U.S. DEPARTMENT OF ENERGY

Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

Advanced Manufacturing and Materials for Hydropower Strategy

U.S. DEPARTMENT OF ENERGY | WATER POWER TECHNOLOGIES OFFICE

Acknowledgments

This strategic plan was drafted by the U.S. Department of Energy's (DOE) Water Power Technologies Office (WPTO) with support from Oak Ridge National Laboratory (ORNL) and Kearns & West, a stakeholder engagement firm. WPTO funded this report.

WPTO engaged multiple stakeholder groups to ensure this strategic plan aligns with the hydropower industry's needs. That valuable feedback informed this document. The stakeholder groups included DOE's Hydropower Vision Advanced Technology Forum, the attendees of ORNL's 2022 Advanced Manufacturing for Hydropower workshop, and the National Hydropower Association's Waterpower Innovation Council.

List of Acronyms

AMM	advanced manufacturing and materials
AMMTO	Advanced Materials and Manufacturing Technologies Office
DOE	U.S. Department of Energy
EAL	environmentally acceptable lubricants
LCA	life cycle assessment
MYPP	Multi-Year Program Plan
O&M	operations and maintenance
ORNL	Oak Ridge National Laboratory
PNNL	Pacific Northwest National Laboratory
PSH	pumped storage hydropower
R&D	research and development
WPTO	Water Power Technologies Office

Executive Summary

Advanced manufacturing and materials (AMM) have shown immense potential to boost the U.S. manufacturing industry, increase American competitiveness, reshore manufacturing capabilities, and revolutionize the energy sector. However, the hydropower industry still heavily relies on traditional manufacturing methods and materials, and the potential benefits of AMM applications to hydropower development remain largely unexplored. The U.S. Department of Energy's (DOE) Water Power Technologies Office (WPTO) is committed to supporting the sustainable growth of both existing and future U.S. hydropower and recognizes AMM as a key opportunity to achieve its mission. The purpose of this strategy is to establish stakeholder-informed, high-priority goals within WPTO's mission that it can target with future research and development (R&D) investments.

Several stakeholder engagements and a quantitative analysis informed this strategy. In 2022, WPTO and Oak Ridge National Laboratory (ORNL) hosted a two-day workshop that brought together DOE representatives, hydropower industry stakeholders (including owners, operators, and original equipment manufacturers), and advanced manufacturing R&D experts. The results of the workshop were combined with literature reviews and additional stakeholder interviews in an ORNL report (Musa et al. 2023). This report characterized the current and emerging manufacturing challenges facing the hydropower industry in the United States and identified numerous opportunities for advancing AMM for hydropower (listed in Table ES-1). The opportunities were categorized into three overarching goals:

GOAL 1

IMPROVE the operational reliability of existing hydropower by minimizing maintenance duration, frequency, and cost.

GOAL 2

EXPAND the design space for hydropower innovations by improving component efficiency, flexibility, and cost.

GOAL 3

ENABLE the adoption of hydropower technologies.

Figure ES-1. AMM for hydropower goals

ORNL then fielded a questionnaire among hydropower sector representatives to quantitatively assess each opportunity on a scale from 1 to 10 based on the perceived value to hydropower stakeholders and the likelihood of adoption. WPTO determined similar scores dependent on the opportunity's alignment to the office's mission and capabilities, taking into consideration other ongoing efforts. These three scores (value, likelihood, and alignment) turned into a combined score using a weighted average. The top 10 scoring opportunities shared common commercialization needs, so they were synthesized into the following eight sub-goals:

- **Sub-goal 1.1**: Facilitate the adoption of in situ application methods for coatings and repairs that minimize outage time and safety risks through demonstrations and process guidance.
- **Sub-goal 1.2**: Validate the performance and durability of coatings and repair methods for hydropower applications through testing and standards.
- **Sub-goal 1.3**: Support decision-making and deployment of sustainable bearing solutions through active stakeholder engagement.
- **Sub-goal 2.1**: Prioritize and deploy adaptable sensors for new and existing hydropower components with a clear value for decision-making.
- **Sub-goal 2.2**: Reduce the capital costs for micro-hydropower through pilot projects of additively manufactured or prefabricated powertrains.
- **Sub-goal 3.1**: Develop methods for quantifying and effectively communicating the value of innovative technologies compared to conventional alternatives.
- **Sub-goal 3.2**: Ensure adequate access to testing capabilities through improved access to existing facilities and the development of new capabilities.
- **Sub-goal 3.3**: Convene multistakeholder groups to expedite the development of targeted standards and testing methods for hydropower applications.

These sub-goals will inform an internal five-year road-mapping effort that will specify activities and funding mechanisms to meet these goals based on available budgets and capabilities. As the AMM and hydropower industries evolve, WPTO will continue to engage stakeholders to ensure proper coordination and collaboration.

Table ES-1. List of AMM for Hydropower Opportunities Categorized by the Most Relevant Goal and Scored According to the Quantitative Prioritization Analysis

OPPORTUNITY	COMBINED SCORE
Goal 1: Improve the operational reliability of existing hydropower by minimizing maintenance duration, frequency, and cost.	
Innovative coatings and application techniques	7.6
Environmentally acceptable lubricants	7.0
In situ repairs using robotics and advanced welding techniques	6.9
Self-lubricating bearings	6.8
Additive manufacturing for tooling	6.5
Functionally graded materials for runners	6.4
Skin-friction reduction and improved surface finishes using modern, unconventional machining	6.4
New metal alloys for powertrain components	5.9
Additive manufacturing for the development of molds for large components	5.8
Goal 2: Expand the design space for hydropower innovations by improving component efficiency, flexibility, and cost.	
Embedded sensors	7.4
Composite materials for powertrain components	6.6
Low-cost materials and manufacturing methods for penstocks, conduits, and pipes	6.6
Unconventional geometries and designs enabled by AMM	6.2
In situ, 3D concrete printing	5.9
Direct metal additive and hybrid manufacturing of small hydropower powertrain components	5.8
Innovative materials for geotextiles, reservoir linings, and geotechnical techniques	5.8
New materials and designs for generators	5.3
Goal 3: Enable the adoption of hydropower technologies.	
Valuation and performance-cost modeling (metrics)	7.3
Testing capabilities for AMM technologies	6.9
Quality assurance and testing standards	6.9
Rapid prototyping using additive manufacturing and polymers for scaled explorative testing	6.6
Advanced imaging techniques for material characterization and qualification	6.0
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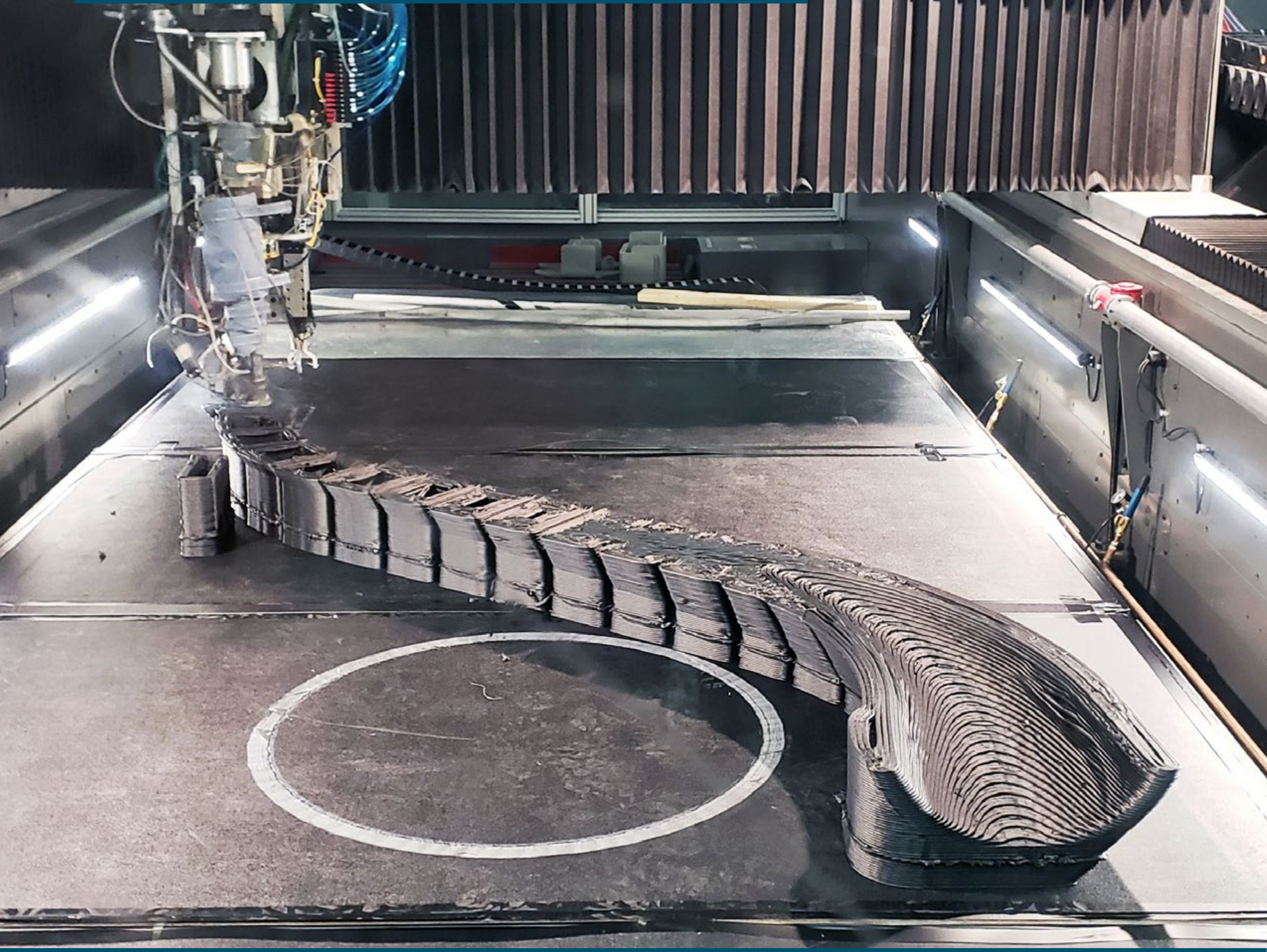


INTRODUCTION 1

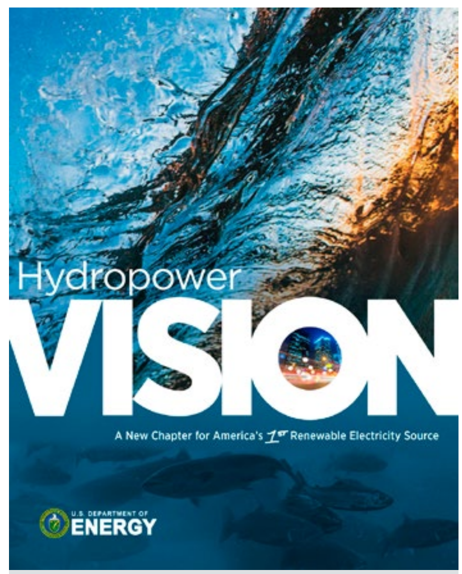
1. Introduction

Advanced manufacturing and materials (AMM) are revolutionizing how the energy sector is built, and the hydropower industry stands to benefit greatly from these new opportunities. The mission of the U.S. Department of Energy's (DOE) Water Power Technologies Office (WPTO) is to enable research, development, and testing of new technologies to advance marine energy as well as next-generation hydropower and pumped storage systems for a flexible and reliable grid. This strategic plan outlines how WPTO can support AMM technologies for hydropower and pumped storage applications.

