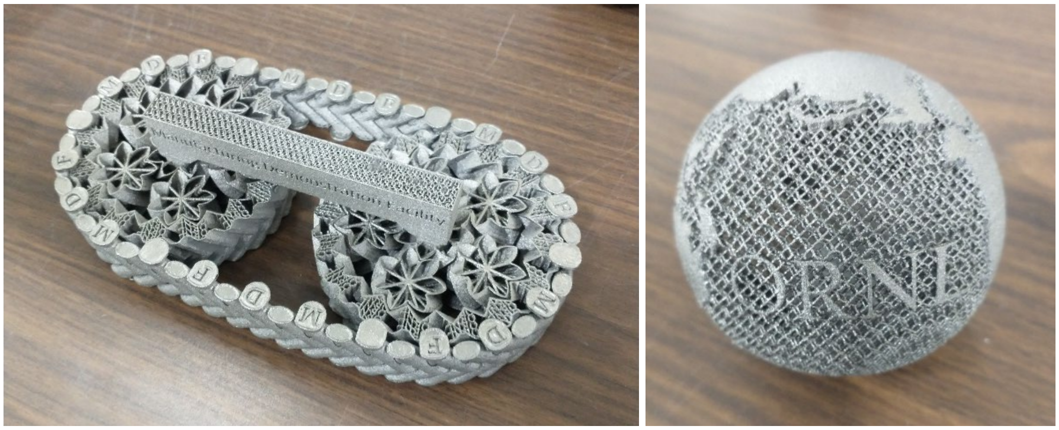

Figure 16. Examples of PBF parts at the MDF.

Larger scale metal AM machines typically rely on DED technology, which can achieve much higher build rates, and build volumes up to more than 5.7 m^3. Although some large-scale DED machines use metal powder feedstock, the largest and highest throughput systems are usually wire fed. The wire can be melted using lasers or wire arc (gas metal arc welding, gas tungsten arc welding, or plasma arc welding) or a combination of both. In contrast to the small-scale PBF systems, the DED process almost always requires machining to achieve acceptable surface quality and geometric tolerances.

Some examples of large-scale DED demonstration parts are shown in Figure 17; specifically, the right panel shows a demonstration part that was built to resemble the typical shape of a propeller (without aiming for a proper design). The ever-increasing build rates and build volumes enabled by this technology present immense opportunities to replace many of the larger castings and forgings traditionally used in the hydropower industry, including wicket gates, shafts, and even a complete turbine runner. Additionally, similar to the PBF technology, there could be some additional opportunities to including light weighting support structures and internal passageways for fluids or wired instrumentation. Although there are many successful DED prints of tooling and demonstration parts, this technology has not yet been widely adopted in industry for direct manufacturing of production parts. Further research is needed in the areas of part validation, testing, and certification to help industry mitigate the risk of adopting the technology.

Figure 17. Examples of DED parts at the MDF.

Although the most suitable applications for the hydropower industry are likely to benefit from direct fabrication of parts, some situations might also benefit from additively manufactured tooling. As with traditional manufacturing, tooling would typically be used in situations that require higher quantities of the same part to achieve a lower individual part cost. Some examples of additively manufactured tools include stamping dies for sheet metal, die casting molds, injection molds, and compression molds. Figure 18 shows some examples of additively manufactured tooling. Use of additively manufactured metal tools is fairly mature in other industries but has not been widely adopted in the hydropower industry.

Figure 18. Examples of additively manufactured tools.

3.1.2 AM of Polymers and Fiber-Reinforced Polymer Composite Parts

Polymer/plastics and fiber-reinforced polymer composites (FRPCs) are the most common AM media. Many small-scale polymer filament printers are available commercially that generally have small build volumes of less than 0.85 m^3; while large-scale systems are often pellet fed and can have build volumes greater than 280 m^3. ORNL and the University of Maine Composites Center[31] are researching large-scale AM and bio-based thermoplastics using a printer with a build space of 18.3 m long × 6.7 m wide × 3 m tall (build volume of 368 m^3) that can print up to 68 kg/h of deposited material (expandable to 630 m^3 and 227 kg/h).

Since the introduction of AM, additively manufactured polymer parts have typically been used for prototyping because of their inherent interlayer weakness. However, more recently, advances have been made to the materials and processes to greatly improve the interlayer strength and overall strength of these parts. Consequently, these parts have more recently been used as end-use parts when the strength properties are sufficient for the intended applications. An interesting example of this is when Cadens[32] incorporated additively manufactured polymer parts in a low-head hydropower application, including a draft tube, inlet thimble, and turbine runner (Post et al. 2020). Figure 19 shows a rendering of these parts that were additively manufactured using carbon fiber–reinforced acrylo-butadiene-styrene and where they were installed in the plant.

[31] https://composites.umaine.edu/.
[32] http://www.cadensllc.com/.

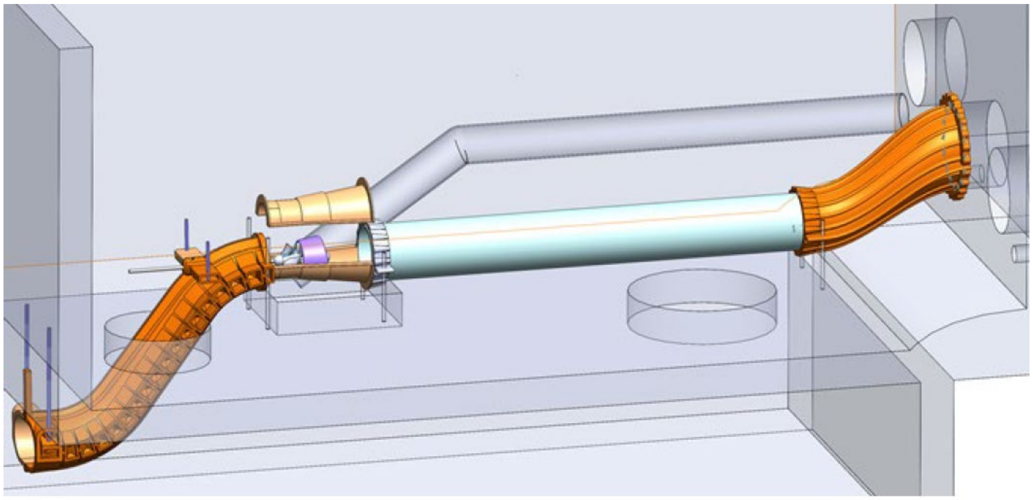

Figure 19. Additively manufactured polymer composites on Cadens facility.[32]

In some situations, direct printing of the end-use parts is not practical or possible because of strength or design limitations. However, in these cases, AM of tooling is becoming more prevalent and has been used to produce layup tools for wind turbine blades, aircraft component manufacturing, and even concrete precasting molds (Appendix B3). Figure 20 shows additively manufactured wind turbine blade molds printed using big-area AM (BAAM). The use of additively manufactured plastic tooling for FRPCs has not been widely adopted in hydropower. This could be because of the limited use of composites in general, which is discussed in Section 3.3.

Figure 20. (Left) printed wind blade mold and (right) finished mold.

Another area with tremendous potential is the complementing of traditional metal casting processes with additively manufactured casting patterns. This allows end users to achieve the same final material casting properties, only much faster and at a lower cost. Appendix B2 presents a case study that used additively manufactured patterns to successfully manufacture hydrofoils and spokes for a hydrokinetic system. The parts presented in the case study were fairly small, but the idea of using additively manufactured patterns would also provide a tremendous advantage for many of the large-scale forgings and castings used in the hydropower industry. In comparison, producing large-scale casting patterns with traditional methods can be very time consuming and labor intensive since the pattern has to be machined from much larger material stock, producing excessive waste, or be built up from smaller material stock, requiring extensive manual labor.

3.1.3 AM of Concrete Structures

Concrete AM systems are available in many different forms, most of which rely on extruding mixed concrete on selective toolpaths to form the desired shapes. Concrete AM has potential for both new construction and the repair of legacy hydropower systems, and there is a range of technologies that can be practically used to facilitate construction and repair depending on the intended size of the parts to be fabricated. These technologies would include direct printing of concrete or printing of molds or forms for use in traditional concrete fabrication.

Gantry-based concrete printing systems are now commercially available (Figure 21) with print volumes as large as 100 × 100 × 18 ft, and larger custom machines can be ordered. These printers are typically used to print buildings, monuments, and large artistic displays. Generally, an end user would contract with a printer owner to fabricate the structure as a service. The printer owner would establish cost to build based on their expected rate of return. These printers can print extremely complex shapes with curved lines or channels. Printing is done on-site, which provides added benefit in overcoming logistics and transportations concerns. The technology is mature and readily available and is being used widely for commercial and residential buildings. Other more demanding applications being tested include wind tower base structures, such as those currently being explored by GE Renewables.[33]

Figure 21. ICON printer building a structure.

The ORNL SkyBAAM system (Figure 22) is a tensioned cable-based system that uses a large overhead crane and three base drives to position the print head. The printer is capable of printing 1,000–,2,000 lb/h. The build rate is somewhat limited by curing of the layers of concrete which is necessary to prevent sagging of the layers. The build volume is limited by the size of the crane employed to do the printing but can be quite large. It was also designed to be relatively easy to set up in remote locations, which could be a significant advantage for construction logistics. SkyBAAM is a research prototype technology that is not yet commercially available; however, it points to the potential to build exceptionally large structures in the future (Atkins et al. 2020).

[33] https://www.ge.com/news/reports/take-me-higher-3d-printed-concrete-could-give-wind-turbines-powerful-lift.

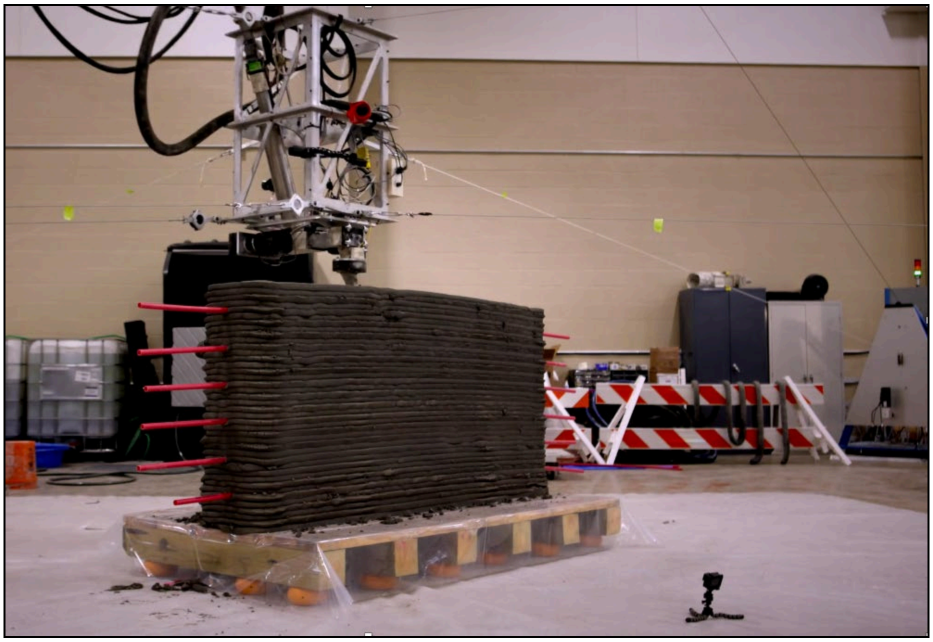

Figure 22. ORNL's SkyBAAM building a test wall.

Some recent studies regarding the use of combinations of concrete, sand, gravel, and rock to construct a dam with a concrete exterior suggest some advantages with respect to safety, economics and construction, and the environment (Jia et al. 2016). The unique use of a concrete overlay placed over the mixed material interior provides the benefits of a gravity-type dam as protection for flood overtopping, while minimizing the volume of concrete throughout the structure.

AM with concrete presents many opportunities for newly constructed dams, but further research is needed to determine how it could be implemented into rehabilitation or repair projects for hydropower.

3.1.4 AM of Tooling for Sand Casting

Recent advances in sand casting involve the application of AM for sand molds using the binder jet process (Upadhyay, Sivarupan, and El Mansori 2017; Le Néel, Mognol, and Hascoët 2018). Binder jet technology is similar to the PBF technology described in Section 3.1.1, only instead of melting the material, a liquid binder is selectively deposited onto the powder to form the part. Using foundry sand as the powder material, sand castings can be made directly as opposed to the traditional sand casting method that requires a pattern to be manufactured first. Use of the binder jet AM process to produce sand casting molds is now a mature and widely used process for cost-effective sand casting. As an example, ExOne[34] now has facilities around the globe where customers can supply a build file and have molds produced on demand. Additionally, the very large commercial binder jet system of 4 × 2 × 1 m by Voxeljet[35] was introduced in 2016, and it could lead to several new applications for large-scale hydropower components. An even larger machine capable of building parts up to 9.5 m in diameter and 60 tons in weight is under development by Fraunhofer and GE Renewables for offshore wind castings.[36] Systems even larger could be built in the future to accommodate the ever-increasing size of components. The maturity and financial viability of this model is a good indicator that most of the risk has been removed from this process.

[34] https://www.exone.com/.
[35] https://www.voxeljet.com/.
[36] https://www.ge.com/news/press-releases/ge-renewable-energy-fraunhofer-igcv-voxeljet-plan-develop-world-largest-sand-binder-jetting-3D-printer-offshore-wind-turbines.

Figure 23 shows an example of a turbine runner that was successfully manufactured using this technology; however, this technology has not yet been widely adopted in the hydropower industry. Sand casting is also discussed in Section 3.2.3.

Figure 23. (Left) sand cast–printed via AM and (right) the resulting runner. From (Kurup et al. 2018). Photo credit: Voxeljet.[37]

3.1.5 AM of Magnetic Material

Many low-head and run-of-river locations are likely to become the face of new hydropower in the next decade. Additionally, as highlighted in Section 2, hydropower operations must become more variable and flexible to complement energy production from more intermittent sources such as solar and wind. To optimize the use of hydropower plants and increase overall powertrain efficiency, innovations in generator technology are highly desired. Therefore, variable-speed generators like those already successfully employed in the wind energy industry might be adapted to hydropower applications and support the development of more small and flexible hydropower plants.

Variable-speed generators rely on the use of permanent magnets in the generator rotors, which poses concerns for the supply chain related to critical materials in the United States. Permanent magnets have been additively manufactured using several different processes, including PBF, binder jetting, and fused deposition modeling. ORNL has developed a process that uses less magnet rare earth materials, thereby reducing reliance on foreign sources of critical materials. ORNL has improved a mixture of materials used to 3D print permanent magnets with increased density, which can yield better performing magnets for wind turbines, electric motors, sensors, and vehicle applications. ORNL is currently part of the Critical Materials Institute, which is led by Ames National Laboratory and involves a wide range of partners including universities, industry, and labs. This partnership is collaborating to develop solutions across critical material life cycles, decreasing costs and uncertainty.[38] This can allow more flexibility for generator designers when considering implementing AM of magnetic structures. Permanent magnet rotors have been demonstrated for both motors and generators, but further research is needed to determine which process designs would be best suited to low-head hydropower generators.

3.2 NOVEL MACHINING AND CASTING PROCESSES

3.2.1 Subtractive Manufacturing

Machining processes can be classified as conventional machining (e.g., milling, turning, and drilling) and nonconventional machining (e.g., laser beam, abrasive jet, electrochemical machining, and electric discharge machining). In conventional machining (also called subtractive manufacturing), metal is removed by a shearing action from interaction with a sharp cutting tool. The machining process can be single point (turning, boring, and shaping) or multipoint (milling and drilling). Significant advances have been made in the modeling of machining processes, either through finite element analysis or through first-

[37] https://www.voxeljet.com/case-studies/foundry/3d-printing-saves-costs-in-sand-casting/.
[38] https://www.energy.gov/eere/amo/critical-materials-hub.

principles modeling (Sadeghifar et al. 2018). For example, analytical modeling of chatter in machining operations using dynamic analysis has seen substantial progress in the past two decades (Altintas et al. 2020). Recent research efforts for machining have focused on leveraging industrial internet of things architecture to monitor the machining process and machine status. This has enabled the application of machine learning and artificial intelligence to optimize machining process parameters (Kim et al. 2018). Nonconventional machining methods are used for machining hard-to-cut materials, complex shapes geometries, microscale machining of part features, and ultraprecision part requirements in surface roughness and tolerances (Jain 2009). Nonconventional methods are classified as mechanical (abrasive jet, water jet, and ultrasonic), thermoelectric (laser beam and electric discharge), or chemical (electrochemical machining) (Jain 2009). Nonconventional methods are seeing increased applications in the automotive, aerospace, electronics, and medical industries.

Another novel research area with subtractive machining includes developing new surface texturing strategies that can affect flow characteristics of fluids moving past the parts. This strategy has been demonstrated as a passive method for reducing friction between two surfaces; a friction reduction of up to 30% was feasible with a textured surface (Bruzzone et al. 2008). Some of the applications include reciprocating components in an automotive engine (Ronen, Etsion, and Kligerman 2001), mechanical seals, sliding bearing, magnetic storage devices, and biomedical devices (Vencl et al. 2019). In addition, reducing hydrodynamic skin-friction drag through surface texturing has a huge potential for energy savings in applications ranging from the propulsion of marine vessels to transporting liquids through pipes (Bidkar et al. 2014). Advanced nonconventional machining methods such as laser beam machining, electrochemical, and electric discharge machining can generate surface features and surface roughness at the microscale and nanoscale (Jain 2009). Nonconventional machining methods are suitable for fabricating textured surfaces for reduced friction. This is achieved by machining surface features (e.g., dimples, pores, and pillars) and reducing the surface roughness to generate surfaces resulting in lower friction losses (Bruzzone et al. 2008; Bidkar et al. 2014). Some examples include laser surface texturing to produce an array of microdimples or pores (Bhaduri et al. 2017), electrochemical micromachining for a dimpled surface (Zhu et al. 2009), and sink electrical discharge machining of surface features (Guo et al. 2019). The application of textured surfaces for lower friction presents an opportunity to reduce losses in a hydropower system; the potential applications would be turbine bales and rotors, and for water flow in pipes, mechanical seals, and bearings. A few challenges exist for the application of lower friction surfaces for hydropower applications. First, the optimal surface texturing patterns for different hydropower applications, such as reducing skin-friction drag in pipes, need to be evaluated. Second, nonconventional machining methods need to be compared and evaluated for feasibility and cost-effectiveness for the desired surface texture.

Appendix B4 presents a new idea showing how surface texturing could be used to improve friction among components.

3.2.2 Hybrid Manufacturing

Hybrid manufacturing processes incorporate both additive and subtractive processes on the same machine (Figure 24). For parts that require higher quality surface finish or more accurate geometric tolerances, this combined process saves time by eliminating the lengthy process of transferring, scanning, and reorienting additively manufactured parts on the machining centers. Those tasks are becoming more cumbersome as the size and scale of additively manufactured parts continues to grow.

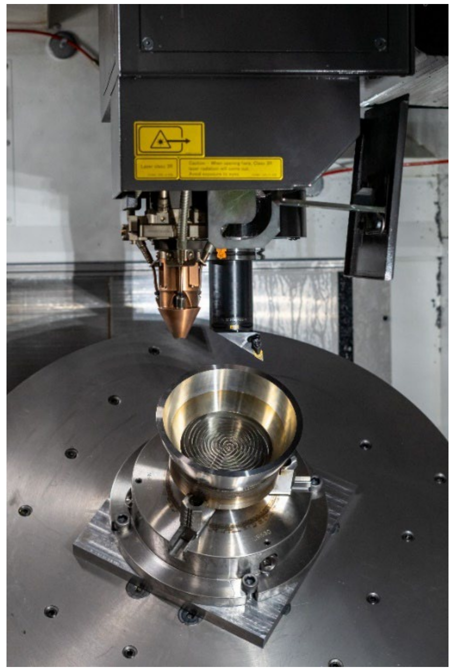

Figure 24. Example of a hybrid manufacturing system at ORNL's MDF.

Another interesting approach for the hybrid process is where the additive processes alternate with subtractive processes throughout a build. This allows for machining areas of a part that would be difficult or impossible to reach if the additive process had already been completed ahead of time. At the end of the build, the part would be complete and would not require any further machining.

Although still a relatively new approach requiring further research, hybrid manufacturing promises the capability to build unique parts that are currently not possible using separate additive and subtractive processes. An obvious hydropower application would be to manufacture a turbine runner with this method to eliminate the need for welding, while still avoiding specialized long-reach machining tools. Figure 25 shows the alternating process steps, where the build alternates between additive and subtractive processes. This demonstrates how the subtractive tool does not need to reach the bottom of the part in Figure 25d since it was already machined in the prior subtractive step shown in Figure 25b.

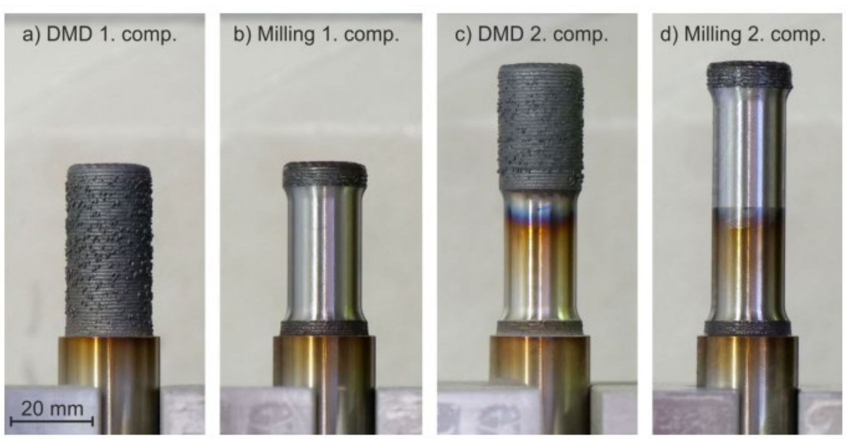

Figure 25. Hybrid process using alternating additive and subtractive processes (Eisenbarth 2020).

3.2.3 Novel Casting Processes

Traditionally, casting includes the steps of melting metal of the desired composition and pouring the metal into a mold (Tlusty 2000). The metal is allowed to cool down and solidify to achieve the desired geometry. Casting is widely used in many industries such as automotive, defense, and construction. Different casting processes are classified according to the material and structure of the mold, which is mainly either expendable or permanent. The most common expendable mold process is sand casting, where the mold can be broken and separated from the casting. As mentioned in Section 3.1.4, AM can offer opportunities to directly print end-use parts and eliminate the need for traditional casting. However, some situations will still benefit from using a traditional casting process. In these situations, there are opportunities for advancement directly related to traditional sand casting processes.

Numerical modeling of the casting process has seen great advances in recent years. This has enabled efficient modeling of metal flow and solidification, which is used to optimize casting parameters in relation to the solidification structure, part material properties, and defects (Pattnaik, Karunakar, and Jha 2012; Stefanescu 2015). Advances in casting processing methods have shown additional improvements. For example, the semisolid casting method can be used to produce near net shape parts (Hirt et al. 2006). Friction stir processing has been shown to reduce defects such as porosities in the casting process and improve material properties (Mishra and Ma 2005). However, the application of casting processes in hydropower has been limited (Kafle et al. 2020). Although multiple hydropower components can be manufactured with castings, the manufacturing of hydropower turbines presents an opportunity because of the large size and the potential geometric complexities (Kafle et al. 2020). Typically, hydropower turbines are manufactured using milling, grinding, and polishing. This can lead to increased costs as the size and geometric complexities of the hydropower turbines increase. The large size limits the use of AM as well. An efficient casting process can significantly reduce the manufacturing costs for hydropower turbines. However, there are several challenges to the application of castings for hydropower turbines. These include design of the casting molds and patterns, strategies for melting and pouring the metal, design of the gating system, and modeling and predicting material properties and defects in the final product. Furthermore, there is the challenge of long lead times due to the design and modeling requirements of the process and process parameters.

An innovative semisolid casting process that is currently under development is presented in Appendix B6. This process aims to achieve a reduced heat input and a superior surface finish compared with traditional sand castings. This process uses a lower melt temperature and a permanent die instead of expendable sand-casting molds.

3.3 INNOVATIVE MATERIALS

Novel material development is a growing and constant area of active research for a wide variety of industries. The hydropower industry can always benefit from new materials that are cheaper, lighter, stronger, more corrosion-resistant, easier to repair, and more environmentally friendly. These material innovations have a high likelihood to increase part lifetime, increase efficiency, and decrease costs associated with O&M. For example, new metal alloys are constantly being developed; Appendix B2 presents a case study where a new aluminum alloy was recently developed to achieve better corrosion resistance over traditional aluminum alloys. New formulations of concrete have recently gained renewed attention and are being developed to be higher strength, self-healing, and more environmentally friendly.

Additionally, as the hydropower industry looks to advanced manufacturing to create next-generation parts, innovative materials for the hydropower industry should also be considered. A particular area of research interest for hydropower will be the adoption of FRPCs, which is discussed in more detail in Section 3.3.1. FRPCs offer opportunities for lighter weight, lower maintenance, and longer service lives of parts than some conventional metallics that are currently used. For example, A WPTO-funded project (DOE-FOA-0001286) awarded to Composite Technology Development, Inc., explored using a carbon FRPC single-blade runner to improve reliability weight efficiency, fatigue resistance, and maintenance reduction (Figure 26).[39]

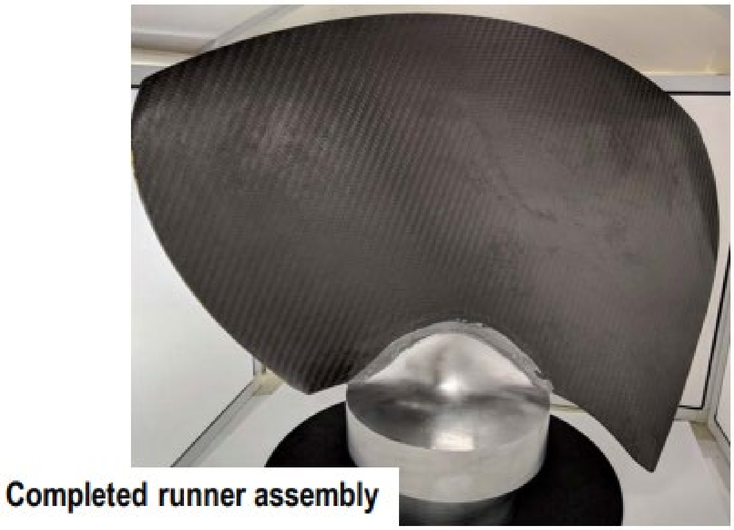

Figure 26. A single-blade carbon fiber polymer composite runner.

Although using FRPCs to manufacture runners is a high impact area, FRPCs offer similar advantages for other hydropower components as well. Other potential applications for FRPCs for hydropower components include composite bearings,[40] [41] composite pipelines or conduits (Kasharin et al. 2015), and composite wicket gates (Vijay et al. 2016). In 2016, the US Army Corps of Engineers sponsored a project exploring using glass FRPCs to replace timber wicket gates. Use of the composite wicket gate improved life expectancy by 35 years and saved $5.29M/location in materials costs alone. Overall, FRPCs are able to make a major impact in cost savings, repairability, life expectancy, and reliability in hydropower components.[42]

Quaranta and Davies (2022) present a comprehensive review of innovative materials that could be suitable for future hydropower applications and discusses their performance, advantages, and limitations. In particular, they review composites for turbines, alternative materials for dams and waterways, innovative bearing and eco-friendly lubricants and seals, aiming at improving performance while reducing costs, maintenance, and environmental impacts.

3.3.1 Fiber-Reinforced Polymer Composites

FRPCs can be used for components that experience high surface stresses such as gates, moveable structures that control water, and runners. These components typically fail before their service life ends because of corrosion, sediment impact, and cavitation erosion. With the correct materials selection, FRPCs could prevent premature failure and extend service lifetimes while light weighting compared with currently used steel alloys. The light weighting of the gates, moveable structures, and runners could decrease wear and tear on motors and hand-operated equipment. This would improve the longevity of

[39] https://www.energy.gov/sites/prod/files/2019/12/f69/08_EE0007248_CTD_Fabian_CompositeHydro_FINAL.pdf
[40] http://www.acmbearings.co.uk/markets/hydropower/
[41] https://www.gallagherseals.com/blog/cip-composites-hydro-applications
[42] https://onlinepubs.trb.org/onlinepubs/conferences/2016/CMTS/Presentations/19.JonathanTrovillion.pdf.

existing equipment and improve operation efficiency and availability of flow-passage devices, especially in emergency situations such as floods or the need to "stop-flow" through turbine operation. Replacement of these types of items that are crucial in emergency situations could occur more quickly with FPRCs and make installation easier because of their light weight.

Most polymer composite materials are considered lightweight compared with metallic materials, but the chemical resistance, durability, and mechanical properties greatly depend on the selected polymer and reinforcing filler. The selected polymer can either be a thermoset or thermoplastic material. Thermosets are polymers that contain irreversible crosslinks between polymer chains, and thermoplastics are polymers that become a melt when heated and that can be remelted once solidified. Table 2 summarizes the characteristics, manufacturing methods, and potential polymers of interest for hydropower.