Section 1 provides context for the role of this strategic plan within WPTO's broader activities. Section 2 provides a brief technical background about the AMM opportunities that could be explored. Section 3 describes the methodology used to prioritize the opportunities for investment using stakeholder input and illustrates the results of the prioritization process across three overarching goals. Finally, Section 4 summarizes a path forward based on these scoping activities.

1.1. Advanced Manufacturing and Materials for Hydropower

Although hydropower technology and designs have evolved over the years, manufacturing of hydropower components still relies heavily on traditional methods and materials. Moreover, while other energy sectors have leveraged AMM techniques to boost manufacturing and increase America's global competitiveness, the hydropower industry has not widely explored AMM's potential benefits. AMM has the potential to alleviate manufacturing challenges stemming from well-known maintenance issues, environmental impact mitigations, and changes in operations while helping to modernize the hydropower fleet, an essential part of the United States' renewable energy portfolio. In fact, in the United States in 2022, hydropower accounted for 28% of all renewable energy generation and 6.2% of the total energy portfolio (U.S. Energy Information Administration 2023). As demonstrated in other energy sectors (e.g., wind), AMM has the potential to enable low-impact growth across the hydropower industry by employing additive manufacturing, novel machining and casting processes, and innovative materials (Mann et al. 2017; Shields et al. 2023).



Cover of the *Hydropower Vision* report, which was released in 2016

1.1.1. Broader Context

This strategic plan sits within the context of several federal strategies. This section briefly summarizes and references the corresponding strategic documents. First, DOE's 2016 *Hydropower Vision* report outlines future pathways for low-carbon, renewable hydropower with a focus on continued technical evolution, increased energy market value, and environmental sustainability (DOE 2016). Importantly, the vision identifies actions that will enable the development and deployment of AMM in support of DOE's overarching hydropower vision. AMM will help advance several key topic areas in the vision, including technology advancement, sustainable development and operation, enhanced revenue and market structures, and enhanced collaboration, education, and outreach. AMM techniques from additive manufacturing to modular civil structures have the potential to help the next generation of hydropower and pumped storage hydropower (PSH) technologies realize high efficiencies and enhanced performance while minimizing environmental footprint and lowering capital costs.

In 2023, DOE updated the Hydropower Vision Roadmap to outline the next era of hydropower development through 2050. While the vision imagines the broader future of hydropower, this strategic plan pinpoints and prioritizes specific opportunities to achieve that vision for AMM.

WPTO's *Multi-Year Program Plan* (MYPP) for hydropower expands on the *Hydropower Vision* by addressing topics that crosscut multiple activity areas (DOE 2022). Directed by the Energy Act of 2020, WPTO's MYPP outlines strategies to address challenges in the hydropower industry and rapidly innovate new solutions.

The MYPP identifies limited opportunities for new, affordable hydropower growth as a key challenge facing the hydropower sector and points to innovations for low-impact hydropower growth as an overarching approach to improving this issue. Intermediate outcomes include cost reductions and commercialization of standard modular hydropower technologies for existing water infrastructure and new stream-reach development, industry pursuit of high-impact advanced manufacturing opportunities for hydropower applications to reduce costs, reduced design cycle and testing time of new hydropower technologies, and increased developer interest in hydropower projects that utilize new value propositions beyond generation. Long-term outcomes include the deployment of new, small, low-impact hydropower projects in the United States that integrate multiple social, ecosystem, and energy needs. Identifying pathways for advanced manufacturing will play a critical role in achieving these outcomes.

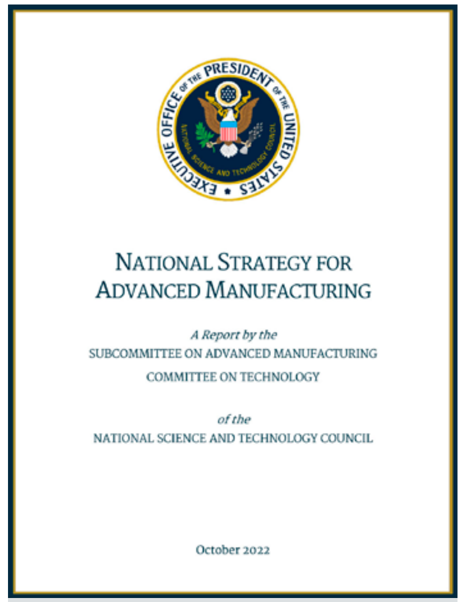
Cover of WPTO's *Multi-Year Program Plan*, which was released in 2022

The MYPP outlines the following Fiscal Year 2021–2025 research and development (R&D) priorities to progress AMM for hydropower:

- Utilize creative funding mechanisms to identify high-impact advanced manufacturing opportunities for hydropower applications.
- Incorporate AMM with the potential to reduce costs or increase performance into the design of hydropower components.
- Evaluate the performance of new advanced manufacturing technologies and methods at a partial and/or full scale.
- Conduct a field demonstration to validate new advanced manufacturing technologies and methods in a real-world site.

More broadly, advanced manufacturing has been identified as a key priority for the Biden-Harris administration. The October 2022 White House National Strategy for Advanced Manufacturing report (National Science and Technology Council 2022) outlines a vision to elevate U.S. leadership in advanced manufacturing on a global scale. Although the White House report does not provide explicit direction or funding for DOE, this strategic plan addresses each of the broad goals and several of the specific objectives highlighted in the White House report, including:

- **Develop and implement advanced manufacturing technologies:** Develop innovative materials and processing technologies (high-performance materials design and processing, additive manufacturing) and lead the future of smart manufacturing (digital manufacturing).
- **Grow the advanced manufacturing workforce:** Develop, scale, and promote advanced manufacturing education and training (expand and disseminate new learning technologies and practices).
- **Build resilience into manufacturing supply chains:** Expand efforts to reduce manufacturing supply chain vulnerabilities (improve supply chain risk management, stimulate supply chain agility) and strengthen and revitalize advanced manufacturing ecosystems (assist technology transition, improve public-private partnerships).


NATIONAL STRATEGY FOR ADVANCED MANUFACTURING

A Report by the
SUBCOMMITTEE ON ADVANCED MANUFACTURING
COMMITTEE ON TECHNOLOGY

of the
NATIONAL SCIENCE AND TECHNOLOGY COUNCIL

October 2022

Cover of the White House *National Strategy for Advanced Manufacturing*, which was released in 2022

1.2. Strategic Plan Inputs

This strategic plan was informed by several stakeholder engagement activities, which are summarized below.

1.2.1. 2022 Advanced Manufacturing for Hydropower Workshop and Oak Ridge National Laboratory Report

In August 2022, WPTO and Oak Ridge National Laboratory (ORNL) hosted a two-day workshop at the lab's Manufacturing Demonstration Facility. The primary goal of the workshop was to bring together more than 50 stakeholders from across the hydropower, academia, national lab, and government sectors to inform an ORNL report explaining current hydropower manufacturing and materials challenges, associated AMM capabilities, and potential solutions. Figure 1 illustrates workshop participants by sector and by industry. The ORNL report, *Advanced Manufacturing and Materials for Hydropower: Challenges and Opportunities,* referred to as ORNL's AMM for hydropower report, details AMM opportunities applicable to hydropower, including additive manufacturing, novel machining and casting processes, innovative materials, and novel coating processes (Musa et al. 2023). These AMM techniques provide significant value propositions when compared with conventional alternatives. Findings from the report and workshop informed the goals and opportunities identified in this strategic plan and will continue to drive and inform future WPTO investments to support AMM for hydropower.

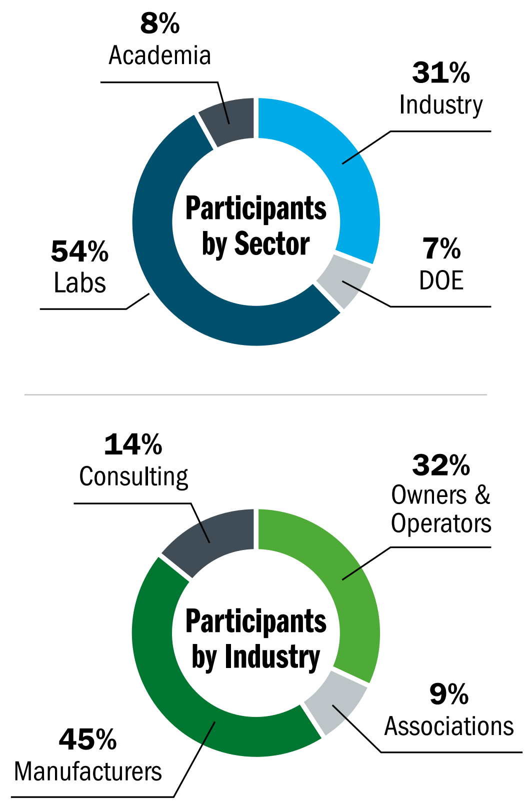


Figure 1. AMM for hydropower workshop participants by sector

1.2.2. 2023 AMM for Hydropower Stakeholder Input Questionnaire

To inform the quantitative prioritization method described in Section 3.1, ORNL sent a questionnaire[1] to hydropower industry stakeholders. The questionnaire aimed to quantify perceptions of 23 AMM opportunities (outlined in Table 1) with respect to their expected value to industry and the likelihood of adoption. More details are included in Section 3.1. Respondents included participants from the 2022 AMM for Hydropower workshop, the National Hydropower Association, the DOE Hydropower Vision Team's Advanced Technology Forum, and other manufacturers, owners, operators, engineers, and consultants. The questionnaire received 32 responses and represented a variety of stakeholder groups as indicated in Figure 2.