Table 2. Comparison between thermosets and thermoplastics

Polymer class	General advantages	General disadvantages	Manufacturing methods	Potential polymers of interest
Thermosets	• Higher mechanical properties • Corrosion resistance • Low thermal conductivity • Higher temperature resistance	• Not easily recycled • Time-intensive manufacturing methods • Lower ductility • Not easily repaired	• Resin transfer molding • Vacuum-assisted resin transfer molding • Filament winding • AM (low TRL) • Pultrusion • Reactive injection molding	• Epoxies • Vinyl esters • Polyesters
Thermoplastics	• Low melting temperature • Easily recycled • High impact resistance • Corrosion and chemical resistance • Easily repaired	• Lower mechanical properties • Susceptible to UV • Lower temperature resistance	• AM (high TRL) • Compression molding • Injection molding • Pultrusion • Thermoforming	• High-density polyethylene • Ultrahigh molecular weight polyethylene • Polypropylene • Polyethersulfone or polysulfone • Polyetherketones • Polyethyleimine

Thermoset materials are typically higher performing than thermoplastics and are typically used in the wind, aerospace, and marine industries. Potential thermoset composites to consider for hydropower applications would be epoxy–glass fiber/carbon fiber composites and vinyl ester–glass fiber/carbon fiber, while a variety of glass- or carbon-filled polymers such as high-density polyethylene, ultrahigh molecular weight polyethylene, polypropylene, polyether sulfone, and polyether ketones could be used for thermoplastic composites. Thermoplastic composites are easily repairable because they can be welded, which can be achieved at temperatures much lower than metallic welding. Furthermore, use of thermoplastics could enable the feasibility for underwater repair, typically considered when components are under water at significant depths, creating the opportunity to decrease downtime from component failure. Oppositely, thermosets cannot be easily welded and would require the part to be grinded down and repaired with more conventional techniques.

Thermoset and thermoplastic composite manufacturing has many differences, but both can be used for making hydropower components. For thermoplastics, most large-scale manufacturing, apart from AM, relies on injection molding and compression molding. Injection molding and compression molding both form the composite to the shape of the mold, which has a high capital cost, but once the mold is in place both methods have short cycle times. Water-assisted injection molding is also a viable technique for thermoplastic manufacturing where water is pushed through the polymer melt after injection to produce channels within the part. For thermoset composites, castings and resin transfer molding are the primary processing techniques that could be used for hydropower components. Much like thermoplastic composite manufacturing, thermoset composites manufacturing relies heavily on mold designs to produce the final part. Often, pre-pregs, which are unidirectional or woven fiber mats bonded together through a partially cured thermoset, are laid up onto a mold and then further impregnated with thermoset resin, typically through resin transfer molding or vacuum-assisted resin transfer molding. For example, a composite runner comprised of glass fiber and vinyl ester could be manufactured through hand layup and resin transfer molding. Thermoset composites typically outperform thermoplastic composites in mechanical properties because of the polymer structure and length of fibers maintained during the manufacturing process.

Although FRPC components have the potential to make a big impact on hydropower technologies, selecting the proper composite system and manufacturing technology will be important to fit the performance needs of certain hydropower components. In composites, fiber orientation greatly influences the material properties and introduces anisotropy. For thermoplastics, fiber orientation is determined during processing based on the processing parameters (e.g., pressure, temperature, and time) and viscosity of the polymer melt as it flows into the mold. When using pre-preg with thermoset composites, the fiber orientation is dictated by how the pre-preg is laid up onto the mold. Although anisotropy is a greater concern in thermoplastic composite manufacturing than thermoset composite manufacturing, hybrid thermoplastic manufacturing techniques such as AM compression molding provide the opportunity to orient the fibers through AM into a mold before compression molding into the final part. The AM part of the process allows the fibers to be oriented in the direction that best suits the final application, and the compression molding part allows for packing of the material to remove porosity. To inform processing and materials section, quantifying the performance metrics and stresses exerted on the currently used components is essential. With all of the potential polymer and fiber candidates and potential processing techniques, there is significant opportunity and potential to further investigate replacing metallic components with FRPCs for hydropower.

3.3.2 Functionally Graded Materials

Using modern metal AM techniques, parts can be manufactured using multiple materials on a single build. These processes can be used with both powder and wire feedstocks and can achieve very close control and adjustment of part chemistry when using multiple materials. This allows designers to take advantage of the desirable characteristics of each material at different locations throughout a part. One opportunity for this technology could be to develop a surface that resists cavitation and erosion on top of a strong and ductile part core. Most of the part would be comprised of the core material (likely stainless steel), so the bulk properties will most closely match those properties. However, there would also be a gradual transition to a different material (likely a carbide ceramic) to provide a wear-resistant outer surface.

This type of part can also be accomplished by applying separate postprocess coatings as presented in Section 3.4; however, this method might prove to be a more reliable and robust solution since it does not rely on chemical bonding and does not have a discrete interface that can suffer from material incompatibilities. This method could be a solution to some of the spalling or de-bonding failures that have traditionally been observed with coatings.

Functionally graded carbide has been explored (Fan, Fang, and Guo 2013). Also, joints of functionally graded carbide to steel have been made (Chen et al. 2013), but the opportunity for laser advanced manufacturing is eminent with laser-based coating trials (Riabkina-Fishman et al. 2001). These works could be leveraged to print base steel or metal materials that have a gradation to carbide material during the entire print, making a functionally graded part where none of the metal is exposed and the carbide outer shell is carefully graded and mechanically and chemically interlocked and integrated into the base metal.

3.3.3 Self-Lubricating Bearings and Environmentally Acceptable Lubricants

As in all kinds of machinery, from transportation to energy productions systems, bearings and lubricants are essential to support rotating components and decreasing friction to improve performance, reduce maintenance, and increase the components' life span. In hydropower, bearings and lubrication are needed in several components, but most importantly in the powertrain and gates. In particular, hydraulic turbines are filled with pressurized petroleum-based mineral oil to lubricate all the bearings of the runner hub, blades, and all the sliding parts (Quaranta et al. 2021). As discussed in St-Germain (2018), oil leakage from hydropower runners causes operational issues and has serious environmental impacts on the local aquatic ecosystem. To address these issues, self-lubricating bearings and EALs are being studied and developed. Self-lubricating bearings are made of tribomaterials (i.e., that have properties well suited for lubrication and against friction and wearing) such as bronze (metal based) or Teflon (plastic based) (Quaranta and Davies 2022). Composites and self-lubricating polymers could be used for thrust bearings in runners and trunnion bearings in gates (Somberg et al. 2021; Saravanan and Emami 2021).

As defined by the US Environmental Protection Agency, EALs are "lubricants that have been demonstrated to meet standards for biodegradability, toxicity and bioaccumulation potential that minimize their likely adverse consequences in the aquatic environment, compared to conventional lubricants" (U.S. Environmental Protection Agency 2011). The most common types of EALs are bio-based oils (derived from natural sources and often referred to as vegetable or plant oils), synthetic esters (formulated chemical synthesis of bio-based materials), and polyalkylene glycols (a type of synthetic lubricant made from petroleum-based material but highly biodegradable). In addition, lubricants include additives to enhance the tribological properties. Conventional additives often contain heavy metal, halogen, and/or sulfur compounds, thus failing to meet the EAL's toxicity or biodegradability requirements. Among the new material propositions for additives, ionic liquids are showing encouraging results as efficient lubricant additives (Zhou and Qu 2017). In particular, researchers at ORNL have recently proposed a new class of ionic liquids as novel lubricant additives for marine energy applications that have demonstrated dramatically reduced marine toxicity from commercial so-called bio-derived additives (10–100 times lower), good biodegradability according to US Environmental Protection Agency standards, and significantly improved lubricity (30%–40% friction reduction and 10–100 times better wear protection), as compared with commercial baselines. The research has resulted in US Patent Application 17/078,668 (2020) and International Application PCT/US2021/043260 (2021). In addition, to help the hydropower industry mitigate the risks of adopting EALs, DOE has recently promoted SBIR and Small Business Technology Transfer funding opportunities in 2018 and 2019 focused on reducing costs and increasing performance.[43] Three small businesses were selected for the Phase II of these funding: Polnox Corporation[44] to develop eco-friendly additives for hydropower lubricants using two of the company's proprietary additives and additional treatments to improve performance; Tetramer Technologies LLC[45] to develop a synthetic biodegradable hydropower turbine oil based on esterified propoxylated glycerol; and

[43] https://www.energy.gov/sites/prod/files/2020/03/f72/EAL-fact-sheet.pdf.
[44] http://www.polnox.com/polnox/Home.html.
[45] https://tetramer.com/.

Rikarbon Inc.[46] to use its proprietary technology to produce and commercialize EALs (BioLubes) from natural oils and plant matter.

3.4 NOVEL COATING PROCESSES

Coatings are applied to the surface of an object to prevent wear and component degradation and to enhance material properties for specific applications. In comparison with heat treatment, alloy processes and coating processes have an advantage over many material enhancement methods since coating layers can reduce the cost and neglect scarcity of materials even though the coating thickness per layer rarely exceeds micrometers. This means less material is needed to form coating layers on substrate materials (Fotovvati, Namdari, and Dehghanghadikolaei 2019). Coatings offer a range of properties such as corrosion/wear resistance, greater surface hardness, modified surface texture, thermal/electrical insulation, enhanced wettability, and hydrophobicity (Bhushan and Gupta 1997; Fotovvati, Namdari, and Dehghanghadikolaei 2019). The most useful coating methods include physical vapor deposition, chemical vapor deposition, micro-arc oxidation, sol-gel, thermal spray, and polymer coatings. Selecting the best coating methods for different applications such as mechanical, corrosion, or biocompatibility requires that the specific type of coating selected be considered carefully (Thakare et al. 2007).

3.4.1 Antifouling Coatings

Antifouling coatings were originally used in marine applications to protect the hulls of ships, but these techniques have been extended to freshwater and were approved as a useful tool for minimizing biofouling effects in hydropower. Management of biofouling in freshwater facilities commonly includes the use of screens, filters (e.g., high-flow microfiltration), chemical injection (e.g., chlorine), thermal backwashing, manual cleaning, and foul-release and biocide release coatings. Based on available literature, coatings are good candidates and have large potential opportunities to eliminate the fouling problem in hydropower facility components. The most common type of antifouling coating is a surface paint that leaches a biocide into the water to remove organisms; however, it also produces toxic substances that are discharged into the water. In response, new coatings have been, or are being, developed, including nontoxic coatings that rely on low-surface tension to create smooth/slippery surfaces. For example, PNNL developed an innovative coating called Superhydrophobic Lubricant Infused Composite (SLIC) that improves hydropower operations and can reduce the need to shut down plants to remove zebra mussels.[47] SLIC is a durable hydrophobic and antifouling coating 10 times more liquid repellant than Teflon and nontoxic. The nanostructured surface holds in place a lubricant-like oil that repels biofouling. Among other advantages, this coating is self-healing, extending its durability; it can be manufactured from inexpensive, readily available materials using common industrial processes; and it can be applied to large and irregular surfaces. On the other hand, a winner of an International Hydropower Association Young Researcher Award proposed to use hydrophobic rare-earth oxide materials as a coating to prevent biofouling.[48] Other new developments in antifouling technology are use of nonmetal fouling repellants in traditional coatings, nontoxic fouling-release coatings, and thermal spray coatings. Corrosion of plant components, drag-induced losses, and scale-formation are other issues that can affect the performance of hydropower systems and can be addressed by using coating techniques. Appendix B5 presents a new idea on how an antifouling coating can be achieved for hydropower parts.

Choosing an appropriate coating requires consideration of the efficacy of the coating, the material to be coated, flow conditions experienced by the component, scouring and other exposure, raw water impacts,

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[46] https://rikarbon.com/.
[47] https://www.pnnl.gov/available-technologies/slic-hydrophobic-and-antifouling-surface-coatings.
[48] https://www.hydropower.org/blog/the-case-for-versatile-hydrophobic-rare-earth-oxide-coatings-in-hydropower-systems.

and various operational constrains. Currently, the development of antifouling coatings faces several challenges:

- Continuous flows and high velocities increase the dissolution rate of biocides and the surrounding coating matrix of ablative coatings, which decreases the coating life span. Reduced life spans without the capability to easily repair coatings will increase downtime and cost.
- Intermittent low velocity flows allow more settlement on foul-release coatings but reduce the dissolution rate for biocide-based and ablative coatings (Wells and Sytsma 2009).
- Antifouling coatings could affect the environment. Chemical methods have been demonstrated to treat biofouling but are expensive and might have detrimental effects on the environment. For example, heavy metal-based coatings are both effective and durable but work by releasing biocides, such as copper, into the surrounding water, which might impact native flora and fauna.
- Large-scale use of coatings in freshwater facilities to mitigate mussel fouling might be uneconomical. Wells and Sytsma (2009) note that the costs for silicone coatings over a five-year period are $127/m^2, with an effective life span of up to six years. Thus, one way to increase cost-effectiveness is to develop coating techniques and materials with life spans of 50+ years (Wells and Sytsma 2009).

Advanced antifouling coatings have the potential to prevent biofouling at a much lower cost without causing harm to the environment, reduce shutdown time for removing fouling, and reduce maintenance time and cost. This could improve the durability, efficiency, and overall performance of the hydropower system by reducing mussel attachment and clogging of water intake and delivery pipes and eliminate the corrosion risk of steel and cast-iron pipelines caused by decay of dead mussels. Additionally, future research could target coatings that achieve other objectives in addition to antifouling, such as corrosion and erosion resistance.

3.4.2 Erosion- and Cavitation-Resistant Coatings

Use of coatings is an efficient way to reduce erosion cavitation, and various coatings and coating methodologies have been developed to increase erosion-cavitation resistance. The coating materials suggested for combating erosion cavitation encompass carbides, cermet of different compositions, intermetallic composites, intermetallic matrix composites with titanium carbide reinforcement, composite nitrides such as titanium aluminum nitride, and elastomers. A few of them have also been used commercially (Singh, Tiwari, and Mishra 2012), such as hard coatings made of tungsten carbide; WC-CoCr (i.e., hard ceramic tungsten monocarbide (WC) phase with a softer cobalt-chrome binder) was used as a significant step in the reduction of turbine erosion (Karimi et al. 1995). The existing coating methodologies for erosion cavitation include thermal spraying, arc plasma spraying, and hard coatings applied by high-velocity oxy-fuel processes. These coating methods have been applied commercially in coating hydropower plants, especially hydropower turbines. In addition, substantial research exists on coating techniques with potential for use in hydropower. This research is at the laboratory level but has shown promise for use in laser surface hardening and cladding, chemical vapor deposition, physical vapor deposition, and plasma nitriding.

The required evaluation of erosion-cavitation coatings for use in hydropower is similar to that for antifouling coatings, such as efficacy of the coating, the material to be coated, flow conditions, scouring and other exposure, raw water impacts, and various operational constrains. The challenges/gaps of erosion-cavitation coating development include the following:

- Damage from erosion and cavitation influenced by several parameters, such as hydrodynamics, component design, environment, and material chemistry, require greater understanding.
- Coatings have several physical interphases that are weak areas where mechanical and electrochemical failures can originate, and some commercial coating methods and materials, such as high-velocity

oxy-fuel, result in microcracking, disbanding, and problems with embedded ceramic solutions when applied on hydropower turbine components (Singh, Tiwari, and Mishra 2012).
- Modeling, testing, and predicting hydro-abrasive erosion are challenging because of the many parameters involved and their complex interactions.

Erosion-cavitation coatings for hydropower eliminate corrosion by isolating the metal from the harsh environment and reduce the effects of cavitation and erosion. The application of coating technologies increases efficiency and asset life and at the same time lowers maintenance costs. Although the coating does not fully prevent erosion of the base material, the time between overhauls is extended. For instance, coatings sprayed on-site might be of inferior quality compared with factory coatings, but runners do not need to be changed and transported. With on-site recoating, frequent coating repairs are feasible, which contributes to limiting erosion propagation.

3.4.3 Self-Healing Coatings

Koochaki et al. (2021) describe development of enriched epoxy coatings with self-healing features on wet surfaces for practical corrosion protection issues. Polyetheramine was chemically engineered by grafting catechol units and was then encapsulated in microcapsules to be embedded into an epoxy resin deposited on steel panels. Scanning electron microscopy analysis revealed formation of the spherical microcapsules, and Fourier transform infrared spectroscopy and thermogravimetric analyses confirmed the successful encapsulation and highly responsive self-healing dosages of catechol-modified polyetheramine. According to the electrochemical impedance spectroscopy results, monotonically increasing variation with time of the charge transfer resistance was correlated with a fast and effective underwater self-healing performance for the sample using a healing agent containing 40% catechol by weight.

3.4.4 Repair Coatings

Among repair coatings, Cold Spray technology is gaining increasing attention by the hydropower community.[49] This process consists of depositing powder particles (1 to 50 µm) onto metallic or dielectric substrates at supersonic speed (300 to 1200 m/s) with a jet of compressed gas (Papyrin et al. 2007). The high-speed impact promotes strong metallurgical bonds between the particles and the substrate, thus accruing material on the treated component. PNNL is leading the research and validation of this technology, taking receipt from the system developed by VRC Metal Systems.[50] In particular, PNNL is studying the use of cold spray to repair hydropower turbines and nuclear waste tanks. The advantage of this technique is that unlike traditional repair methods such as arc welding, cold spray does not melt the material deposed or the treated surface; in contrast, the heat of traditional arc welding can melt and degrade the metal of turbine blades, increasing the likelihood of cavitation. PNNL's team has recently shown that material deposited with cold spray demonstrates hardness, corrosion resistance, and/or wear resistance properties that can exceed those of the base metal. Specifically, cold spray can produce a material with a three times higher resistance to cavitation compared with stainless steel plate or filler metal and an eight times improvement when compared with heat-affected zones from common hydropower turbine repairs.[51] Since blade erosion caused by cavitation and sediments is one the most typical and recurring types of damage occurring in hydropower plants, cold spray can offer a faster and more economical solution by reducing downtime and repair frequency.

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[49] https://www.pnnl.gov/news-media/cold-spray-help-keep-turbines-spinning.
[50] https://vrcmetalsystems.com/.
[51] https://www.pnnl.gov/cold-spray.

4. KEY TAKEAWAYS AND OPPORTUNITIES

This report was prepared based on information gathered through literature review and direct engagement with experts in the hydropower field and advanced manufacturing research. Specifically, Section 2 presents the challenges in hydropower that could be solved with the advanced manufacturing opportunities discussed Section 3. In August 2022, WPTO and ORNL hosted a two-day workshop at ORNL's MDF to gather insights from stakeholders across the hydropower and AMM industries. The first day of the workshop was designed to fill any gaps that the initial literature review effort might have missed regarding the challenges and opportunities described previously. The second day began with conversation about prioritizing the opportunities for investment and identifying next steps. Insights from the workshop have already been incorporated throughout this report, and a full summary is provided in Appendix A. This section aims to briefly summarize the main takeaways gathered during all the activities that led to the preparation of this report and discuss future R&D opportunities in support of WPTO's strategic planning.

4.1 AMM SOLUTIONS

Table 3 maps the AMM opportunities/technologies to the hydropower challenges they can address. The challenges relate directly to the organizational structure of Sections 2.2 and 2.3. The opportunities were compiled from Section 3 and the workshop, but the list is not exhaustive. In addition, although opportunities might address multiple challenges, they are listed only once for brevity.

Table 3. Mapping of advanced manufacturing opportunities to hydropower challenges

Challenge	Opportunity
Existing hydropower	
Component maintenance and repair	• In situ repairs using robotics and advanced welding techniques (e.g., cold spray for cavitation repair) • Health monitoring for predictive maintenance using embedded sensors • 3D scanning of legacy parts for digital twins and AM • Direct additive and hybrid manufacturing of components, especially for powertrains and legacy parts (e.g., DED, PBF, friction stir welding) • Erosion- and cavitation-resistant materials, coatings, and application techniques • Self-healing coatings for corrosion protection on wetted surfaces • Unmanned and/or underwater drones for inspections and repairs in hard to access locations (e.g., penstocks and submerged gates)
Evolving operating conditions	• Functionally graded materials for improved runner performance • AM for higher complexity parts (e.g., integrated channels for cooling, sensors, and aeration)
Supply chain issues	• AM for tooling (e.g., using metal deposition) • AM for molds and binder jet for sand casting molds • Direct additive and hybrid manufacturing of traditional components • Advanced imaging techniques for material characterization and qualification (e.g., x-ray tomography) • Locally sourced or recycled materials for AM • Modular approaches that lead to increased economies of scale
Environmental mitigations	• Biofouling-resistant coatings • AM to facilitate unconventional geometries and designs (e.g., fish-friendly turbines, fish attraction and/or exclusion, fish passage, sediment bypass, and aeration systems) • EALs

Table 3. Mapping of advanced manufacturing opportunities to hydropower challenges (continued)

Challenge	Opportunity
	New hydropower
Increasing the value proposition for small hydropower	• Direct additive and hybrid manufacturing of new components with an increased design space enabling component design optimization • New metal alloys for improved component performance • Composite materials for powertrain components enabling new runner shapes, better material performance, and lightweighting • Low-cost conveyance (e.g., plastics and composites) and structural (e.g., concretes) materials • In situ 3D concrete printing (e.g., dry and underwater concrete printing and large-scale 3D cement printers) • Prefabricated structures for powerhouse or auxiliary structures • Rapid prototyping using polymers for scaled explorative testing
Retrofit technologies for NPDs and other infrastructure	• Plug-and-play designs using precast formwork (e.g., high-density polyethylene siphons with integrated generation equipment) • Low-cost materials (e.g., high-density polyethylene, fiberglass, and fiber-reinforced polymers) and manufacturing methods (e.g., centrifugal casting) that enable penstock, conduit, and pipe retrofits
Technologies to enable pumped storage and flexible hydropower	• Innovative membrane materials for closed-loop PSH (e.g., polyester-based fabric with a flexible PVC coating) • New materials and designs for generators (e.g., variable-speed, permanent magnets, and superconducting generators) • Innovative materials for geotextiles, reservoir linings, and soil treatments in general to reduce seepage through the core and underneath the dam

The opportunities employ diverse technologies but have similar value propositions that help solve the corresponding challenges. These value propositions include the following:

- **Reducing O&M costs:** AMM technologies, such as self-healing coatings, can reduce O&M costs by expediting repair processes and eliminating certain routine maintenance practices. These costs are attributed to both the cost of the maintenance activity and the opportunity cost of unit downtime. Robotics and in situ repair, such as cold spray for turbine runners, can eliminate the need to disassemble the runner hub, thus reducing worker hours and downtime for maintenance. AMM technologies that increase durability and decrease component complexity can also decrease the frequency of required maintenance.
- **Reducing lead time and capital cost:** AMM technologies can provide comparable performance benchmarks with reduced costs and lead times. This could include technologies, such as sand-casted molds using binder jetting, that can reduce the time and cost for a step in the supply chain (producing the mold) or eliminate the step all together. For example, some additive and hybrid applications can reduce the number of separate parts required, thus eliminating assembly and shipping times. Modular technologies also provide economies of scale, helping reduce the development time and cost challenges attributed to custom designs. On-site construction might require additional expertise but can reduce lead times and the need for on-hand spare parts. Additionally, given the age of certain legacy parts, engineering drawings can be lost and need to be remade before manufacturing the replacement. Three-dimensional scanning technologies can quickly build models of old parts, thus reducing the need for manual measurements.
- **Improving component or system performance:** AMM can allow direct performance (efficiency, durability, and operating range) improvements compared with conventional alternatives. For example,

functionally graded materials allow components to have the surface properties of one material and the bulk properties of another. In the case of turbine runners, a cavitation- and corrosion-resistant surface material (e.g., stainless steel) could grade smoothly into a high strength, lightweight, and cost-effective bulk material (e.g., carbon steel). Composite materials could improve strength/stiffness-weight ratios, allowing for lightweight parts and a lighter, more mass-efficient machine.

- **Increasing the design space:** AMM enables system and component designs that might not be feasible with conventional technologies, opening to a complete redesign of overall configuration, cost, and scales. For example, embedded channels for sensors, cooling, and aeration are difficult to produce using conventional casting and forging, while AM simplifies this challenge. Additionally, advanced materials such as composites and polyester-based membranes might enable new configurations of hydropower technologies, potentially reducing weight, production costs, and O&M costs. AMM can, in general, enable custom design (since tooling can be easily and quickly made or modified) and the optimization of small hydropower development. AMM could also encourage adoption of nonconventional design shapes that have been limited (or precluded) by traditional manufacturing methods, potentially opening to new environmental mitigations ideas.
- **Reshoring and increased availability:** Manufacturing methods such as in situ AM or the use of recycled materials can reduce reliance on foreign imports, thus increasing supply chain reliability and security. Any technologies that diversify the materials portfolio can improve availability. For example, during rapid prototyping, manufacturers can break down early versions and use the material to print later versions, at least until the material quality significantly degrades, which can be up to six times for certain polymers.
- **Validation and certification for commercial adopters:** First adoption is a key challenge for hydropower innovation in the United States, given the maturity and limited market size. Digitalization technologies for both component health monitoring and manufacturing quality certification are key solutions for reducing the risk of adoption, providing the data necessary to communicate expected component performance.
- **Increasing worker safety and satisfaction:** Robotics and automated manufacturing and maintenance processes, such as surface finishing and metal casting or underwater repairs, can help reduce the human safety risks that are present in foundries, factories, and hydropower plants, particularly for submerged and confined space activities. These technologies also help address the workforce limitations described in the following section and eliminate the worker hours needed for undesirable (e.g., repetitive, arduous, and time-consuming) tasks, thus improving worker satisfaction.
- **Environmental improvement and risk reduction:** Technologies such as EALs can have direct environmental performance improvements compared with their traditional counterparts. Depending on the impact, this could result in reduced fines and fewer operational restrictions. Additive and hybrid manufacturing methods could reduce the cost to create complex and customizable designs for fish passageways, screens, aeration devices, and other environmental mitigation measures commonly found in hydropower plants. Other technologies, such as innovative biofouling-resistant coatings that prevent the growth of zebra mussels, can reduce O&M costs without the toxicity, low biodegradability, and durability challenges of traditional coatings.
- **Informed decision-making:** Greater awareness of plant operations can be very valuable for decision makers, enabling predictive maintenance activities that minimize unit downtime. AM allows sensors to be embedded within components without significant structural issues. These sensors, along with advanced imaging techniques, can help quantify the quality of the manufacturing process to support component certification/quality assurance. Once the sensor infrastructure is in place, a host of tools, such as digital twins and wear and fatigue models, are available to turn raw data into monetizable insights. Finally, since many plants are decades old, it can be difficult to retain drawings and details for legacy parts. Scanning technologies can model these parts to inform rehabilitation and replacement.

4.2 NONTECHNOLOGICAL INDUSTRY NEEDS

As shown in Section 4.1, there are many ways in which AMM can remedy challenges in the hydropower industry. Investment in R&D related to these technologies could help solve the technical and cost challenges associated with implementation of the opportunities, but many nontechnological solutions are needed to address industry concerns regarding technology adoption. For example, many of the solutions provided in this report are low TRL and need time, money, and collaboration to develop. Several steps are needed to commercialize even readily deployable technologies from first adopter buy-in to skilled technicians who can implement them. During the second day of the workshop, many nontechnological industry needs were identified that are also intended to boost industry confidence in adopting new manufacturing technologies. The following sections summarize these needs, which include workforce development, increased data collection and dissemination, industry advisory groups, development of standards, and the expansion of testing infrastructure. These themes are highly interrelated and feed naturally into the next steps proposed in Section 5.

4.2.1 Workforce Development

Given the timing of hydropower development, which peaked in the 1970s, much of the existing hydropower workforce is approaching retirement. Consequently, there is a need to train a new workforce and recruit skilled professionals, along with continued education of the existing workforce. This need applies to both hydropower- and AMM-related roles, which are ever evolving as technologies progress. Proposed solutions include a workforce "skills swap" (e.g., having someone from DOE work at an OEM for a day), cross-sector information exchanges, and developing guidelines for education and training. Teaching material on advanced manufacturing topics could be incorporated into college curricula, existing continuing education platforms for licensed professionals, and industry organization resource libraries. The inherent challenge with workforce development in this case is that workers can learn through the experience of implementing AMM technologies, but technology adoption benefits from having experienced workers. Leveraging expertise from how advanced manufacturing is applied in other fields, such as wind, could greatly benefit the hydropower workforce.

4.2.2 Increased Data Collection and Dissemination

Little data is available on the cost-effectiveness, efficiency, quality, and durability of advanced manufacturing components and the related techniques in hydropower. Without adequate data, the hydropower industry is often unable to evaluate risks and rewards associated with new technologies. Part of the problem is conducting the studies and tests needed to generate the data, but a larger part is compiling and disseminating that data in a user-friendly way. Often data is proprietary, collected in nonhomogeneous formats, and incomplete (lacking the variables needed to fully interpret its meaning). The Hydropower Fleet Intelligence project[10] at ORNL is working to solve some of these data challenges, but they will require a communal effort to solve. Creating metrics and performance standards, as suggested in Section 5.2.4, and establishing a platform for collecting relevant open-source data and tools could help alleviate these issues (Smith et al. 2022). Additionally, creating guidelines or policies that address the issues related to intellectual property rights, such as platforms that blind the data, could benefit data sharing in the community.

4.2.3 Industry Advisory Groups

Given the evolving natures of AMM and hydropower, it is important for stakeholders to have continued dialogue about the challenges, opportunities, and priorities in this space. During the workshop, participants expressed interest in forming an industry steering committee that would bring together multiple disciplines to target AMM for hydropower. This committee, along with existing stakeholder groups such as the Centre for Energy Advancement through Technological Innovation and the Electric Power Research Institute, could facilitate continued dialogue through workshops, conferences, and virtual seminars. Having a centralized community would also facilitate data sharing and the dissemination of research.

4.2.4 Standards Development

Standards, such as those developed by ISO and ASTM International, are a key way of lowering adoption risk. However, advanced manufactured parts often lack these standards since they are newer, and quality assurance can be difficult for unique designs, such as additively manufactured parts. Organizations such as ORNL's MDF are developing born-qualified components that integrate quality assurance into the printing and postprocessing procedures, but this technique is far from ubiquitous. The creation of standards within the industry-accepted organizations will require community coordination to define and quantify performance requirements, as well as to advocate for the adoption of these standards. Workshop participants suggested the mapping of critical components and important properties of components to expedite this effort.