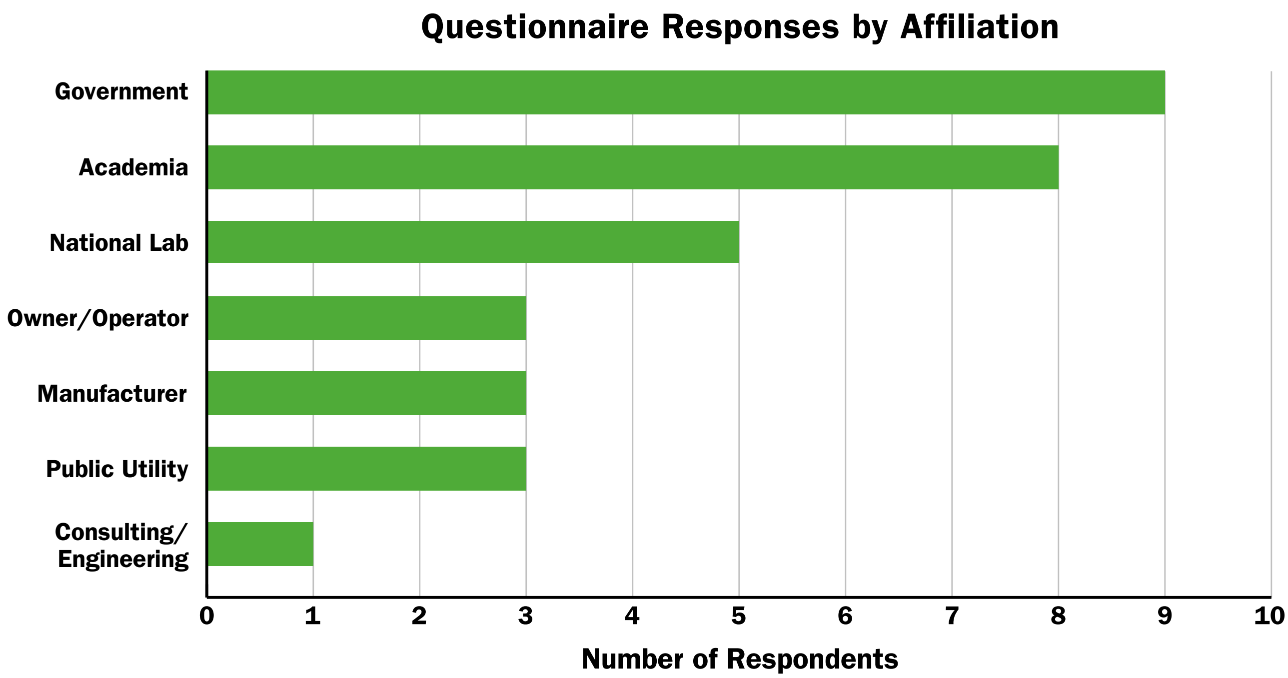


Figure 2. AMM for hydropower stakeholder input questionnaire responses by affiliation

[1] The questionnaire is available at: https://forms.office.com/pages/responsepage.aspx?id=ZU40UYBo3EubDMtI45yjtTnddOhaaCFNoW-FFfwKxhpUODNQU0FZV0xGVE9aS0VGNlFZMUFWTjRDNi4u

2 TECHNICAL BACKGROUND

2. Technical Background

2.1. Hydropower Industry Challenges Requiring Innovation

Both the current hydropower fleet and emerging hydropower projects face an array of technological and material challenges. The aging infrastructure of existing hydropower plants is one of the leading contributors to dam failure and unexpected outages that occur due to sudden component failure. Over time, some equipment becomes more expensive to replace or rehabilitate. According to ORNL's AMM for hydropower report, major challenges facing existing hydropower include "legacy part replacement, component maintenance and repair, evolving operating conditions, supply chain issues, and data access" (Musa et al. 2023). Additionally, external factors like climate change and environmental mitigation pose new challenges that must be considered in hydropower manufacturing and operations. An overview of some of these challenges and potential solutions is depicted in Figure 3.

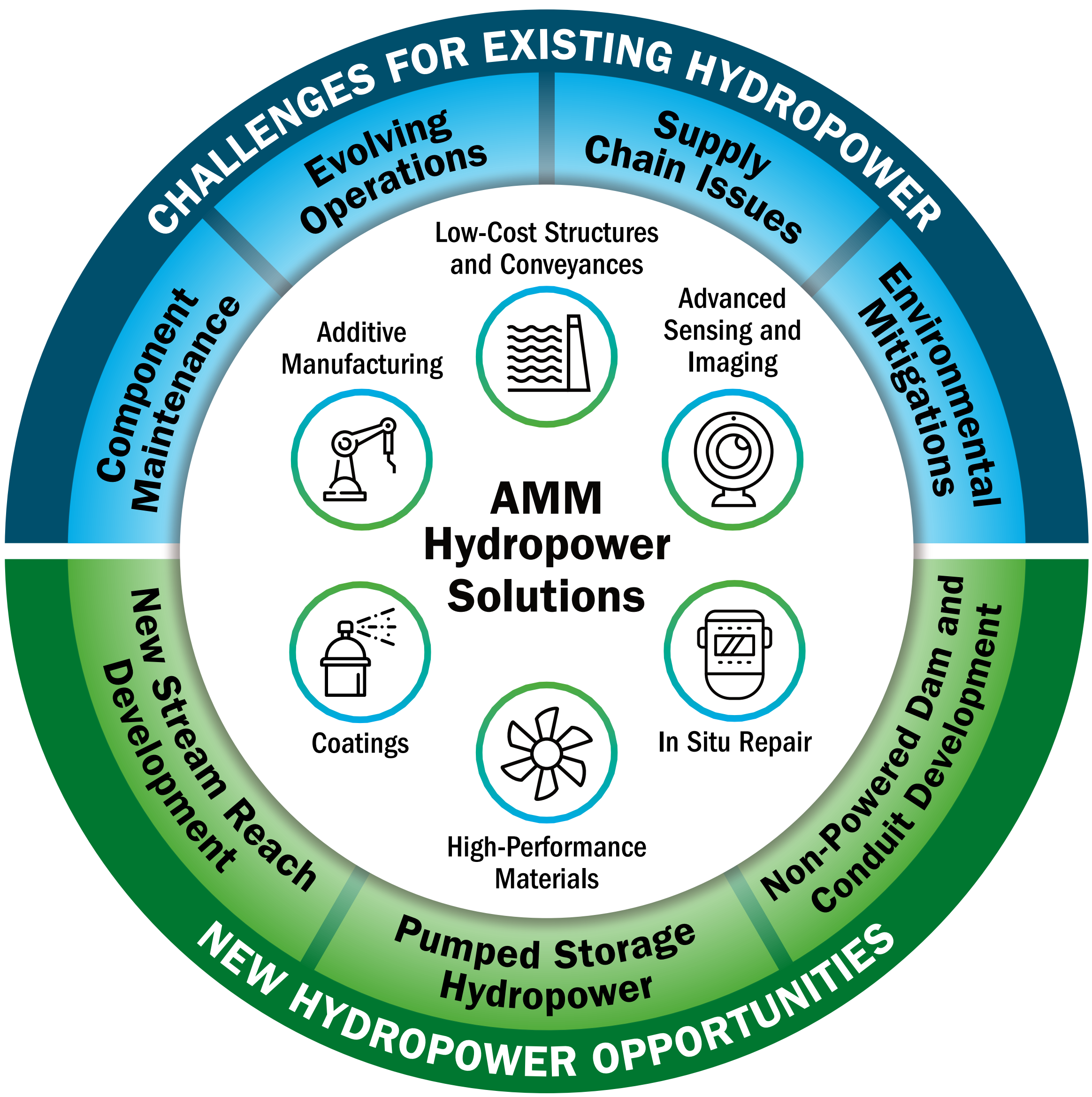


Figure 3. Summary of AMM for hydropower challenges and example opportunities

The scale of new development and changes in the global energy sector are driving hydropower to evolve to achieve new levels of economic and technical performance. In particular, a significant portion of hydropower growth opportunities will stem from small hydropower (10 megawatts or less), including non-powered dam and conduit retrofits (Hadjerioua et al. 2012; Hansen et al. 2021; Sasthav and Oladosu 2022). Smaller projects are typically more expensive per kilowatt compared to larger projects because they cannot benefit from economies of scale related to higher heads (O'Connor et al. 2015). Adopting advanced manufacturing could help reduce capital costs and increase economic viability. The integration of variable renewable resources (e.g., wind and solar) will require additional energy storage, such as PSH, and more operational flexibility (i.e., more frequent starts and stops, ensure black start capability, etc.) compared to the grid demands of previous decades. The availability of storage and flexibility can be increased through advanced manufacturing methods supporting powertrains, conveyance, and structures that expand storage development, increase the life span of the technology, and ensure rapid maintenance.

Increasing hydropower sustainability through environmental mitigation measures (e.g., improved fish passage designs) is another major need in both existing and future hydropower projects. AMM may increase the design space of possibilities, enabling the adoption of nonconventional designs and shapes that may have been limited or precluded by traditional manufacturing methods, potentially creating new options for environmental mitigation.

Ice Harbor Dam in Washington uses a run-of-river system, which requires little water storage. *Photo from Sarah Wagoner, U.S. Department of Energy's Make a Splash Photo Contest*

Beyond technical challenges, the hydropower industry faces increasing supply chain issues, including sourcing of equipment and parts that are challenging to produce domestically (e.g., steel castings and forgings for turbine runners and windings for large unit generators), global shortages and shipping bottlenecks for material and components for electronics (i.e., microchips and digital components), and workforce limitations (Uría-Martínez et al. 2022). AMM can create alternatives to the traditional sources of components that can be more rapidly and reliably procured.

2.2. Goals

Valuable stakeholder input from the 2022 AMM for Hydropower workshop, ORNL's AMM for hydropower report, DOE's ongoing Hydropower Vision process, and other research helped WPTO set three AMM goals for hydropower innovation (see Figure 4).

The first goal aims to improve the operational reliability of existing projects by minimizing maintenance duration, frequency, and cost. Aging infrastructure and technologies are sparking more frequent repairs, replacements, and, in some cases, upgrades. According to ORNL's hydropower market report (Uría-Martínez et al. 2022), the average ages of conventional hydropower and PSH plants are 64 and 45 years, respectively. Maintenance is extremely complicated and costly due to technical challenges, the highly specialized skill set and tools required, and lost revenues associated with required shutdowns. Any innovation offered by AMM that reduces the number of interventions, simplifies processes, and cuts downtime will improve the contributions of the existing U.S. hydropower fleet, extend its life span, and potentially expand its generation capacity.