4.2.5 Testing Capabilities

Finally, testing is a key part of promoting adoption of AMM technologies because it supports data generation, the development of standards, and improved designs. As discussed in a report on hydropower testing capabilities (Musa et al. 2022), full-scale testing is a key testing gap that would lower the adoption risk of late TRL technologies, and advanced manufacturing is a recommended target area for investment. Additionally, AMM could also play a key role in partial scale testing since geometries can often be scaled down proportionally. The report by Musa et al. 2022 identifies two initiatives, including a hydropower testing network and a federal test facility, to fill gaps in US hydropower testing capabilities. Industry advisory groups could help determine the types of testing equipment and projects that would best benefit the field.

5. NEXT STEPS AND PATHWAYS

This report demonstrates how the advanced manufacturing industry can play a role in solving some of the hydropower industry's hardest challenges. The Advanced Manufacturing for Hydropower Workshop kickstarted the dialogue between these two industries, and additional efforts are needed to deliver actionable solutions for the nation's water infrastructure. All the relevant stakeholders, including utilities, hydropower operators, manufacturers, and research scientists (as illustrated by the triple helix in Figure 6), must be involved. This report compiles information from the hydropower industry challenges and the AMM opportunities to promote future work and conversations. This concluding section highlights potential action items that DOE and its academic and industry partners can lead through their roles as R&D organizations.

The first key action is to identify and prioritize mechanisms for investing in the AMM solutions described throughout this report. This prioritization effort should assess the potential impact of the solution on the industry, the cost of the solution (both R&D and implementation costs), the time required to implement (i.e., short-, medium-, or long-term solutions), and the associated risks. These risks should include the variability in time, cost, and impact, as well as any additional considerations for the solution, such as environmental impacts. The effort could also assess which funding mechanisms are best suited to each kind of solution. Examples include SBIR investments, funding opportunity announcements, national laboratory projects, and other strategic partnerships.

Prioritization should be conducted with the relevant stakeholders. Therefore, another key step is to form a steering committee or subgroup of experts to continue the discussion. The intended outcomes of such a committee would be to build a common understanding of current technologies and research, pinpoint priority industry challenges and corresponding AMM solutions, and strengthen partnerships among industry, academia, and national laboratories. The committee should include owners and operators, manufacturers, consulting firms, "on-the-ground" manufacturing workers, national laboratories, academic research institutions, DOE, and international partners with experience in advanced manufacturing. Key questions for the steering committee to address include the following:

- What are the specific industry needs and key components?
- What information on existing AMM is already available? What information gaps need to be filled with new research and data acquisition?
- What are high, medium, and low priorities for industry? How do these priorities translate into specific AMM solutions?
- What are some pathways for improving standards? How can each sector contribute to the development of better standards?
- How can each sector support technologies that are already implemented or close to being implemented while simultaneously creating a space to explore other challenges and solutions?
- How can AMM fit into current business models since advanced manufacturing does not present a typical business case?

The last key effort discussed here is the dissemination of information. By widely sharing information about the challenges and opportunities within AMM and hydropower, these industries can garner ideas from others, attract a workforce eager to tackle these problems, and elicit resources to invest in these solutions. This dissemination could include research articles, standards development, newsletters and web publications, conferences, training and recruiting events, site tours, and innovative social media approaches. This report sets the stage for innovation and collaboration in the fields of hydropower and advanced manufacturing, which are key to the health and safety of communities, the environment, and the energy system.

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APPENDIX A. WORKSHOP REPORT

APPENDIX A. WORKSHOP REPORT

ORNL
ADVANCED MANUFACTURING FOR HYDROPOWER WORKSHOP
DRAFT SUMMARY
AUGUST 2–3, 2022

A.1 Introduction

A.1.1 Workshop Background, Goals, and Objectives

DOE's WPTO and ORNL hosted the Advanced Manufacturing for Hydropower Workshop from August 2 to 3, 2022. The meeting was held in person at ORNL's MDF with the option for virtual participation via Zoom. Kearns & West, a third-party stakeholder engagement and facilitation firm, facilitated the workshop.

The primary goal of the workshop was to bring together stakeholders across the hydropower industry, academia, and government sectors to help inform an ORNL report prioritizing hydropower challenges and associated AMM capabilities. The workshop also aimed to foster relationships among sectors and identify key next steps for collaboration. The ORNL report will support the DOE WPTO in developing a strategic roadmap aimed at identifying future funding opportunities and collaborative projects.

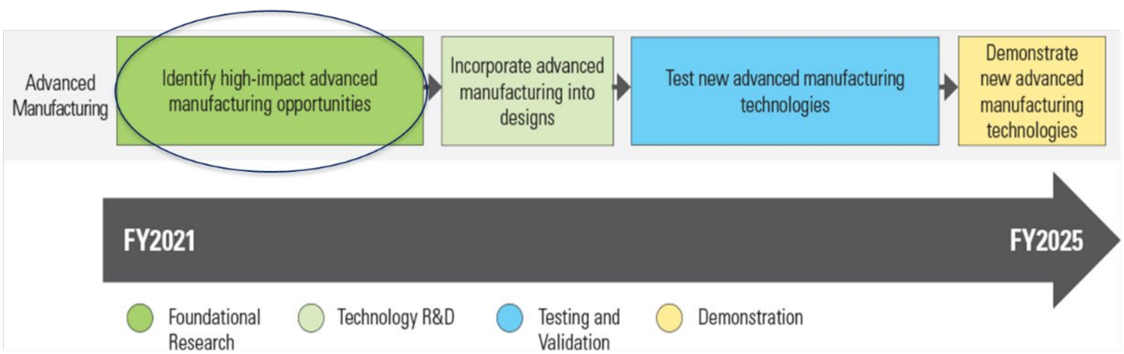

Figure A-1. DOE WPTO timeline for advanced manufacturing research and development.

Key takeaways from this summary will be incorporated into the ORNL report.

A.1.2 Workshop Participation and Structure

ORNL, DOE, and Kearns & West (the workshop planning team) invited stakeholders from the hydropower industry, DOE's national laboratories, and academia, with the goal of representing a cross-section of interests from universities, consulting firms, government agencies, independent associations, manufacturers, and owners and operators. In total, 75 participants, including the workshop planning team, attended. A full list of participants is provided a the end of this appendix.

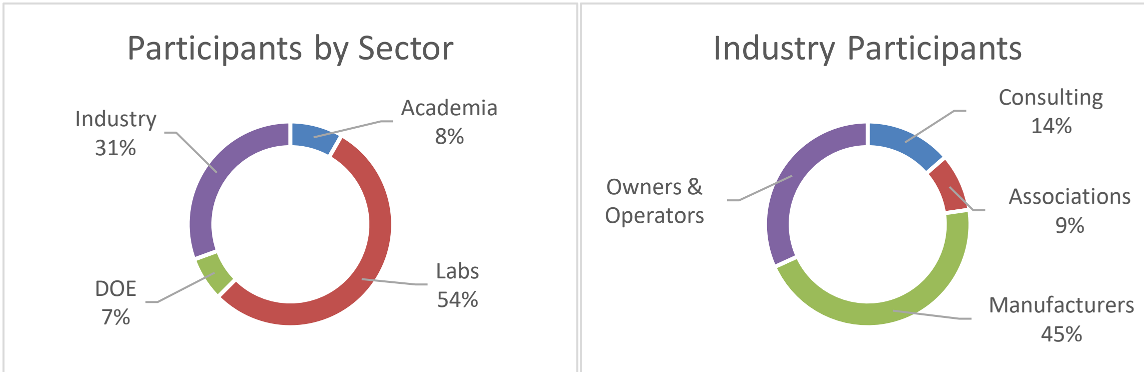

Figure A-2. Advanced Manufacturing for Hydropower Workshop participants by sector and type.

Most of the workshop took place in breakout room discussions that included a mix of participants from each sector. Using the virtual whiteboarding tool, Miro Board, participants brainstormed, documented, and analyzed current hydropower manufacturing challenges, potential advanced manufacturing solutions, and opportunities for collaboration. Breakout rooms were led by facilitators and notetakers from DOE, ORNL, and Kearns & West. Broadly, day one focused on manufacturing, materials, and supply chain challenges, and day two focused on potential advanced manufacturing solutions and identifying pathways for further exploration. The full workshop agenda is provided a the end of this appendix.

The workshop also provided opportunities for participants to explore in-depth manufacturing capabilities of the national laboratories. Specifically, participants heard from ORNL and DOE staff, toured the MDF, and received presentations from the other labs.

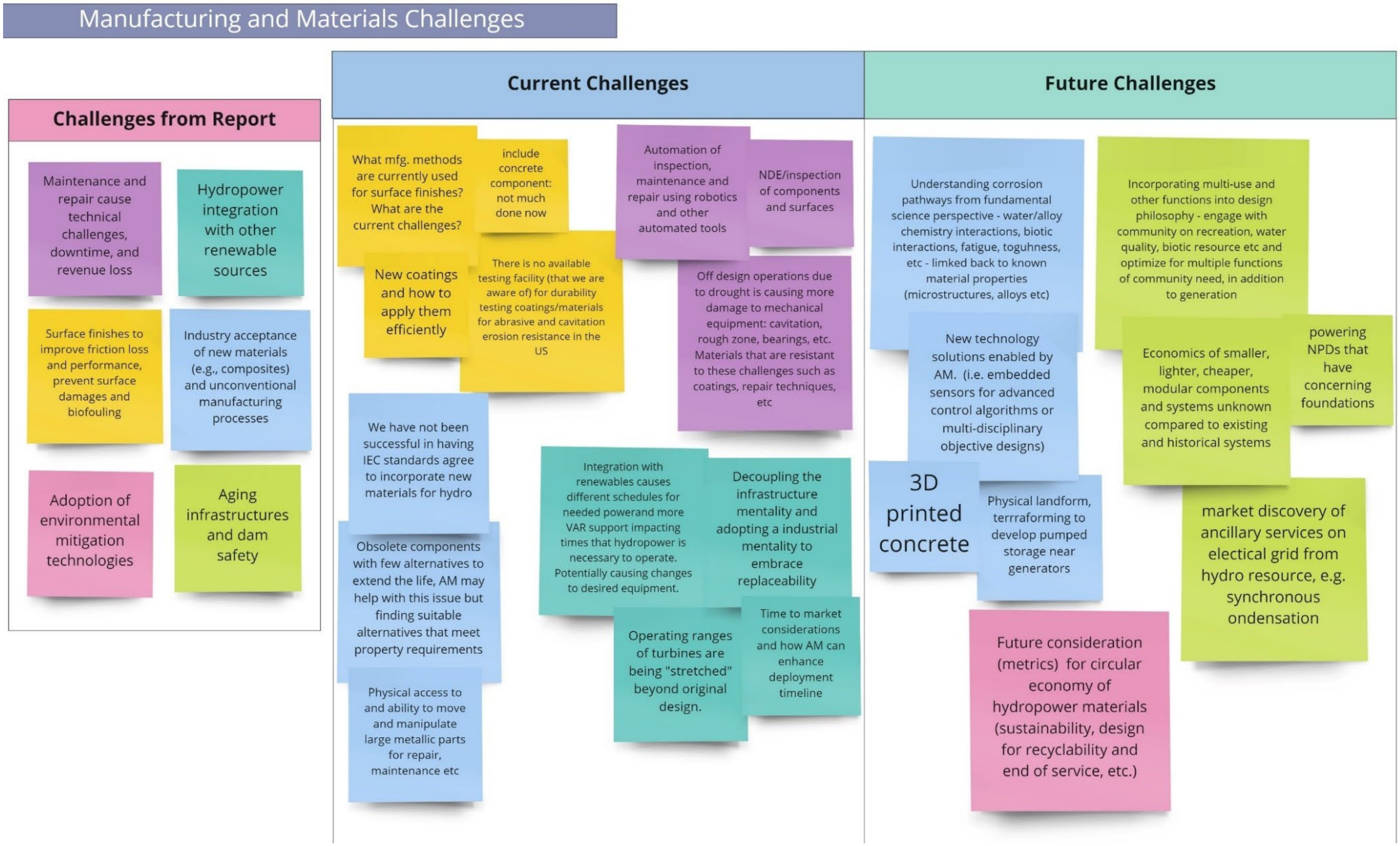

Figure A-3. Advanced Manufacturing for Hydropower Workshop Miro Board example.

A.1.3 Summary Approach

Drafted by Kearns & West, this summary synthesizes information from the Miro Boards, breakout room notes, and plenary discussions. This summary is intended to provide an overview of key themes and related discussion highlights. It does not include a comprehensive description of all items discussed during the workshop and does not detail technical information presented to the full group. Generally, each section identifies key takeaways from the discussion and related comments by participants. Key takeaways were determined based on comments brought up across breakout groups. All comments captured throughout the summary are not-for-attribution (i.e., commentors are not identified by name). The ideas presented in the summary represent feedback from industry and do not reflect the views of DOE.

A.2 Day One: Discussion Highlights and Key Themes

A.2.1 Welcome, Introductions, and Key Background Information

Mirko Musa, ORNL water resource engineer and workshop lead, welcomed participants, reviewed the workshop objectives, and explained the intended outcomes. Bob Slattery, manager of industrial collaborations at the MDF, provided an overview of the MDF and its potential role in advanced manufacturing for hydropower moving forward. Following their remarks, Kelsey Rugani, senior facilitator at Kearns & West, reviewed the workshop ground rules and the agenda for day one.

Workshop Objectives:

- *Discuss challenges for the hydropower industry and opportunities surrounding advanced manufacturing for hydropower*
- *Identify priorities to inform the roadmap for hydropower manufacturing and R&D funding needs*
- *Provide overview capabilities of the MDF*

To set the context for further discussion, Katie Jackson, Engineer and Hydropower Technology Manager at DOE WPTO, provided an overview of DOE's vision for the hydropower program and explained how the workshop will contribute to the DOE Advanced Manufacturing Strategic Roadmap. Mirko and Rocio Uria Martinez, ORNL Researcher, provided additional background on the report. Mirko discussed some of the pre-identified manufacturing and materials challenges to the hydropower industry, while Rocio highlighted key pre-identified supply chain challenges. These ideas were presented to participants prior to the workshop.

A.2.2 Breakout Room 1 and 2: Current and Future Challenges for the Hydropower Industry

In breakout rooms, participants reviewed the pre-identified manufacturing challenges for the hydropower industry and began to brainstorm additional current and future materials, manufacturing, and supply chain challenges. While the discussion intended to focus on industry challenges, participants also began to explore potential challenges associated with using advanced manufacturing techniques in hydropower.

Key Themes: Current Manufacturing, Materials, and Supply Chain Challenges

Overview of Key Themes: Current Challenges

- *Adapting manufacturing to increase environmental friendliness*
- *Maintenance, repair, and repower*
- *Supply chain, political, and economic issues*
- *Workforce development*
- *Data collection, case studies, and demonstration around advanced manufacturing*

Adapting manufacturing to increase environmental performance

Participants identified the need to adapt manufacturing to increase environmental performance and comply with increasingly stringent environmental requirements. Specific comments include the following:

- Materials for oil free hubs can potentially harm the environment and create additional operations, maintenance, life span, and materials challenges
- Incorporating oxygenation in designing turbines to be more fish friendly is a significant challenge
- Industry is uncomfortable pursuing environmentally friendlier options without data demonstrating the success of prior efforts
- Varying environmental restrictions at the local, state, and federal levels

Maintenance repair and repower

Participants shared a number of comments related to maintenance, repair, and repower. Related comments included the following:

- Rapidly aging infrastructure is increasing the need for repairs
- Replacing legacy parts can be particularly challenging
- There is a need for more in situ repair and monitoring, but in situ repair and monitoring present significant logistical and mechanical challenges
- In situ inspection is also a critical need but presents similar challenges

Supply chain, political, and economic issues

- Social, political, and economic factors cause supply chain disruption and unpredictability
- Reliance on international markets for production contributes to logistical bottlenecks, creates additional transport challenges for large parts, makes it more difficult to obtain replacement parts, and can contribute to quality issues
- Workflow and production bottlenecks at OEMs in the United States create lags in the time it takes to ship and receive parts and machines
- There is a lack of large casting in the United States, and the United States relies entirely on foreign countries (e.g., China, Brazil) for critical components (e.g., turbine runners, generator windings)

Workforce development

Participants highlighted that an aging workforce, worker shortages, and insufficient training on advanced manufacturing pose significant challenges to the industry's willingness and capacity to develop advanced manufacturing methods. Participant comments included the following:

- There is not a lot of expertise on new manufacturing techniques such as additive and subtractive manufacturing, coatings, hybrid, and non-conventional materials
- There is a lack of technicians and tradespeople
- Welders and similar roles are often working in other industries
- The workforce is aging out at a higher rate than can be replaced in the market, exacerbating worker shortages
- Higher quality and quantity of trainings on new methods and modern technologies is needed

Data collection, case studies, and demonstration around advanced manufacturing

Participants across breakout groups noted that there is currently little available data on advanced manufacturing for hydropower. Participants specifically highlighted that, without adequate data on advanced manufacturing cost effectiveness, efficiency, quality, and durability, the hydropower industry is often unable to evaluate risks associated with new technologies. Participants commented on the following issues related to data collection, case studies, and demonstration:

- Contributes to hesitation around cost and investment in new methods of maintenance and repair and other new technologies
- Can be a particular challenge for developing and implementing environmentally friendly technologies
- Makes it difficult to assess how common certain challenges are across groups or to see where solutions could apply to other cases
- More thorough testing is needed to understand whether new materials will meet material property specifications
- Within research and data analysis, there is a key need to quantify risk of failure for advanced vs. conventional materials

A.2.3 MDF Tours and Information Sessions

Following the breakout discussions, participants had the opportunity to tour the MDF. The tours enabled participants to see firsthand the advanced manufacturing capabilities of the facility and served as a foundation for discussing advanced manufacturing solutions for hydropower on day two. After the tour, ORNL technical experts led 30 min information sessions to provide more in-depth information on specific machines and techniques that participants saw on the tour.

Table A-1. Advanced Manufacturing for Hydropower Workshop MDF information sessions

Information sessions	
Topic	**Technical experts**
Additive manufacturing: metal and magnetic materials, polymers and concrete	Peter Wang, Brian Post
Novel manufacturing and machine processes	Jaydeep Karandikar, Dawn White
FRPCs	Mitchell Rencheck, David Nuttall
Digitalization: modeling, simulation, robotics, and in situ monitoring	Pradeep Ramuhalli, Michael Sprayberry
Coatings	Caitlyn Clarkson, Peeyush Nandwana

A.3 Day Two: Discussion Highlights and Key Themes

A.3.1 Welcome and Preview of Day Two Agenda

Mirko welcomed participants back to the workshop, and Kelsey provided a brief recap of the key themes discussed on day one. She also previewed the agenda for day two and noted that the day's discussions would focus on identifying solutions and prioritizing opportunities for advanced manufacturing moving forward.

A.3.2 Breakout Room 3: Advanced Manufacturing Solutions for Industry Challenges

Broadly, participants discussed the applicability of current and future advanced manufacturing capabilities to current and future hydropower challenges that were addressed during day one of the workshop. Participant comments on how advanced manufacturing can help solve industry challenges are noted in Table A-2.

Table A-4. Advanced Manufacturing for Hydropower Workshop advanced manufacturing solutions for industry challenges

	Advanced manufacturing solutions for hydropower
Challenge	**Solution**
Material properties and proving materials	• Composite materials offer significantly improved strength/stiffness-weight ratios, allowing for lightweight parts and a lighter, more mass efficient machine • It is possible to tailor surface properties to improve cavitation and resistance • Creates opportunities for large metal castings • New material developments from advanced manufacturing processes (e.g., new alloys, new polymer mix, multiple material solutions)
Design space	• Opens design space for complete redesign of turbines, gensets, runners, and their overall configuration, cost, and scale. • Enables component design with alternate materials (e.g., composites) to potentially reduce weight production costs and O&M costs • Allows for design optimization for low head/small hydropower projects • Enables custom design for each application because tooling can be made quickly
Maintenance and repair	• Can minimize assembly, welding, and finishing requirements of complex parts • Can directly print channels (e.g., cooling lines or sensors) into parts, allowing for higher complexity but simultaneously higher part efficiency pieces (e.g., bearing housings) • Potential to build specific components or to augment existing difficult build parts • Additive and hybrid solutions can support an array of maintenance and repair issues
Supply chain challenges	• Helps to diversify materials portfolio • Provides more opportunities to diversify sourcing • Can allow for a modular approach to manufacturing • Reduces assembly and compilation into minimal parts solutions • Can allow for making smaller parts on-site • Can decrease lead times to manufacture

Across breakout rooms, participants also highlighted rapid prototyping, embedded monitoring sensors, hybrid solutions, digitalization, advanced imagine tools, and serial production as advanced manufacturing techniques that can help address industry challenges.

Presentations: National Lab Capabilities

During lunch on day two, participants received presentations from the other labs. Broadly, the presentations detailed current advanced manufacturing capabilities of each lab, providing context for what may already be achievable in advanced manufacturing for hydropower and laying the groundwork for subsequent discussions. Below are brief summaries of some of the capabilities noted in presentations from the Idaho National Laboratory (INL), Argonne National Laboratory (ANL), PNNL, Sandia National Laboratories (SNL), and NREL.

INL

A list of capabilities and key points from INL's presentation are outlined here.

- Welding technology techniques
  - Gas tungsten arc welding (GTAW) wire arc AM (WAAM)
  - GTAW multi-WAAM with three wire additions for functionally graded components
  - Hybrid/tandem laser arc AM
  - DED laser
- Plasma jet printing
- Powder bed printing
- Laser-engineered net shaping (LENS)
- Digital light printing
- High-velocity oxygen fuel (HVOF) coatings capabilities (amorphous metallic corrosion–resistant and wear-resistant coatings)
- Electric field–assisted sintering (EFAS) capabilities
  - Nano EFAS (beamline capable)
  - Micro EFAS (DCS-5; 5 ton)
  - Fuji Dr. 515 (5 ton)
  - Direct current sintering furnace (DCS-25-10; 25 ton)
  - DCS-800 (800 ton)
  - Continuous EFAS
- INL's EFAS capabilities provide the full spectrum and multi-scale offerings from research to industrial scale.
  - Advantages of EFAS over conventional methods include extremely fast processing speeds, up to 90% energy savings, and exotic microstructures.

ANL

ANL's presentation noted an array of AMM capabilities, including the following:

- Manufacturability and scalability of parts:
  - Scaled production of complex organic or inorganic additives
  - Production-scale hard coatings for wear/corrosion and friction (e.g., ultrafast boriding, low friction diamond-like carbon)
  - Life cycle assessment and techno-economic assessment modeling
  - In situ analysis of manufacturing processes
- Reliability:
  - Root cause analysis of failed components
  - Accelerated testing and material validation (e.g., powertrain components)
- Maintainability and risk mitigation:
  - Nondestructive analysis (electrochemical impedance spectroscopy to detect alkali-silica reaction in concrete)
  - Embedded/printed sensors
  - AI/machine learning–based modeling for predictive maintenance
  - Autonomous repair

PNNL

PNNL's presentation highlighted key capabilities related to solid phase AM and assembly. Capabilities and key points from the presentation are outlined here.

- Solid phase processing involves the application of a high shear strain during metals synthesis or fabrication and results in material properties superior to melt-based processes, closer to and, in some cases, exceeding base material properties.
- Friction stir AM variants
  - Plate stacking
  - Friction stir assembly
  - Friction stir deposition
  - Friction stir surfacing
  - Cold spray

SNL

SNL's presentation noted several advanced manufacturing capabilities and machines, with a focus on AM techniques. Specific technologies highlighted in the presentation are listed here.

- WAAM on HAAS 5-Axis Milling Center
- ProX 200 laser PDF, materials sciences lab, including several add-ons:
  - FLIR IR camera
  - High-speed optical camera
  - Two-color pyrometer
  - Sieve station
- LENS, including several add-ons:
  - FLIR IR camera
  - Two-color pyrometer
  - Melt view camera
  - Heated build plate
  - Five powder hoppers
- High-throughput processing and characterization of refractory high-entropy alloys, with a library of unique alloys within each AM specimen and characterization of local composition, hardness, and grain structure, enabling structure–properties relationships (big data)
- Aspex FEI scanning electron microscope for powder characterization
- Malvern powder size analyzer and Mercury Scientific avalanche angle for powder characterization
- Monitoring powder reuse: SNL tracked powder size, morphology, and EDS composition with reuse and noted an increase of satellites and agglomerates; observation of highly spherical, ferrite particles; an increase in fines and reduction in larger particles; and the collection of over 30 reuses with powder under Ar. They also highlighted the following:
  - Material properties remain stable
  - 316L stainless steel is a robust material for processing and properties.

A.3.3 Breakout Room 4 and 5: Boosting Industry Confidence and Prioritizing Opportunities

Participants explored ways to increase industry confidence around non-conventional manufacturing technology and materials and began to discuss potential ways to prioritize challenges and opportunities. Key themes from the discussion are noted here, along with related participant comments.

Boosting Industry Confidence

Overview of Key Themes: Boosting Industry Confidence

- *Increase research and data collection*
- *Improve standards, testing, and demonstration*
- *Start small*

Increase research and data collection

Participants noted across breakout rooms that the hydropower industry may be reluctant to pursue advanced manufacturing techniques because they have not seen data demonstrating the cost effectiveness, quality, and longevity of advanced manufacturing. They consistently expressed that more data and higher quality data would help industry more adequately assess risk and support the business case for incorporating advanced manufacturing.

Key ideas for expanding research and data collection included the following:

- Compiling the results of existing studies and openly sharing that data with all relevant stakeholders
- Figuring out a way to store key data sets on a central digital platform (e.g., Peregrine)
- Evaluating the effectiveness of advanced manufacturing in helping projects meet evolving compliance requirements
- Performing full life-cycle analyses on parts and machines made with advanced manufacturing
- Evaluating proven models for migration to advanced manufacturing in other renewables spaces, including aerospace, nuclear, wind, and solar
- Comparative cost modeling, data access, testing, and modeling to evaluate return on investment and tradeoffs (e.g., cost vs. duration)
    - Employing third-party data collection to ensure neutrality, credibility, and quality

Participants also noted several questions related to data collection and research:

- What data sets would be most important to help provide industry the necessary level of confidence to progress advanced manufacturing solutions?
- How can labs and academia work to make key data sets available to the public?
    - While there is not a lot of current research on advanced manufacturing for hydropower, there is a lot of broader data on advanced manufacturing solutions in other spaces. What opportunities might there be to utilize existing research?

Improve standards, testing, and demonstration

Participants across breakout rooms noted that improvements to standards, testing, and demonstration may help boost industry confidence in advanced manufacturing. Related comments are summarized here.

- Standards and effective demonstration can help increase confidence in part quality and enhance the trust in parts made using advanced manufacturing methods. This includes dedicated demonstration and testing facilities.
- There is currently a push for standardization in other industries, but not specifically for hydropower.
- A lot of coordination across sectors will be needed to develop standards.
- There may be opportunities for demonstration and testing at retiring plants.
- If DOE were to expand testing and demonstration for advanced manufacturing, it would alleviate some of the current risk that industry faces.
    - While demonstration is a "big ask" in terms of money, a test facility could enable more while protecting some of the intellectual property (IP).

Start small

Participants highlighted that building smaller parts and taking a modular approach to advanced manufacturing could decrease the cost and industry risk. Comments are summarized here.

- Starting with smaller parts rather than "trying to make the whole turbine" can provide important data and help build industry confidence overtime
- Taking "baby steps" by starting with smaller parts can also mitigate supply chain challenges by alleviating transport challenges that come with transporting large parts
    - Modularity decreases financial and infrastructure risk for industry and may reduce supply chain issues

A.3.4 Prioritizing Challenges and Opportunities

After identifying ideas to help increase industry confidence in advanced manufacturing, participants started to prioritize advanced manufacturing opportunities based on the TRL (i.e., the maturity of current technologies and capabilities) and level of acceptability (i.e., industry's level of confidence in and willingness to implement a given technology or approach). While participants began to map out these options on a Miro Board chart, they broadly agreed that they need more time to discuss challenges and potential solutions before defining priorities.

A summary of suggestions made across breakout rooms during the prioritization exercise is compiled here. Although participants emphasized that these ideas need further development, the suggestions may serve as a starting point for upcoming conversations. The group noted that advanced manufacturing solutions that are already deployed should be left off for now.