Figure 4. AMM for hydropower goals

The second goal aims to expand the design space for hydropower innovations by improving component efficiency, flexibility, and cost. This goal refers to all AMM advancements that will enable ideas, innovations, and nonconventional designs that are currently impossible with traditional manufacturing methods or too risky to be adopted by current hydropower projects. Activities under this goal may expedite future development, improve sustainability, and potentially lead to new development opportunities.

One of the reasons for separating these first two goals, even though certain technologies apply to both, is the applicable stakeholders. The first goal may target existing hydropower owners and operators for large, medium, and small hydropower. The second goal focuses on stakeholders for new hydropower development (developers, regulators, investors, etc.), which, based on the available potential of hydropower developments, will largely focus on small hydropower, including non-powered dam retrofits and pumped storage. One of the primary challenges for small hydropower is improving net benefit (reducing costs and increasing generation). Compared to conventional hydropower, AMM technologies for small hydropower may focus on different objectives, such as being inexpensive and replaceable, as opposed to durable and resilient.

The third goal aims to enable the adoption of hydropower technologies created with innovative AMM technologies. Since the hydropower industry is mature and an important inertial part of the grid, stakeholders may be resistant to adopting or investing in technologies that have not been properly tested or that cannot clearly demonstrate the potential benefits compared to the risks. In addition, the hydropower sector is a long-term investment area with approximately 2,300 hydropower plants and 44 pumped storage plants in the United States (Johnson and Uría-Martínez 2023). As such, the ability to try out new technologies and methods and apply lessons to other plants is relatively limited compared to other energy sources. Therefore, this goal refers to all the activities required to validate technologies manufactured using AMM and nonconventional methods with the objective of de-risking the adoption by hydropower manufacturers, owners, and operators.

2.3. AMM Opportunities to Solve Hydropower Industry Challenges

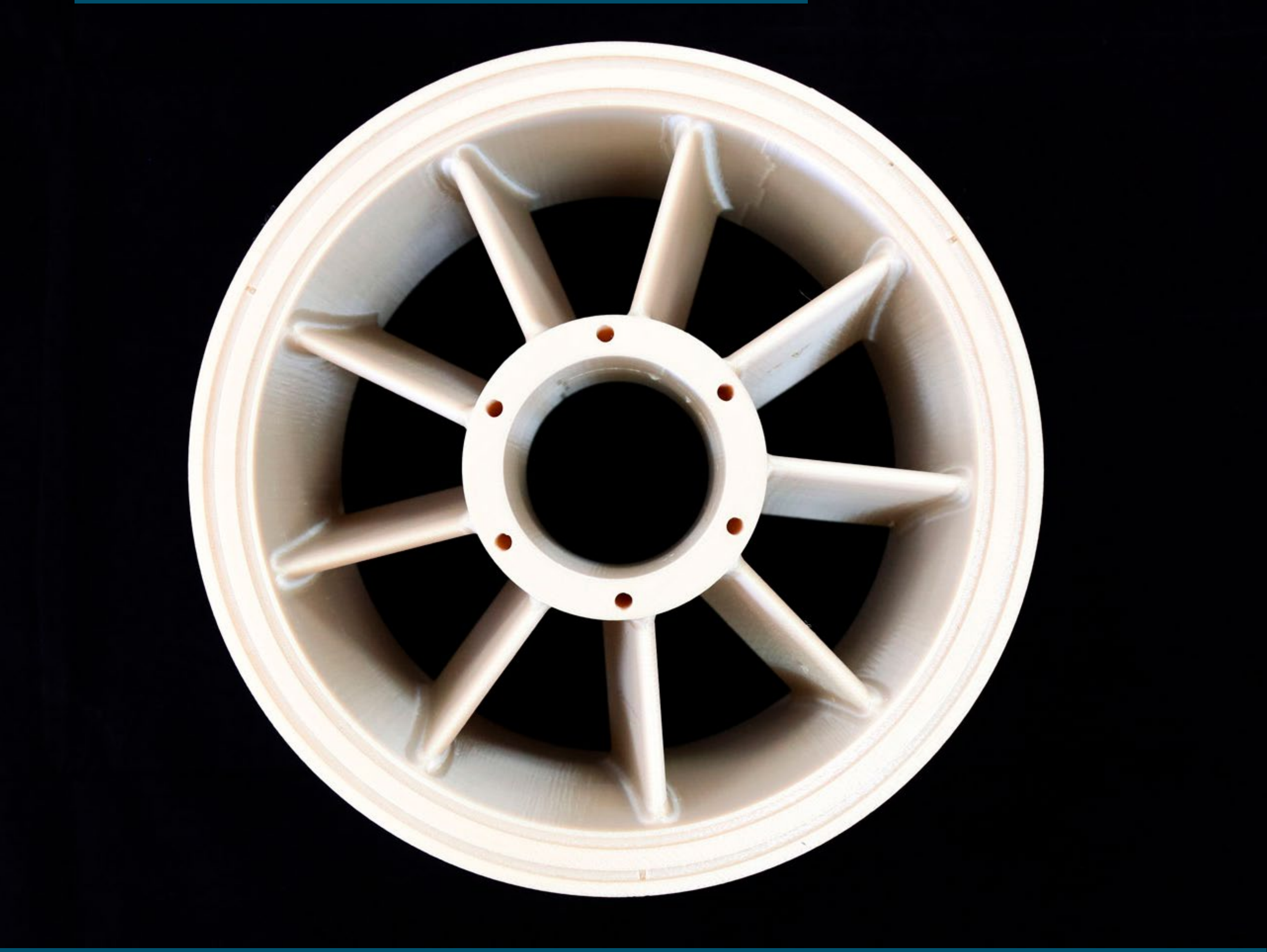
AMM offers unique opportunities to solve some of the hydropower industry's most pressing challenges while enhancing cost savings, increasing efficiencies, and reducing financial and safety risks. For the purposes of this report, "opportunities" refer to technologies, methodologies, resources, or other activities that provide value to the hydropower industry as a whole. ORNL's AMM for hydropower report identifies several of these value propositions (Musa et al. 2023):

- **Reducing operations and maintenance (O&M) costs:** AMM technologies may reduce O&M costs by streamlining repair processes and eliminating routine maintenance processes.
- **Reducing lead time and capital cost:** AMM technologies can provide comparable performance benchmarks with reduced costs and lead times.
- **Improving component or system performance:** AMM can allow for direct performance improvements compared to conventional alternatives.
- **Increasing design space**: AMM enables system and component designs that might not be feasible with conventional technologies, potentially requiring a complete redesign of overall configuration, costs, and scales.
- **Reshoring and increased availability:** Manufacturing methods such as in situ additive manufacturing or the use of recycled materials can reduce reliance on foreign imports, increasing supply chain reliability and security.
- **Validation and certification for commercial adopters:** 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.
- **Environmental improvement and risk reduction:** Advanced manufacturing technologies can have direct environmental performance improvements compared with their traditional counterparts, which could result in reduced fines and fewer operational restrictions.
- **Informed decision-making:** AMM may allow sensors to be embedded in components as they are manufactured, enhancing data collection for decision-making and enabling predictive maintenance activities that minimize unit downtime.

ORNL's AMM for hydropower report also lists potential hydropower-relevant AMM opportunities identified through a literature review and stakeholder engagement (Musa et al. 2023). Most of these opportunities offer multiple value propositions, depending on specific use cases. Table 1 provides a list of 23 opportunities that WPTO deemed to be relevant for this analysis. While this list may not be fully comprehensive, the questionnaire did not produce any additional opportunities to include for prioritization. If an opportunity fell under multiple goals, it was categorized into the most relevant goal. Tables A1 to A-3 in the Appendix provide brief descriptions of each opportunity, along with high-level activities that WPTO would likely invest in for further development.

Table 1. List of AMM for Hydropower Opportunities by the Most Relevant Goal

Goal 1:	**Improve the operational reliability of existing hydropower by minimizing maintenance duration, frequency, and cost.**
New metal alloys for powertrain components	
Additive manufacturing for the development of molds for large components	
Additive manufacturing for tooling	
In situ repairs using robotics and advanced welding techniques	
Innovative coatings and application techniques	
Skin-friction reduction and improved surface finishes using modern unconventional machining	
Functionally graded materials for runners	
Environmentally acceptable lubricants (EALs)	
Self-lubricating bearings	
Goal 2:	**Expand the design space for hydropower innovations by improving component efficiency, flexibility, and cost.**
Direct metal additive and hybrid manufacturing of small hydropower powertrain components	
Unconventional geometries and designs enabled by AMM	
Embedded sensors	
Composite materials for powertrain components	
Low-cost materials and manufacturing methods for penstocks, conduits, and pipes	
New materials and designs for generators	
In situ, 3D concrete printing	
Innovative materials for geotextiles, reservoir linings, and geotechnical techniques	
Goal 3:	**Enable the adoption of hydropower technologies.**
Quality assurance and testing standards	
Valuation and performance-cost modeling (metrics)	
Testing capabilities for AMM technologies	
Rapid prototyping using additive manufacturing and polymers for scaled explorative testing	
Advanced imaging techniques for material characterization and qualification	
Life cycle assessment (LCA) for AMM and promotion of locally sourced or recycled materials	



3 STRATEGIC PRIORITIES

3. Strategic Priorities

The strategic planning team conducted a quantitative prioritization exercise to analyze which of the AMM for hydropower opportunities were the most impactful, most likely to succeed, and most aligned with WPTO's mission and capabilities. The following section describes the prioritization methodology, which included input from both hydropower stakeholders and WPTO. The resulting scores are reported within each of the three goals.

3.1. Quantitative Prioritization Methodology

This methodology focused on quantifying three key features of each opportunity: the value to the hydropower industry if successfully implemented, the likelihood to be implemented given adequate investment, and alignment with WPTO's mission and capabilities. These features were represented as scores (termed value, likelihood, and alignment) between 1 and 10, with 10 representing the best score and 1 representing the worst score. The value, likelihood, and alignment scores were then compiled using a weighted average to create a combined score, which determined the prioritization ranking within each goal. The following two subsections outline how the scores were derived.

3.1.1. Value and Likelihood Scoring Based on Stakeholder Perception of the Industry

The value and likelihood scores are intended to represent the perceived impact on the hydropower industry. As such, it was important to get hydropower stakeholders' input on the scores. The questionnaire described in Section 1.2 asked respondents to score the value and likelihood of each opportunity with the same 1–10 scale. The questionnaire provided a brief description of the opportunity, which touched on both the definition of the technology and what WPTO would address within the opportunity. It is important to note that the questions were framed around scoring stakeholder perceptions of the industry rather than solely objective technical feasibility because adoption also requires a subjective awareness of the technology and its applications to the stakeholder's challenges. The respondents were also given space to comment on why they selected their top priorities, suggest activities or outcomes of interest, and list additional opportunities not mentioned in the questionnaire. The results of the survey are discussed in Section 3.2.

3.1.2. Alignment Scoring Based on WPTO Internal Mission and Capabilities

While an opportunity may be valuable to hydropower stakeholders, it is also important to understand WPTO's role in supporting the opportunity. For example, industry groups, technology investors, or other offices within DOE may be better equipped to tackle certain challenges based on the timing and scale of the required investment. For example, given typical budget cycles, WPTO can best support short-term projects (shorter than three years). In addition, project budgets, which may typically range from $200,000 to $1 million per year, need to be balanced with other priorities and resources within the office. As part of a federal agency, WPTO is meant to serve a nationwide audience. Therefore, WPTO prefers to invest in opportunities that apply broadly to many types of hydropower facilities (new and existing), as well as many types of systems or components within facilities. It is also important for WPTO to make effective use of funds by not duplicating efforts or investing in technologies that will succeed without additional support. These factors were assessed using the point distribution rubric shown in Table 2, which results in a WPTO alignment score between 1 and 10 for each AMM opportunity. WPTO determined the factor selections for each opportunity. The resulting scores and discussion are described in Section 3.2. An important distinction to note is that WPTO did not score these opportunities at-large, but rather by the high-level activities described in Tables A-1 to A-3 in the Appendix that WPTO would invest in to promote the opportunity. **Therefore, the WPTO alignment score does not indicate the office's position regarding the value or feasibility of the technology;** rather, it indicates a self-reflection on how effectively WPTO would advance the opportunity compared to other organizations.

Table 2. WPTO Alignment Score Rubric

FACTOR	0 POINTS	1 POINT	2 POINTS
Investment Cost	High (>$10 million)	Medium ($3 million–$10 million)	Low (<$3 million)
Investment Timing	Long (>5 years)	Medium (3–5 years)	Short (<3 years)
Hydropower Market Applicability	Low (Limited to a small subset of the existing fleet or new development types with low potential)	Medium (Applies to a subset of the existing fleet and/or several types of new development)	High (Broadly applicable to existing and new hydropower facilities)
Hydropower Component/System Applicability	Low (Applies to a single system or component)	Medium (Applies to a select few hydropower systems or components)	High (Broadly applicable to multiple systems or components)
Needed WPTO Investment	Low (Likely to succeed without WPTO support or considerable overlap with ongoing activities)	Medium (WPTO may benefit from existing commercialization)	High (WPTO investment is likely required for success)

3.1.3. Calculating the Combined Score

The different procedures implemented for the stakeholder perception (value and likelihood) scores and the WPTO alignment score required the use of weighting factors to balance out the impact of each criterion in the averaged combined score. For example, the average of value and likelihood scores from the 32 respondents tended to be high. The average value scores ranged from 6.0 to 8.3 across all the opportunities, whereas the likelihood score ranged from 5.4 to 7.6. These score averages indicate an overall positive response to the identified opportunities. The standard deviations for the value scores ranged from 1.3 to 2.2 and for the likelihood scores from 1.5 to 2.2. On the other hand, the WPTO alignment score was a single, collaboratively selected score for each opportunity based on the criteria in Table 2, which resulted in a range from 1.0 to 9.0. To account for the variations in range and to highlight the importance of industry perspectives in WPTO's decision-making, the alignment score was weighted with a factor of 0.5. As such, the combined score was computed using the following weighted average equation:

$$Combined = [(1.0 \times Value) + (1.0 \times Likelihood) + (0.5 \times Alignment)] / (1.0 + 1.0 + 0.5)$$

3.2. Prioritization Results

The following subsections present the scores for each opportunity according to their most relevant goal. The discussions provide additional context about WPTO's scoring and highlight common themes across the opportunities. The written comments regarding highest priorities provided through the questionnaire generally matched stakeholder's quantitative responses. In addition to the opportunity prioritization, respondents were asked to comment on the most impactful activities that may support the hydropower sector. The recommended activities from the stakeholders (from highest to lowest number of mentions) were demonstrations (12), workshops/training (12), studies (six), full-scale testing (five), guidelines (two), collaboration/partnerships (two), tools (two), and data gathering (two). In practice, each activity depends on the selected opportunity, and the conclusion briefly discusses some high-priority next steps.

3.2.1. Goal 1: Improve the Operational Reliability of Existing Hydropower by Minimizing Maintenance Duration, Frequency, and Cost

Table 3. Prioritized Opportunities to Improve Operational Reliability

OPPORTUNITY	SCORES (1–10)			
	VALUE	LIKELIHOOD	ALIGNMENT	**COMBINED**
Innovative coatings and application techniques	8.0	7.4	7.0	**7.6**
EALs	7.5	7.1	6.0	**7.0**
In situ repairs using robotics and advanced welding techniques	8.3	7.6	3.0	**6.9**
Self-lubricating bearings	7.5	7.5	4.0	**6.8**
Additive manufacturing for tooling	6.3	6.5	7.0	**6.5**
Functionally graded materials for runners	7.0	6.5	5.0	**6.4**
Skin-friction reduction and improved surface finishes using modern unconventional machining	6.4	6.0	7.0	**6.4**
New metal alloys for powertrain components	6.1	5.7	6.0	**5.9**
Additive manufacturing for the development of molds for large components	6.9	6.5	2.0	**5.8**

While this goal specifically addresses support of the existing fleet, the highest priority opportunities across all three goals (including coatings, embedded sensors, environmentally acceptable lubricants [EALs], and in situ repair) broadly aim to ensure that existing technologies continue to perform their jobs rather than developing new parts. This result reflects the maturity of technologies within the industry and the relative size of existing hydropower compared to new hydropower development. The focus on existing technology is highlighted by *innovative coatings and application techniques,* which has the highest combined score. Coatings are a well-established industry, but the hydropower industry has not been fully utilizing coatings to combat common issues such as cavitation, corrosion, erosion, and biofouling. This is beneficial from the WPTO perspective because R&D activities can focus on application of the technology to new use cases rather than coating development, thus reducing investment cost and time. WPTO invested in coatings through a Small Business Innovation Research program topic in spring 2023, but the diversity in coating technologies and use cases (penstocks, blades, piping, gates, etc.) means that multiple investments can lead to increased success. WPTO's Marine Energy Program also has significant ongoing interest in the development and commercialization of biofouling-resistant coatings that could be leveraged in hydropower. Further stakeholder engagement could be used to identify the use cases that are of highest priority, although several coatings on the market are multipurpose, which could be advantageous for the industry. *Skin-friction reduction and improved surface finishes* can also be included in the realm of coatings with a niche application in reducing head losses. Depending on the technology, coatings can target O&M cost reductions, performance improvements, environmental risk reduction, and worker safety improvements. Since coatings are a long-term solution, it will be necessary to understand or model the costs and benefits over the life of the target component.

Pacific Northwest National Laboratory is working on a new spray coating to repair dam turbines. *Photo from Andrea Starr, Pacific Northwest National Laboratory*

Another key theme is the focus on the ability to modify/repair components quickly and easily. *In situ repairs using robotics and advanced welding techniques* scored the highest for both stakeholder scores and scored third overall with the inclusion of the alignment score. While the high costs and timelines to develop repair technologies were factors, one of the primary reasons the WPTO alignment score brought the combined score down was because the office is already investing in this area through a multi-year project on cold spray repair of runners conducted at the Pacific Northwest National Laboratory (PNNL) (PNNL 2023). Similar to coatings, advanced welding techniques like cold spray are well developed in the industry. Thus, the PNNL project is targeting a key issue of being able to use these techniques on-site using manual or robotic applicators, which limit the significant costs and outage time associated with removing the turbine from the hub. However, in situ repair presents many challenges that are not present at typical industrial facilities, such as ensuring safe working conditions and enabling access to necessary equipment. For example, applying coatings or repairs in small, confined penstocks over long distances can be particularly hazardous without technologies like robotics. Cold spray is one of several repair techniques, including others such as spark plasma sintering and thermal spray, that could address this opportunity. In some respects, *functionally graded materials* also fit within this theme because carbon steel runners can be clad with stainless steel in high-cavitation areas for improved material properties. Regardless of the technology, the speed, safety, and performance of the application process are the primary challenges to address. This could be done by creating portable manual or robotic technologies, reducing complexity in the repair process, improving technology adaptability to various repair situations, and increasing visibility on repair performance. Given the maturity of repair technologies, investment in this area should likely focus on development and testing of application techniques and consider the cross-compatibility of the techniques across multiple technologies.

Another theme within this goal is to develop methods for maintaining or improving bearing life sustainably. *EALs* and *self-lubricating bearings* both tackle the challenge of replacing oil lubrication systems and scored second and fourth, respectively. Existing lubrication systems can be harmful to the environment in the event of leaks and pose several maintenance challenges, such as ensuring proper oil filtration. Oil leaks to the environment must be reported to the regulatory entities and may incur fines. While EALs and self-lubricated bearings can reduce environmental risk, they may not directly lead to a reduction in regulatory burden since leaks of any lubricant must still be reported even if environmentally benign. ORNL's AMM for hydropower report and WPTO's previous investments in EALs through small-business and other commercialization grants showed that these two technologies are relatively mature; however, they are not widely commercialized in the hydropower field (Musa et al. 2023). Notably, WPTO's interest in the topic started in the mid-2010s as the U.S. Bureau of Reclamation and the U.S. Army Corps of Engineers were tasked with investigating the use of EALs. The work of WPTO awardees has validated the comparable performance of EALs to traditional mineral oils but highlighted the challenges of relative cost and compatibility with existing systems. Self-lubricated bearings are also being tested at PNNL with newly assembled equipment. As such, investment in these technologies should prioritize demonstration and deployment for the purposes of regulatory and stakeholder adoption. Further research could also determine the costs and benefits of using EALs versus self-lubricated bearings for different cases, including the challenges of replacing or integrating into existing lubricant systems. For each of these opportunities, it will be important to leverage research from other sectors, like marine energy, wind, and thermal generation, to support growth in hydropower.

Finally, *additive manufacturing for large-scale molds* could be an important technology for reducing foreign reliance on supply of large metal components like runners. Notably, several participants in the stakeholder perception survey commented that additive manufacturing for large-scale molds is a high priority for them. The challenge of procuring large-scale metal components is common across industrial sectors, including the wind and nuclear industries. The low WPTO alignment score was driven by the overlapping interest with DOE's Advanced Materials and Manufacturing Technologies Office (AMMTO), whose mission is to support the manufacturing sector at large. In fact, AMMTO released in 2023 the Domestic Near Net Shape Manufacturing to Enable a Clean and Competitive Economy funding opportunity, which relates directly to this topic (AMMTO 2023). The activity for *new metal alloys for powertrain components* is also focused on adapting material advancements from other industries to the hydropower field. Conventional carbon and stainless steel alloys have seemingly performed reliably; therefore, a key challenge for new metal alloys will be validating long-term performance improvements and bringing down costs relative to the conventional alternatives. This opportunity scored a 5.9, lower than the score of 6.6 received by *composite materials for powertrain components* (included in Goal 2), which has generally been an attractive opportunity for small hydropower applications. Despite the low scores, these opportunities are still valuable options for investment and will continue to be monitored by WPTO and potentially incorporated into other opportunity areas depending on industry interest over time.