Table A-3. Advanced Manufacturing for Hydropower Workshop advanced manufacturing challenges and opportunities prioritization matrix key

Green	High industry TRL, high industry acceptability
Yellow	Low industry TRL, high industry acceptability
Orange	High industry TRL, low industry acceptability
Red	Low industry TRL, low industry acceptability

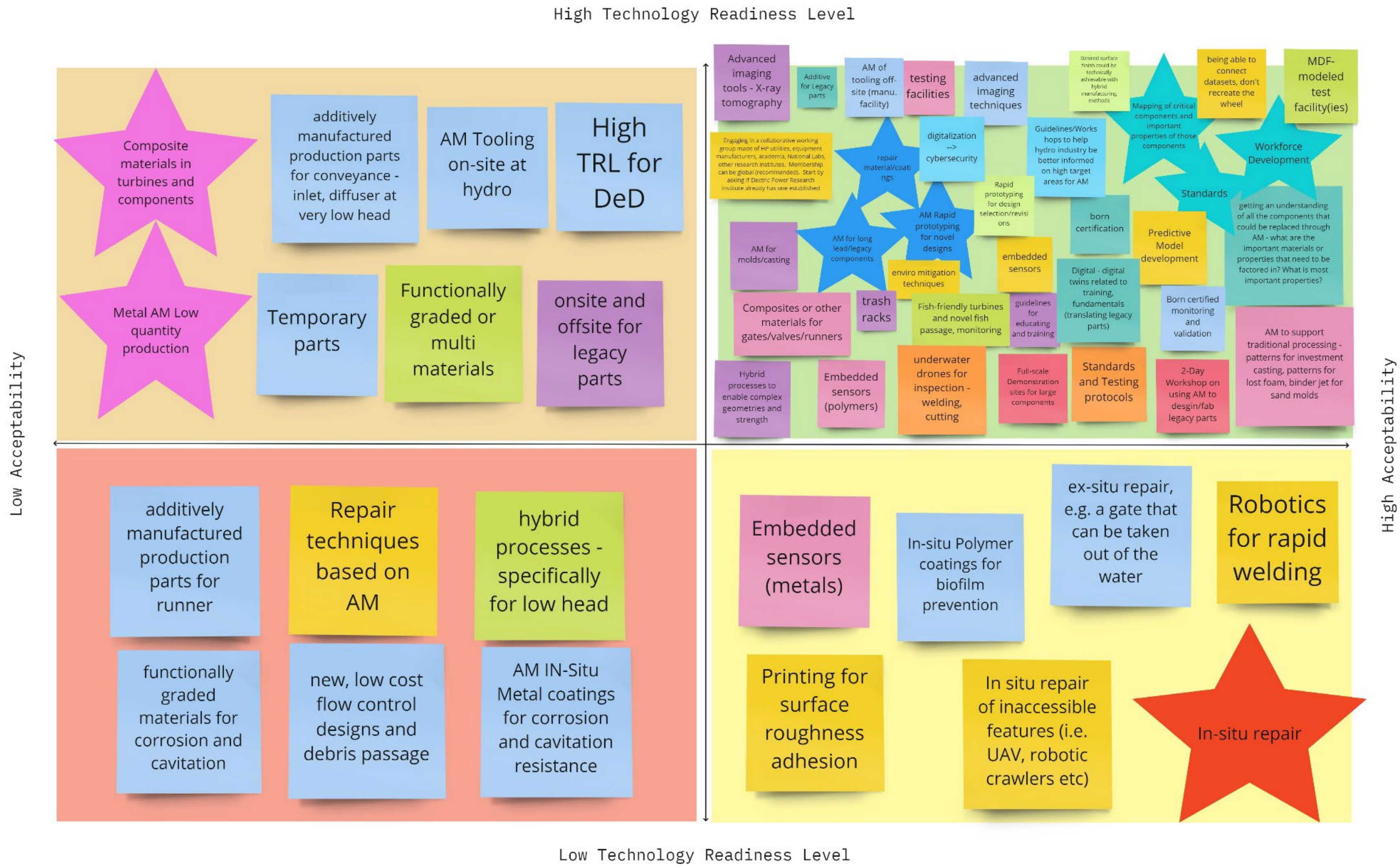

Figure A-4. Advanced Manufacturing for Hydropower Workshop opportunities prioritization matrix (Figure A-5 shows a close-up of the green quadrant).

A.4 Overall Key Takeaways: Prioritization

A.4.1 Each group categorized solutions similarly

Notably, across breakout rooms, participants "grouped" similar ideas into similar categories (e.g., multiple breakout rooms categorized general "in situ repair" as low TRL and high acceptability, and no breakout rooms categorized general "in situ repair" differently). Although there were no major points of divergence reflected across breakout groups, some groups drew more detailed distinctions when discussing specific technologies (e.g., groups categorized "embedded sensors [polymers]" as high TRL and high acceptability but categorized embedded sensors [metals] as low TRL, high acceptability).

A.4.2 There may be more effective metrics for prioritizing solutions than "TRL" and "acceptability"

Multiple participants in one breakout group noted the desire to use different metrics to prioritize solutions. Specifically, participants suggested using the metrics "high risk vs. low risk" and "high reward vs. low reward" as a more effective framework for prioritizing solutions. Generally, participants defined *risk* as the perceived potential impact of an advanced manufacturing technology on cost, reliability, efficiency, and longevity. Generally, participants defined *reward* as the return on investment for a particular technology.

A.4.3 There are a number of solutions and technologies that participants viewed as both high TRL and high acceptability and may be ripe for shorter term exploration

Participants across breakout rooms shared agreement on many of the high TRL, high acceptability solutions. Generally, participants considered these to be solutions that industry would be comfortable implementing given potential business risk and how developed the technologies already are. Following the breakout discussions on priorities, participants had a plenary-wide discussion. Key notes from the plenary discussion on these items are summarized here, and the full list of suggestions is provided in Figure A-5.

- **Workforce development and information sharing:** Suggestions included a workforce "skills swap" (e.g., having someone from DOE work at an OEM for a day), cross-sector information exchanges, utilizing existent data sets, and developing guidelines for education and training.
- **Industry steering committee:** DOE WPTO noted that there was interest in forming an industry steering committee prior to the COVID-19 pandemic. Participants highlighted that steering committee members could be recruited from multiple disciplines and focus specifically on developing advanced manufacturing for hydropower.
- **Standards:** Participants suggested the mapping of critical components and important properties of components. They noted that this process might involve talking to facilities workers to understand key problems, suggested the possibility of exploring the topic through a report, and emphasized the importance of having the right voices in the room.
- **Technical topics and solutions:** Technical advanced manufacturing solutions in this category included the following:
    - Biofouling on metals
    - Evaluating the existing fleet to see if machines need to be re-coated
    - AM for long lead time or legacy components
    - Advanced manufacturing rapid prototyping for novel designs and design selection/revisions
    - Embedded sensors (polymers)

- Advanced manufacturing to support traditional processing (e.g., patterns for investment casting and lost foam, binder jet for sand molds)
- Digital twins related to training and translating legacy parts
- Fish-friendly turbines and environmental mitigation techniques
- Composites or other materials for gates/valves/runners, as well as lightweight parts and more mass efficient machines
- Hybrid processes to enable complex geometries and strength and desired surface finishes
- Advanced imaging tools (e.g., x-ray tomography)
- Trash racks
- Underwater drones for inspection (welding, cutting)

Figure A-5. Advanced Manufacturing for Hydropower Workshop opportunities prioritization matrix green quadrant (high TRL, high acceptability opportunities).

A.5 Conclusion: Key Takeaways Around Next Steps: A Collaborative Path Forward

In breakout rooms and in a final plenary session, participants discussed opportunities for DOE, national laboratories, academia, and industry to collaborate on moving forward. Although participants were not yet ready to pinpoint specific technologies, they agreed that continuing the conversation is a critical next step for identifying the benefits and intended outcomes of advanced manufacturing solutions. Participants brainstormed ideas surrounding a steering committee or similar group to continue exploring advanced manufacturing solutions and contribute to the R&D roadmap. Participant ideas and comments are summarized here.

Figure A-6. Advanced Manufacturing for Hydropower Workshop next steps summary.

A.5.1 What are some of the benefits and outcomes of ongoing discussions?

Participants agreed that additional conversations are needed to define priority opportunities and plan for future collaboration among sectors. Comments on the intended benefits and outcomes of these discussions are noted here.

- Discussions will help more clearly define priority industry needs and potential solutions for challenges
- Information sharing will help build a common understanding of current technologies and research
- Discussions should include how to create pathways for data collection and research
  - Increasing collaboration and strengthening partnerships will help distribute risk across sectors so that not all risk is falling on industry

A.5.2 Who should be included in these ongoing discussions? What voices should be brought to the table?

Throughout the workshop and in the final plenary discussion, participants noted that more voices should be brought into the conversation on advanced manufacturing. Beyond owners and operators, manufacturers, academia, and labs, participants suggested that the following stakeholders should be included in future discussions.

- On-the-ground manufacturing workers to provide an understanding of day-to-day materials, manufacturing, and logistics challenges
- Representatives in other renewables industries who have experience in advanced manufacturing to share how their experience with advanced manufacturing may apply to the hydropower space
  - International partners with experience in advanced manufacturing to share how their experience with advanced manufacturing may apply to the hydropower space. Participants specifically highlighted Eastern Europe and China.

A.5.3 What are some existing spaces that can be leveraged to continue the conversation?

Participants identified several existing conferences, organizations, and other spaces that could provide space for these ongoing conversations:

- Clean Currents and other hydropower conferences
- Funding opportunity announcements and technical assistance programs
- MDF public-private partnership opportunities
    - Consortia such as ASME and EPRI

A.5.4 What are key questions to address in future discussions?

Participants suggested questions to be addressed in future discussions, including the following:

- What are specific industry needs and key components?
- What information on existing advanced manufacturing already exists? What information gaps need to be filled with new research?
- What are high, medium, and low priorities for industry? How do these priorities translate into specific advanced manufacturing solutions?
- What are some pathways for improving standards? How can each sector contribute to the development of better standards?
- How can each sector support technologies that are already implemented or close to being implemented while simultaneously creating a space to explore other challenges and solutions?
    - How can advanced manufacturing fit into current business models given that advanced manufacturing doesn’t present a typical business case?

A.6 Workshop Materials

Table A-4. Advanced Manufacturing for Hydropower Workshop participant list

Name	Association	Job title
Academia		
Dan Finke	Penn State University	Associate Research Professor
Prabhakar Pagilla	Texas A&M	Associate Dean for Research
John Arimond	University of Maine	Business Development Manager
Andrew Gifford	University of Maine	Engineer V, Marine Composites
Bradley Jared	University of Tennessee, Knoxville	Associate Professor, UT Department of Mechanical
Consulting		
Morgan Nachman	Kearns and West	Project Coordinator
Kelsey Rugani	Kearns and West	Vice president
Brennan Smith	HDR, Inc.	Senior Hydropower Consultant
Dylan Smith	Nexight Group	Consultant
Jack Holmes	Nexight Group	Consultant
DOE		
Colin Sasthav	DOE	Hydropower Engineer at DOE WPTO
Jake Herb	DOE	AAAS Fellow, DOE WPTO
Christopher Hovanec	DOE	Technology Manager at DOE Advanced Manufacturing Office
Kathryn Jackson	DOE	Engineer and Technology Manager at DOE WPTO
Blake Marshall	DOE	Technology Manager at DOE Advanced Manufacturing Office
Independent associations		
Jose Zayas	ACORE	EVP, Policy & Programs
Daniel Purdy	EPRI	Senior Technical Leader, EPRI
Manufacturers		
Sam Kent	ANDRITZ Hydro Corp	Chief Mechanical Engineer
Vito Gervasi	Cadens	Advanced Manufacturing Design Engineer
Randel Mueller	Cadens	Co-founder
Brandon Davis	Emrgy Inc.	Sr. Mechanical Engineer
Juan Pablo Cilia	General Electric	Senior Additive Design Engineer
Lillie Ghobrial	General Electric	Technology Partnerships GE Renewables
Kelsey Seto	Natel Energy	Senior Mechanical Engineer
John Kinard	Voith Hydro	Sr. Manager, Business Development
Sharon Atkin	Percheron Power	Project Development Director
National laboratories		
Aaron Greco	ANL	Group Leader, Interfacial Mechanics & Materials
Gabriel Ilevbare	INL	Manager
Derek Berry	NREL	Senior Wind Technology Engineer
Christopher Smith	PNNL	Project Manager
Charles Weatherspoon	PNNL	Hydropower Research Engineer
Jonathan Pegues	SNL	R&D Mechanical Engineer
Caroline Carter	ORNL	Summer intern
Caitlyn Clarkson	ORNL	R&D Associate Staff Member
Hope Corsair	ORNL	R&D Staff
Lora Davis	ORNL	Operations Manager, Water Power Program
Ryan Dehoff	ORNL	Section Head, Secure & Digital Manufacturing
Scott Deneale	ORNL	Water Resources Engineer
Amy Elliot	ORNL	Advanced Manufacturing Senior Researcher

Table A-4. Advanced Manufacturing for Hydropower Workshop participant list (continued)

Name	Association	Job title
Carly Hansen	ORNL	Water Resources Engineer
Ahmed Hassen	ORNL	R&D Staff
Jesse Heineman	ORNL	Technical Staff Member
Shih-Chieh Kao	ORNL	Water Power Program Manager
Jaydeep Karandikar	ORNL	R&D Staff
Vlastimil Kunc	ORNL	Section Head Composites Science and Technology
Luke Meyer	ORNL	Mechanical Engineer
Mirko Musa	ORNL	Research Scientist/Water Resources Engineer
Peeyush Nandwana	ORNL	Researcher in Powder Metals and Material
David Nuttall	ORNL	Engineering and Science Support
Gbadebo A. Oladosu	ORNL	Senior Research Economist
Ronald Ott	ORNL	Acting Division Director, Manufacturing Science Division
Soydan Ozcan	ORNL	Senior R&D Scientist
Vincent Paquit	ORNL	Group Leader, Energy Systems Analytics
William Peter	ORNL	Advanced Manufacturing Program Manager
Brian Post	ORNL	Group Leader, Manufacturing Systems Design Group
Pradeep Ramuhalli	ORNL	Distinguished Scientist
Mitch Rencheck	ORNL	Postdoctoral Research Associate
Bob Slattery	ORNL	Industry Collaboration Manager
Scott Smith	ORNL	Group Leader Intelligent Machine Tools
Michael Sprayberry	ORNL	R&D Associate Staff Member
Kevin Stewart	ORNL	Water Resources Engineer
Chien-Yung Tseng	ORNL	Postdoctoral Research Associate
Rocio Uria Martinez	ORNL	R&D Staff
Derek Vaughan	ORNL	R&D Assistant Staff
Peter Wang	ORNL	R&D Staff, ORNL
Daniel Webb	ORNL	CFTF Technical Professional
Dawn White	ORNL	Senior Staff Scientist
Owners and operators		
Ben Burnham	USACE	Acting Associate Technical Director
Cole Sergi	USACE	Mechanical Engineer, USACE HDC
Locke Williams	USACE	Mechanical Engineer, USACE
Erin Foraker	USBR	Power/Energy and Water Infrastructure Research Manager
David Tordonato	USBR	Materials Engineer
Daniel Fisher	TVA	TVA Project Manager
Curt Jawdy	TVA	Advisor to VP of Innovation and Research

A.7 Agenda

Day One Agenda

Event	Time
Working Breakfast: Welcome, Introductions, and Logistics	8:00am – 8:30am
DOE Vision	8:30am-9:00am
Overview of Current Manufacturing Challenges & Supply Chain Issues	9:00am-9:30am
Breakout Rooms: Current Challenges for the Hydropower Industry	9:30am-12:15 pm
Working Lunch: Breakout Room Summaries	12:15pm – 1:15pm
MDF Overview and Technology Collaborative Program	1:30pm-2:00pm
MDF Tours	2:00pm – 3:45pm
In Depth Capabilities of the MDF: 30-Minute Info Sessions	3:45pm – 4:45pm
Wrap Up, Next Steps, and Adjourn	4:45pm -- 5:00pm
Optional Social Hour/Dinner at The Chop House	6:00pm – 7:30pm

4 OAK RIDGE National Laboratory

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Day Two Agenda

Event	Time
Working Breakfast: Recap Day one and Preview Day Two	8:30am – 9:00am
Breakout Rooms: Advanced Manufacturing, Solutions for Hydropower, Part 1	9:00am – 10:15am
Breakout Rooms: Advanced Manufacturing, Solutions for Hydropower, Part 2	10:15am – 12:00pm
Working Lunch: Working with National Labs	12:00pm – 1:30pm
Plenary Session: Summaries from Breakout Rooms and Prioritization of Opportunities and a Collaborative Path Forward	1:30pm – 3:00pm
Wrap Up, Next Steps, and Closing Remarks	3:00pm – 3:15pm
Optional Networking and Continued Discussion Around Machines	3:15pm

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Figure A-7. Advanced Manufacturing for Hydropower Workshop day one and day two agendas.