3.2.2. Goal 2: Expand the Design Space for Hydropower Innovations by Improving Component Efficiency, Flexibility, and Cost

Table 4. Prioritized Opportunities to Expand the Design Space for Hydropower Innovations

OPPORTUNITY	SCORES (1–10)			
	VALUE	LIKELIHOOD	ALIGNMENT	COMBINED
Embedded sensors	7.5	7.4	7.0	**7.4**
Composite materials for powertrain components	7.2	6.8	5.0	**6.6**
Low-cost materials and manufacturing methods for penstocks, conduits, and pipes	6.9	6.5	6.0	**6.6**
Unconventional geometries and designs enabled by AMM	6.7	6.2	5.0	**6.2**
In situ, 3D concrete printing	6.4	5.4	6.0	**5.9**
Direct metal additive and hybrid manufacturing of small hydropower powertrain components	6.4	6.1	4.0	**5.8**
Innovative materials for geotextiles, reservoir linings, and geotechnical techniques	6.6	6.4	3.0	**5.8**
New materials and designs for generators	6.8	6.0	1.0	**5.3**

Utilizing advanced techniques and materials expands the number of possible designs for new hydropower developments, which face a multitude of economic and operational challenges. *Embedded sensors* scored the highest from both stakeholders and WPTO within this goal. Digitalization is a major trend across the hydropower fleet, enabling the power of data to help make O&M and investment decisions. The Hydropower Fleet Intelligence project at ORNL, for example, is creating models to predict the remaining useful life of hydropower components (ORNL 2023). However, obtaining the necessary high-quality data is a key challenge. Embedded sensors, which typically leverage additive manufacturing to integrate sensors into components during the manufacturing process, provide additional data points to better monitor a structure's health and to prevent unnecessary downtime. It is important to note that embedded or advanced sensors apply to both new developments and existing facility retrofits. There are also many use cases for predictive maintenance models, such as changing operating modes for a new market or planning when to conduct repairs. However, the use cases differ among hydropower plants depending on the types of data available. Thus, the primary research questions focus on which types of sensors for which components and for what type of analytic applications will be the most useful for the widest group of stakeholders. Once these questions have been answered, the AMM solutions for embedding the sensors can be developed.

3D-printed hydropower components in front of Melton Hill Dam. *Photo from Carlos Jones, Oak Ridge National Laboratory*

Three of the opportunities—*composite materials, unconventional geometries,* and *direct metal additive/hybrid manufacturing*—involve developing cost-effective and high-performing powertrain components. While combined stakeholder scores all exceeded 6.0, indicating generally positive attitudes, they scored lower relative to the other opportunities within this goal. The underlying challenge for these opportunities is that AMM capabilities, like direct metal additive/hybrid manufacturing, need time and investment to scale, and therefore are currently most suitable for small hydropower applications. Because small hydropower projects are more expensive to build on a per-kilowatt basis, development across the United States has been relatively slow with limited opportunities to learn from deployments. Moreover, one noteworthy strategy for this space could be to leverage experiences with micro-hydropower (less than 100 kilowatts), like in canals, conduits, or off-grid applications, where the financial and environmental risks are lower and number of available sites is higher (Kao et al. 2014, 2022). As AMM capabilities mature at larger scales and lessons are learned from smaller deployments, hydropower applications could be scaled to larger sites. This would also leverage reduced licensing burdens, since the Federal Energy Regulatory Commission provides exemptions for small hydropower (less than 10 megawatts) and qualifying conduits (Federal Energy Regulatory Commission 2023). Of these three opportunities, composites scored the highest and direct metal additive the lowest. Studies could compare the lifetime costs and benefits of various materials for different micro-to-small hydropower applications.

Identified as a top-three priority within the goal, *low-cost materials and manufacturing methods for penstocks, conduits, and pipes* was scored above average by both stakeholders and WPTO. The discussion above related to micro-hydropower also applies to this opportunity. Commercially available and cheap materials, like high-density polyethylene, fiberglass, and fiber-reinforced polymer, can be readily used for micro-hydropower projects with smaller hydraulic and structural requirements. This opportunity also pairs well with industry's focus on non-powered dams, where one of the largest challenges is cost-effectively routing water over, through, or around a dam. The majority of non-powered dams are small and low-head (Sasthav and Oladosu 2022); therefore, one way to increase the head is to add long conveyances, which would require inexpensive materials without considerable friction losses or maintenance challenges (Oladosu et al. 2021). Another potential solution is through siphons, which use suction to convey water over a dam and into a powerhouse. Siphon designs have been successful in Europe but are rare in the United States and have not been a focus of WPTO investments to date. Studies or demonstrations that aim to understand the advantages and costs of siphon designs and long, low-cost penstocks for retrofitting non-powered dams could lead to the deployment of new facilities.

Two of the opportunities focused on innovative civil works—*in situ, 3D concrete printing* and *geotextiles, reservoir linings, and geotechnical techniques*—scored comparatively low at 5.9 and 5.8, respectively. These technologies could be applied to existing facilities through dam rehabilitations but are often discussed in the context of new developments. For example, *in situ, 3D concrete printing,* which aims to reduce transportation costs and construction times by manufacturing modular structures on-site, has been considered through the Standard Modular Hydropower project (Witt et al. 2017). However, several factors, including site-specific geotechnical challenges and the high unit costs of low-head hydropower, have limited stakeholders' perceptions on the feasibility of modular new stream-reach development. *Geotextiles, reservoir linings, and geotechnical techniques* are also an important field, particularly for PSH where water retention is a key issue. However, stakeholder engagement has indicated that, although the technologies are relatively mature, the applications of the technologies are limited given the slow growth of pumped storage systems. Reducing the costs and risks of civil works at new facilities is still a major challenge, since civil works can represent close to half of initial capital costs for new low-head developments, as well as a large portion of cost uncertainty (O'Connor et al. 2015). It will be important to continue monitoring costs and emerging civil works innovations that can garner stakeholder buy-in.

The *new materials and designs for generators* opportunity was scored the lowest by WPTO and relatively low by stakeholders, although several participants noted this as a priority in the questionnaire. This topic includes using additive manufacturing of magnetic materials for permanent magnet generators to be used in small hydropower plants, where they would likely be the most cost-effective. Generators are a shared technology across many energy sectors, including wind and natural gas. Generators and electromechanical equipment together represent approximately 37% of initial capital costs on average for low-head, non-powered dams (O'Connor et al. 2015). Given the high costs and timelines needed for technology advancement, research into this space will likely be incorporated as an add-on to other small hydropower demonstration efforts, rather than dedicated investment in this opportunity. WPTO will continue to monitor advancements of innovative generators from other sectors and stakeholders' perceptions on the applications within hydropower.

3.2.3. Goal 3: Enable the Adoption of Hydropower Technologies

Table 5. Prioritized Opportunities to Enable the Adoption of Hydropower Technologies

OPPORTUNITY	SCORES (1–10)			
	VALUE	LIKELIHOOD	ALIGNMENT	**COMBINED**
Valuation and performance-cost modeling (metrics)	6.9	6.9	9.0	**7.3**
Testing capabilities for AMM technologies	7.2	7.0	6.0	**6.9**
Quality assurance and testing standards	7.1	7.1	6.0	**6.9**
Rapid prototyping using additive manufacturing and polymers for scaled explorative testing	6.3	6.8	7.0	**6.6**
Advanced imaging techniques for material characterization and qualification	6.5	6.5	4.0	**6.0**
LCA for AMM and promotion of locally sourced or recycled materials	6.0	5.9	6.0	**6.0**

Goal 3 focuses on the activities that can support technology acceptance, commercialization, and deployment, in part, by quantifying or reducing risk to adopters. The hydropower industry is mature with experienced operators and technologies. As such, it is critically important to provide apt justification for the deployment of a new technology. While not the highest score by stakeholders, *valuation and performance-cost modeling (metrics)* was prioritized to be the highest after inclusion of the WPTO alignment score. The nature of the activity (studies to create metrics for performance benchmarking) fits well within the capabilities at DOE and the national laboratories. Cost-benefit trade-offs must be assessed at the early stage of the development process to enable adoptability by consumers. While metrics like the levelized cost of energy and cost per kilowatt are established benchmarks for powertrain technologies, they often fail to fully capture the inherent value of certain AMM applications. For example, composites or metal alloys that are more resistant to cavitation may not only last longer, reducing O&M costs, but also allow the unit to operate in a wider range of conditions, increasing grid value. Whole-life cost models could examine the balance of costs, benefits, and risks through model-driven simulation analyses or data-driven empirical estimates. Having higher visibility into these factors is especially important for smaller hydropower projects where profit margins are tighter and at higher risk of overruns. Another related challenge is communicating these factors in an effective way to the proper stakeholders, which may include financiers, owners, manufacturers, regulators, etc. The resulting scores for the top three opportunities in this goal reflect a logical process from a business development perspective where technology developers need to understand the value proposition and risk profile up front before investing in deployment.

The two testing-related topics—*testing capabilities for AMM technologies* and *quality assurance and testing standards*—scored very similarly and were well received by WPTO and stakeholders. The former opportunity focused on developing the physical infrastructure to enable testing, and the latter centered on developing standard testing procedures. WPTO has been interested in this topic for several years. Following congressional direction, ORNL completed a scoping study on hydropower testing needs (Musa et al. 2022), which identified two complementary initiatives: the coordination of a network of existing testing facilities to be connected with technology developers, and the development of a full-scale test facility for small hydropower technologies. The need for testing is driven by the limited number of hydropower facilities in the United States, the long development timelines, and the importance of those units to the grid, which reduce the industry's ability to gain experience through numerous deployments. The report showed that, while partial-scale, flow-through hydraulic test rigs and larger open-channel labs (e.g., flumes, tow tanks, and wave basins) are available, there are limited to no full-scale, flow-through labs meant to simulate real site conditions. A federally owned facility could meet this need but would require significant time and investment. Establishing coordinated testing efforts will contribute to the improvement and/or development of standards and quality assurance for novel hydropower components manufactured through AMM. Standards, the expert-certified guidelines for products and production methods, are necessary to de-risk the adoption of innovative technologies. These standards vary in maturity for different topics; therefore, the highest priority needs for specific standards should be identified. Fish passage testing and extended duration durability testing for new blade shapes and materials are likely two of the highest priority areas (Musa et al. 2022). DOE may also use its convening power to bring together multiple stakeholders to help develop these standards. WPTO's experience with standards in the Marine Energy Program on ocean energy devices can provide a valuable baseline for future work.

Main Channel facility at the Saint Anthony Fall Laboratory of the University of Minnesota. *Photo from Mirko Musa, Oak Ridge National Laboratory*

The other three opportunities—*rapid prototyping, advanced imaging,* and *LCA*—are niche commercialization solutions. While the average stakeholder scores were at or above 6.0, indicating an overall positive attitude to these opportunities, they ranked medium to low compared to the rest of the activities in this goal. The WPTO scores reflected positively due to the limited cost and scope that would likely be attributed to WPTO's related activities focused on dissemination and deployment of hydropower-specific applications. These opportunities may be better suited for established AMM-focused entities such as AMMTO or the AMM community at large. It is important to note that prototyping and material qualification of AMM components for hydropower should be considered best practices when developing novel AMM technologies.

3.3. Discussion and Synthesis

The analysis helped identify several high-priority opportunities that WPTO can support. The top 10 opportunities across the three goals, with combined scores of 6.6 and above, fit well into WPTO's mission and capabilities. Some opportunities are new to WPTO while others build on existing efforts, so it is important to understand how future WPTO efforts will continue to advance opportunities. As prefaced in Section 3.2, several of these opportunities share common needs and challenges. For example, both *EALs* and *self-lubricating bearings* aim to replace existing lubrication systems that can be harmful to the environment and, while there are commercially available solutions, they face barriers to first adoption. The following sub-goals were created to leverage these commonalities and provide more specific direction about the types of activities needed to advance the relevant opportunities. The sub-goals are listed with a brief rationale and the related high-priority opportunities with the combined scores in parentheses.

Sub-goal 1.1: Facilitate the adoption of in situ application methods for coatings and repairs that minimize outage time and safety risks through demonstrations and process guidance.

- **Rationale:** Removing powertrain components from service requires considerable cost and downtime. In situ repair and coating application is an attractive solution for many use cases, but adopters must ensure staff safety without significant trade-offs in cost or performance. Applying in situ practices at existing plants with clear guidance on the added value and safety precautions will enable expansion to other facilities.
- **Related opportunities:** Innovative coatings and application techniques (7.6); in situ repairs using robotics and advanced welding techniques (6.9).

Sub-goal 1.2: Validate the performance and durability of coatings and repair methods for hydropower applications through testing and standards.

- **Rationale:** The value of coatings and repair methods depends largely on the duration with which the technology can meet its performance goal. While site conditions are unique, extended duration testing can help provide estimates for return on investment. Use of existing standards or development of new standards will support replicability to other site conditions.
- **Related opportunities:** Innovative coatings and application techniques (7.6); in situ repairs using robotics and advanced welding techniques (6.9).

Sub-goal 1.3: Support decision-making and deployment of sustainable bearing solutions through active stakeholder engagement.

- **Rationale:** Both EALs and self-lubricating bearings are being validated for performance under existing efforts. Significant challenges remain in understanding how to integrate these technologies into existing systems. These challenges must be remediated through active engagement with plant owners and operators, which may result in additional research needs.
- **Related opportunities:** EALs (7.0); self-lubricating bearings (6.8).

Sub-goal 2.1: Prioritize and deploy adaptable sensors for new and existing hydropower components with clear value for decision-making.

- **Rationale:** Numerous software tools, like digital twins, rely on accurate and real-time data to inform operational decisions. These data can be difficult to attain due to a lack of sensors, data quality issues, and confidentiality concerns. WPTO should identify the high-priority data needs for these applications and investigate technologies to acquire those data. These sensors may be embedded through advanced manufacturing or integrated via novel methods.
- **Related opportunities:** Embedded sensors (7.4).

Sub-goal 2.2: Reduce the capital costs for micro-hydropower through pilot projects of additively manufactured or prefabricated powertrains.

- **Rationale:** Additive manufacturing and non-steel, prefabricated materials, like high-density polyethylene pipes, are mature and can be cost-effective alternatives, particularly at smaller scales. Composite materials are also lightweight and durable but have not been implemented at the megawatt scale. Deployments of these technologies at the micro-hydropower scale (less than 100 kilowatts) may lead to cost-effective new projects and lessons about how to scale these technologies to larger sizes.
- **Related opportunities:** Composite materials for powertrain components (6.6); low-cost materials and manufacturing methods for penstocks, conduits, and pipes (6.6).

Sub-goal 3.1: Develop methods for quantifying and effectively communicating the value of innovative technologies compared to conventional alternatives.

- **Rationale:** Investments in AMM are inherently risky for hydropower plants that are expected to operate reliably for decades. Over long-lived projects, the technologies have many cost and benefit trade-offs that need to be considered when deciding to invest. Whole-life cost modeling tools are needed to not only accurately model the net benefit but also to effectively communicate those benefits to adopters, which is often done by comparing alternatives.
- **Related opportunities:** Valuation and performance-cost modeling (metrics) (7.3).

Sub-goal 3.2: Ensure adequate access to testing capabilities through improved access to existing facilities and the development of new capabilities.

- **Rationale:** Testing at realistic plant conditions is a key step for the commercialization of most AMM technologies and has been an ongoing area of interest for WPTO and the hydropower industry. The prudent approach is to first ensure that stakeholders have adequate access to existing capabilities, then build out new capabilities for any remaining gaps.
- **Related opportunities:** Testing capabilities for AMM technologies (6.9).

Sub-goal 3.3: Convene multistakeholder groups to expedite the development of targeted standards and testing methods for hydropower applications.

- **Rationale:** Standards can be an effective tool for decreasing the risk of technology adoption but require gaining consensus from interested stakeholders. WPTO can leverage its convening power and existing organizational relationships to expedite standards development for specific applications, like EALs.
- **Related opportunities:** Quality assurance and testing standards (6.9).

4 CONCLUSION

4. Conclusion

From increased efficiencies and cost savings to enhanced performance and streamlined development processes, AMM innovations have the potential to advance low-impact growth across the hydropower industry and ensure that hydropower maximizes its role in America's clean energy future. WPTO supports this clean energy transition through strategic investments in AMM methods and technologies that apply to a variety of hydropower facilities, systems, and components.

This strategic plan sits within several department- and office-level contexts and aims to better understand how the opportunities within the AMM space could be applied to support program objectives. Prior scoping work by ORNL identified a suite of potential investment opportunities; therefore, a primary outcome of this document is prioritization of those opportunities, described by the tables in Section 3. WPTO carefully considered both stakeholder input and its funding capabilities and mission to inform the prioritization in a quantitative manner.

This process resulted in three goals and eight sub-goals, which relate to the top 10 opportunities identified in the prioritization analysis. These sub-goals emphasize the need for stakeholder collaboration on testing and standards to boost technologies over the hurdle for first adoption. Notably, the sub-goals also focus on late-stage commercialization of existing technologies, including those from other sectors, rather than explicit development of new technologies. Hydropower is an important long-term grid resource, so the reliability of AMM technologies must be validated over extended durations and communicated effectively to the relevant stakeholders (e.g., first adopters and regulators). However, there is still room to invest in novel technologies like additive manufacturing and composites. Strategically, these technologies may best be applied to micro-hydropower applications where investment risk is lower and development timelines are faster. Multiple successes at the microscale can support expansion to larger hydropower applications, like at non-powered dams.

Combined with other efforts, WPTO's investments across these high-priority AMM opportunities will advance more reliable operations, expand the design space for hydropower, and enable the adoption of new hydropower technologies using innovative AMM techniques. This document is one step in the process of developing a program plan that will guide investment in each specific field. Now that the list of opportunities has been prioritized into a condensed set of sub-goals, WPTO can begin to identify possible funding mechanisms to achieve these goals. This process will be conducted through internal road-mapping based on available budgets, capabilities, and collaborative efforts. WPTO will continue to engage with hydropower stakeholders to ensure that investments are directly addressing their needs.

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Appendix: Opportunity Descriptions

The following tables provide a brief description of each opportunity, its value proposition to the hydropower industry, and the types of activities that WPTO could pursue to advance the opportunity. For more in-depth details, please refer to the ORNL report, *Advanced Manufacturing and Materials for Hydropower: Challenges and Opportunities* (Musa et al. 2023).

Table A-1. Summary, Value Proposition, and Activity Descriptions for Each Opportunity Related Closely to Goal 1

OPPORTUNITY NAME	DESCRIPTION AND VALUE PROPOSITION	ACTIVITY DESCRIPTION
Goal 1:	**Improve the operational reliability of existing hydropower by minimizing maintenance duration, frequency, and cost.**	
New metal alloys for powertrain components	New metal alloys (e.g., high-entropy alloy) may have improved structural properties (e.g., better strength-to-weight ratios with a higher degree of fracture resistance and tensile strength) and erosion/corrosion resistance. The use of additive manufacturing technologies could enable or facilitate implementation of new alloys, eventually replacing current casting and forging processes, thus reducing reliance on foreign imports. Custom alloys and multi-material parts for specific needs could be created.	Identify, develop, and test metal alloys from other industries or applications that could be used for hydropower powertrains (turbines, generators, and electrical interconnections).
Additive manufacturing for the development of molds for large components	Additively manufacturing molds for high-volume metal parts could significantly reduce the costs and time associated with large castings and help reshore the production of large components in the United States. This will also reduce the lead time for some essential powertrain components (e.g., turbine runners and generators), reducing downtime and revenue losses during refurbishment and upgrades. Examples include binder jetting for sand cast and lost foam molds of large metal runners. These opportunities eliminate the need for traditionally made plug molds, which add significantly to the lead time and cost of the casting process.	Demonstrate new casting methods using additive manufacturing for large (high-volume) components.
Additive manufacturing for machine tooling	Additively manufactured tooling (e.g., die-casting molds, injection molds, and compression molds) using different material might facilitate the production of small-scale components and the reintroduction of legacy parts (i.e., components that are no longer in production or whose original drawings are missing). Use of additively manufactured metal tooling is fairly mature in other industries but has not been widely adopted in the hydropower industry.	Identify and prioritize applications for additively manufactured tooling that enables faster production times (potentially in situ) and lowers costs.