APPENDIX B. EMERGING HYDROPOWER MANUFACTURING CASE STUDIES AND PROPOSED IDEAS

APPENDIX B. EMERGING HYDROPOWER MANUFACTURING CASE STUDIES AND PROPOSED IDEAS

Appendix B provides case studies for research projects that have been performed in recent years, as well as some novel ideas that could potentially be applied to the hydropower landscape. The case studies shown in Appendices B1–B3 were performed by ORNL and industry partners to demonstrate advanced manufacturing capabilities and to compare lead time and cost with traditional manufacturing methods. The advanced manufacturing methods used in the case studies are now fairly mature and have TRL in the 7–9 range. The proposed ideas shown in Appendices B4–B6 were submission entries for the I AM Hydro Prize hosted by DOE and WPTO in 2020.[6] These submissions are based on relatively new concepts, so the TRLs are in the 1–6 range.

APPENDIX B1. CASE STUDY: US BUREAU OF RECLAMATION ADVANCED MANUFACTURING REPLACEMENT PART

The US Bureau of Reclamation collaborated with ORNL's Water Power Program and MDF to determine the feasibility and cost of additively manufactured replacements for hydropower legacy parts that are no longer in production. The sample part selected for the study was a log boom anchor at Nimbus dam. As can be seen from Figure B-1, the anchor failed due to corrosion and was in need of replacement.

The log boom anchor was redesigned by the Bureau (Figure B-2) to be additively manufactured on a concept laser machine. The number of aluminum parts was reduced from 3 to 1, and the mass was reduced by approximately 50%.

The advanced manufacturing part successfully passed all nondestructive load tests performed by the Bureau.

The estimated cost of the traditionally manufactured log boom anchor is $1,800, while the cost of the new advanced manufacturing log boom anchor is $1,570 for a quantity of six.

Figure B-1. Old (left) and new (right) conventionally manufactured log boom anchors.

Figure B-2. Redesigned advanced manufacturing log boom anchor.

APPENDIX B2. CASE STUDY: EMRGY ADVANCED MANUFACTURING TOOLING

Emrgy is a small startup company started in 2014 that developed modular hydrofoils to be installed in human-made canals for hydrokinetic renewable energy generation. ORNL worked with Emrgy to demonstrate the use of advanced manufacturing in the production of the hydrofoils and spokes for the hydrokinetic system. Specifically, ORNL printed and finished machined patterns for both the hydrofoils and spokes that were subsequently used in a sand-casting manufacturing process. Emrgy used the sand castings for a pilot installation in Denver, Colorado, where the parts represented an 78% cost savings from the previous prototype build that was manufactured using subtractive manufacturing. In addition, the castings were completed with ORNL's newly developed AlCeMg alloy that will be tested for performance improvements, including higher corrosion resistance in a water application than the 6160-alloy used previously. The project successfully demonstrated the use of additive manufactured patterns to cost-effectively produce parts for use in a hydrokinetic renewable energy generation application. For additional information, please refer to the original report (Richardson and Chesser 2017).

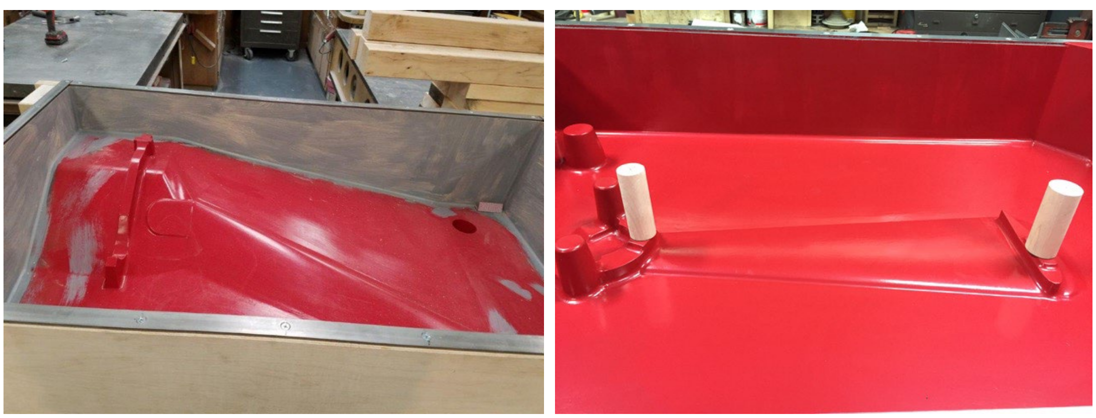

Figure B-3. Hydrofoil and spoke pattern boxes.

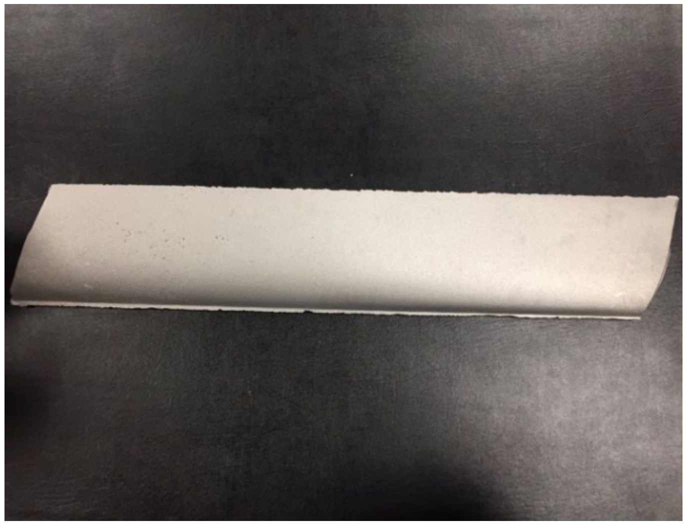

Figure B-4. Final casting made using 3D-printed patterns.

APPENDIX B3. CASE STUDY: GATE ADVANCED MANUFACTURING TOOLING

Molded concrete can be made using polymer molds; the technology has been demonstrated with the fabrication of large quantities of architectural features for large buildings. Since polymer advanced manufacturing machines now have large print volumes (more than 100 ft in the longest print axis), the size of the concrete molded parts can be quite large, although structural integrity of the polymer molds given the weight of the molded concrete would have to be accommodated. For architectural features, wood molds have been typically hand made in the past. In (Love et al. 2019), corresponding polymer molds were printed and then postmachined. Once tested, it was found that the wood molds lasted for 20 pourings, while the printed polymer molds lasted for 200 pourings. The end result was that although the printed molds cost three times as much to fabricate as the wooden molds, the capability to use the printed molds for ten times as long as the wooden molds provided a factor of three reduction in the cost per pouring. This particular approach to concrete advanced manufacturing has significant value for smaller components of hydropower systems.

Foundation or passage modules might well require modular components made from concrete. These components could be either printed, as described in the next section, or cast using molds made using advanced manufacturing. The actual casting of the concrete could be done either at the assembly location or off-site with the components transported to the site. Figure B-5 shows patterns printed from acrylo-butadiene-styrene with 20% carbon fiber for use in fabricating precast concrete windows for a New York City skyscraper.

Figure B-5. Printed patterns and precast concrete part.

APPENDIX B4. I AM HYDRO SUBMISSION: SUPER FRICTIONLESS SURFACES

I AM Hydro Prize Submission: Super Frictionless Surfaces Quasi-R

Quasi-R® is an oxynitride nano pillar surface that forms as an epitaxial surface texture when the special vibratory open plasma beam impinges on any surface.

Innovation:

- Nano-textured surfaces comprising high modulus nanoscale pillar-oxynitride-asperities that can yield significant benefits for dry and lightly lubricated friction-pairs

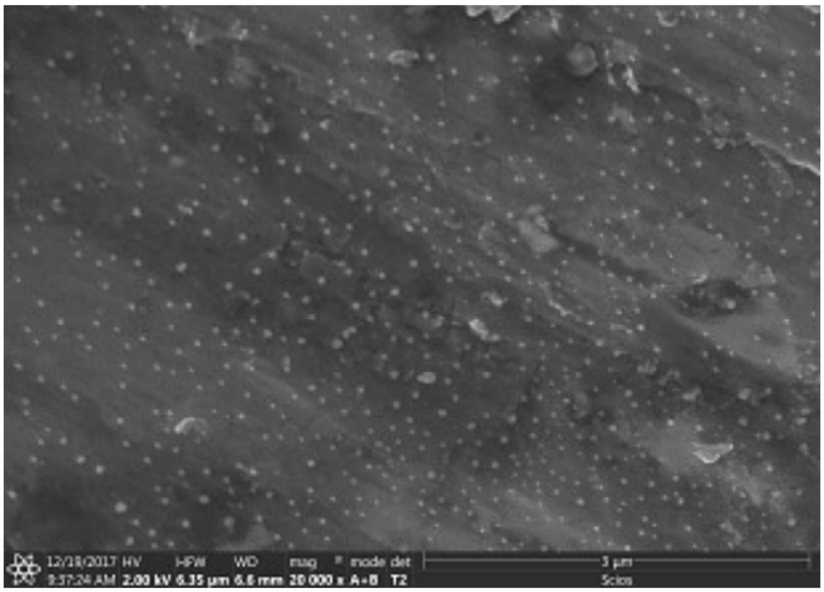

Figure B-6. Nanoscale pillar surface (Quasi-R®) produced rapidly by the plasma-metal interaction.

Feasibility:

- Processing cost of 1 US cent/m^2 for improved surfaces

How does the specific idea reflect metrics?

Metric	Evaluation
Hydropower LCOE	Savings of a substantial part of the ~114 EJ/year energy used to overcome friction
Construction/manufacture time	Depends on the size of the part
Project development risk	High
Scalability and applicability	Can be used in at any scale
Potential market size	Can potentially be applied in all hydropower industries
Environmental impact	Nontoxic effect on the environment
TRL	Readiness level is ~3; system is to be proven for a hydropower application

APPENDIX B5. I AM HYDRO SUBMISSION: ANTIFOULING COATINGS

I AM Hydro Prize Submission: Antifouling Coatings for Hydropower Cost Reduction

Interphase material (IPM) has developed an innovative, nontoxic, water-based surface coating for antifouling called THERMOPHASE.

Innovation:

- Adhesion of organic and inorganic debris is prevented.
- Coating can be applied directly or recirculated in water system.

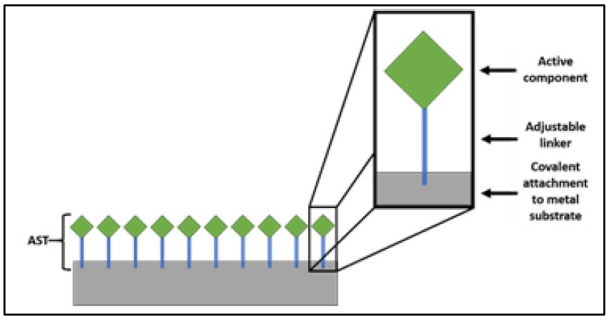

Figure B-7. Mapping of advanced manufacturing opportunities to hydropower challenges. Diagram of IPM's antifouling coating applied to a surface.

Feasibility:

- Capability to prevent biofouling from mussels has been demonstrated.
- THERMOPHASE has been successfully used to improve heat exchanger efficiency in heating, ventilation, and air conditioning and power generation applications.

How does the specific idea reflect metrics?

Metric	Evaluation
Hydropower LCOE	Improves performance of the system and reduces maintenance cost by reducing fouling and corrosion while also improving heat transfer
Construction time	No related information here
Project development risk	No information related here
Scalability and applicability	Can be used at any scale
Potential market size	Has potential to be applied broadly in hydropower the industry
Environmental impact	Nontoxic effect on the environment
TRL	Nanomaterial coatings significantly reduced biofouling on marine vessel surfaces and led to substantial reductions in heat transfer resistance in large, commercial heat exchangers

APPENDIX B6. I AM HYDRO SUBMISSION: SEMISOLID METAL CASTING

I AM Hydro Prize Submission: Semisolid Metal Casting for Hydroturbines

Semisolid casting for hydropower turbines eliminates expensive machining by reaching the final form of the hydroturbine blade.

Innovation:

- Metal is melted in a range of temperatures between the solidus and liquidus temperatures to a slurry state.
- A gas-fired cokeless furnace produces an oxygen-free atmosphere in the hearth and overcomes the problem of oxide inclusions associated with semisolid casting of stainless and low-alloy castings.

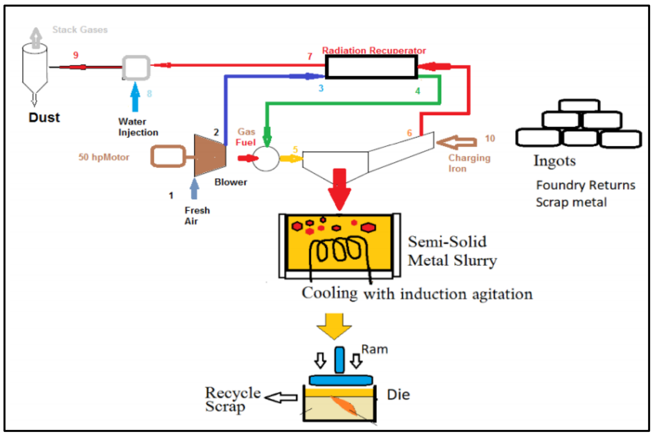

Figure B-8. Proposed semisolid casting of hydroturbine blades using a twin chamber cokeless furnace.

Feasibility:

- Methods for semisolid casting of certain alloys are described in literature.

How does the specific idea reflect metrics?

Metric	Evaluation
Hydropower LCOE	Saves \$100 to \$150 per installed kW in capital expenditures, leading to savings of \$50M to \$75M on a greenfield 500 MW hydropower plant
Construction/manufacture time	Depends on the size of the part
Project development risk	Low since the semisolid casting method has been proven in the literature
Scalability and applicability	Can be used to manufacture a wide range of part sizes in the hydropower system
Potential market size	Can be applied in multiple hydropower parts
Environmental impact	Not applicable
TRL	Between 4–6 for hydropower applications