OPPORTUNITY NAME	DESCRIPTION AND VALUE PROPOSITION	ACTIVITY DESCRIPTION
In situ repairs using robotics and advanced welding techniques	Advanced techniques and robotics such as cold spray for cavitation repair, advanced welding, and unmanned vehicles and/or underwater drones, could address repairs in situ, avoiding (or significantly reducing) component disassembly and shipment to repair shops, and reach areas that are difficult/impossible to access (e.g., penstocks and submerged gates). This can significantly reduce costs, downtime, and losses, while also improving human safety.	Demonstrate and deploy techniques for in situ repairs that reduce downtime and improve maintenance quality.
Innovative coatings and application techniques	Coatings can reduce or eliminate erosion, cavitation, corrosion, and biofouling. This may improve generation performance, increase component life span, and reduce maintenance. If cost-effective solutions are proposed, innovative coatings can overall increase revenue.	Develop and test coatings that are resistant to erosion, cavitation, corrosion, and biofouling, as well as the methods for cost-effectively applying them. This activity should further develop technologies explored in prior work, as well as explore new opportunities.
Skin-friction reduction and improved surface finishes using modern unconventional machining	Improved surface finishing may reduce hydrodynamic skin-friction drag and reduce hydraulic losses for pipes and blades, thus increasing generation performance.	Study the impact of new subtractive machining techniques that improve surface finish and surface texturing.
Functionally graded materials for runners	Functionally graded materials use multiple materials on a single build to improve runner performance, reliability, and longevity. Examples include cavitation- and erosion-resistant surfaces (e.g., carbide ceramic) built into a strong and ductile core (e.g., stainless steel).	Develop and test functionally graded designs.
EALs	Lubricants are essential to support rotating components and decreasing friction to improve performance, reduce maintenance, and increase components' life span. 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. Adoption of EALs will improve environmental acceptability and facilitate the permission process.	Research to expand the commercialization of EALs.

OPPORTUNITY NAME	DESCRIPTION AND VALUE PROPOSITION	ACTIVITY DESCRIPTION
Self-lubricating bearings	Bearings support rotating components and decrease friction to improve performance, reduce maintenance, and increase components' life span. Self-lubricating bearings 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), avoid the use of petroleum-based mineral oil. Composites and self-lubricating polymers have recently become more widely used for hydropower applications; however, further development will lead to additional benefits.	Explore new bearing materials to further improve the bearing properties. Demonstrate and test self-lubricating bearings.

Table A-2. Summary, Value Proposition, and Activity Descriptions for Each Opportunity Closely Related to Goal 2

OPPORTUNITY NAME	DESCRIPTION AND VALUE PROPOSITION	ACTIVITY DESCRIPTION
Goal 2:	**Expand the design space for hydropower innovations by improving component efficiency, flexibility, and cost.**	
Direct metal additive and hybrid manufacturing of small hydropower powertrain components	Small hydropower powertrain components might be good candidates for direct metal additive and hybrid manufacturing. Additive and hybrid manufacturing has several advantages over traditional methods, including earlier procurement of feed material stocks instead of depending on the lengthy procurement of raw material stock. It also might complement or eventually replace current casting and forging processes, thus potentially reducing reliance on imports from overseas while supporting reshoring U.S. capabilities. It also supports more complex designs, often allowing for lighter, more efficient parts with additional functionality, and more easily achieved special alloys and multi-material parts with potentially reduced waste. Applications for smaller parts are fairly mature already, but the upper limit on size is rapidly increasing with ongoing research in additive manufacturing. Therefore, hybrid manufacturing could likely target large powertrain components as well in the near future.	Study the techno-economic feasibility of direct additive and hybrid manufacturing for small hydropower powertrain components. This activity should also contribute to the ongoing effort to increase the size of possible parts. Part of this effort will focus on new technologies to increase the deposition rate of additive processes, as well as improving the overall efficiency of hybrid processes.

OPPORTUNITY NAME	DESCRIPTION AND VALUE PROPOSITION	ACTIVITY DESCRIPTION
Unconventional geometries and designs enabled by AMM	Additive manufacturing may enable the adoption of complex geometries, shapes, and new designs that are currently not feasible with existing manufacturing technologies. Complex shapes might improve component efficiency and environmental mitigation. Examples include fish-friendly turbines, fish attraction and/or exclusion, fish passage, sediment bypass, aeration systems, etc.	Build and test designs with unconventional geometries that are difficult to construct with existing manufacturing.
Embedded sensors	Additive and hybrid manufacturing can simplify the creation of channels for embedded sensors that are currently complicated to produce using conventional casting and forging. Embedding sensors directly during manufacturing decreases the installation costs and enables the health monitoring of components throughout their life span. Component health monitoring is crucial for the implementation of digital twins and decision-making for maintenance and operations.	Study the applications of embedded sensors, their potential value for decision-making, and methods for manufacturing related components.
Composite materials for powertrain components	Composite materials are currently not commonly utilized in the hydropower industry. However, they offer improved strength/stiffness-weight ratios, allowing for lighter-weight components, lower maintenance, and longer duration. Fiber-reinforced polymer composites might represent a potential area of research for hydropower applications. Runner blades for small powertrain could be a direct application; other potential applications include bearings, pipelines or conduits, and wicket gates. Of particular interest are the erosion and fatigue properties of selected composite materials. Use of composite materials should also be the subject of techno-economic analysis to compare with existing and other emerging technologies.	Demonstrate and test composite materials for powertrain components and study the techno-economic feasibility as compared to existing and other emerging technologies.

OPPORTUNITY NAME	DESCRIPTION AND VALUE PROPOSITION	ACTIVITY DESCRIPTION
Low-cost materials and manufacturing methods for penstocks, conduits, and pipes	Low-cost, non-steel materials could be adopted for water conveyances and penstocks to reduce costs, facilitate installation, and improve flexibility for maintenance and retrofits. For example, reinforced, plastic-based material might be easier to install and join, potentially reducing overall civil construction costs. High-density polyethylene, fiberglass, fiber-reinforced polymer, and centrifugally cast, fiber-reinforced polymer mortar applications could be used for penstocks, draft tubes, and other pipeworks for future developments or replacements. Siphons with embedded generation technology installed over non-powered dams could represent a cost-effective, flexible, and easy-to-install solution that might avoid time-consuming and expensive modifications to the dam structure.	Study and demonstrate the application of low-cost materials and manufacturing methods for micro and small hydropower designs, which can include canal, conduit, and non-powered dam retrofits.
New materials and designs for generators	Innovations in generator technology are highly desired to adapt to future trends in hydropower: smaller generation units, integration with variable renewable sources, and more PSH capacity. AMM can enable new generator designs, improve mixture of materials, reduce reliance on foreign sources of critical materials, and reduce costs. Magnets could be additively manufactured using several different processes, including powder bed fusion, binder jetting, and fused deposition modeling.	Investigate the feasibility of various AMM technologies to enable low-cost or variable-speed generators.
In situ, 3D concrete printing and precast concrete structures	In situ, 3D concrete printing and/or precast concrete sections may facilitate the construction of powerhouse and other auxiliary structures and potentially support repair and rehabilitation of existing structures. Underwater construction techniques would massively reduce construction time and costs and reduce environmental impacts by reducing the use of cofferdams and other water diversion techniques.	Demonstrate in situ, 3D concrete printing and/or precast concrete sections for hydropower applications.
Innovative materials for geotextiles, reservoir linings and geotechnical treatment, and alternative storage methods	Innovative materials could be employed to improve geotechnical performance and promote proper water quality, while reducing overall costs. Examples include geotextiles, reservoir linings, and innovative soil treatments to reduce seepage. Membranes and other elastomers could be used as alternative storage (e.g., closed-loop PSH).	Demonstrate innovative materials for geotextiles, reservoir linings, and soil treatments. Investigate the use of membranes for closed-loop PSH.

Table A-3. Summary, Value Proposition, and Activity Descriptions for Each Opportunity Closely Related to Goal 3

OPPORTUNITY NAME	DESCRIPTION AND VALUE PROPOSITION	ACTIVITY DESCRIPTION
Goal 3: Enable adoption of hydropower technologies.		
Quality assurance and testing standards	Standards, such as those developed by the International Organization for Standardization and ASTM International, are a key to lowering risks and enabling adoption. Advanced manufactured parts often lack certifications under these standards since they are newer, and quality assurance can be difficult for unique designs. The creation of standards will require community coordination to define and quantify performance requirements, as well as to advocate for the adoption of these standards.	Develop standards for nondestructive testing of hydropower components produced using additive manufacturing, as well as methods for born-certified manufacturing. Mapping of critical components and important properties of components will help to expedite this effort.
Valuation and performance-cost modeling (metrics)	Specific metrics must be identified and/or developed to quantify the costs, benefits, and risk of adopting hydropower technologies created via AMM. Conventional metrics used in hydropower research include levelized cost of energy, construction and maintenance time, development risks, scalability and applicability, market size, sustainability, and technology readiness level. These metrics are not necessarily applicable or sufficient to evaluate AMM technologies. Collaborative efforts between the hydropower industry, AMM R&D, and academia could compose the right suite of metrics.	Establish metrics that quantify the costs and benefits for additively manufactured hydropower components to better communicate the value proposition of adopting select technologies.
Testing capabilities for AMM technologies	Testing technologies created via AMM is essential to validate performance, reliability, and durability of the component, address criticalities and optimize designs, and develop necessary standards. Demonstration projects are critical to accelerate adoption and commercialization.	Invest in equipment and infrastructure to test AMM technologies at full and partial scales, such as a dedicated, full-scale hydropower test facility.
Rapid prototyping using additive manufacturing and polymers for scaled explorative testing and education	Many innovations at lower technology readiness levels are tested at partial scale. AMM could play a key role during partial-scale testing and design optimization. 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. This could also represent a great opportunity to train a new workforce and recruit skilled professionals, along with continued education of the existing workforce.	Develop and promote applications of commercially available, 3D-printed polymer models for educational or communication purposes, as well as for early-stage design optimization and testing.

OPPORTUNITY NAME	DESCRIPTION AND VALUE PROPOSITION	ACTIVITY DESCRIPTION
Advanced imaging techniques for material characterization and qualification	Advanced imaging techniques during manufacturing (e.g., X-ray tomography and high-performance image processing) can help quantify the quality of the manufacturing process and the material characteristics to support component certification against specific standards and quality assurance. This includes related imaging technologies for nondestructive testing, evaluation, and inspection.	Invest in capabilities for advanced imaging techniques that enable improved material characterization and qualification.
LCA for AMM and promotion of locally sourced or recycled materials	LCA of components created via AMM could promote increased sustainability of hydropower technologies, addressing quality assurance and cost-benefits metrics. This could include the promotion of locally sourced or recycled materials during plant construction or component manufacturing.	Develop programs or methods for reducing the life cycle impacts of hydropower components, such as through material recycling using advanced manufacturing.

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