Clean Energy Manufacturing Analysis Center

Analysis of Supply Chains and Advanced Manufacturing of Small Hydropower Systems

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Technical Report
NREL/TP-6A20-71511
July 2018

Contract No. DE-AC36-08GO28308

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Prepared under task number WAPP.10344.02.01.01

CEMAC is operated by the Joint Institute for Strategic Energy Analysis for the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy.

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NOTICE

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Acknowledgments

For its support of this project, we thank the U.S. Department of Energy's (DOE's) Water Power Technologies Office (WPTO), especially the technical WPTO lead, Marisol Bonnet. The authors are also thankful for the support from and in-depth discussions with the market team at Oak Ridge National Laboratory (ORNL) (e.g., Rocio Uría-Martinez and Megan Johnson) and with hydropower manufacturers that have provided valuable input for this work.

List of Acronyms

2x5 MW	representative system made up of two 5-MW Kaplan-style turbines
ABS	acrylonitrile butadiene styrene
AM	additive manufacturing
BAU	business-as-usual
CAD	computer-aided design
CAPEX	capital expenditure
CEMAC	Clean Energy Manufacturing Analysis Center
CF	carbon fiber
CNC	computer numerical control
DFMA	design for manufacturing and assembly
DOE	U.S. Department of Energy
E-glass	glass fiber with epoxy matrix
ft	feet
GW	gigawatt
hr	hour
HTS	Harmonized Tariff Schedule
IDEA	Integrated Design and Economic Assessment
IGV	inlet guide vane
kg	kilogram
lb	pound
LCOE	levelized cost of electricity
mm	millimeter
MW	megawatt
NPD	non-powered dam
NREL	National Renewable Energy Laboratory
NSD	new stream-reach development
O&M	operations and maintenance
ORNL	Oak Ridge National Laboratory
PV	photovoltaics
R&D	research and development
SHP	small hydropower
SLM	selective laser melting
SWOT	strengths, weaknesses, opportunities, and threats
UNIDO	United Nations International Development Organization
USITC	U.S. International Trade Commission
WPTO	Water Power Technologies Office

Executive Summary

Clean energy manufacturing is a sector of increasing importance both in the United States and worldwide. In the United States, it has been presented as an engine for job creation in a sector of the U.S. economy that was hit hard by the 2008–2009 recession. The Clean Energy Manufacturing Analysis Center (CEMAC), sponsored by the U.S. Department of Energy (DOE), conducts credible, objective, industry-relevant, recurring, and consistent analyses of clean energy technologies. In this project, the National Renewable Energy Laboratory (NREL) and Oak Ridge National Laboratory (ORNL) collaborated in a hydropower manufacturing and supply chain analysis primarily for the U.S. small hydropower (SHP) market to provide insights on supply chain constraints, manufacturing cost, location factors, and opportunities for hydropower using advanced manufacturing technologies. The goal of the project is to improve understanding of the manufacturing opportunities in the U.S. hydropower supply chain, specific competitive advantages, and factors for manufacturing location decisions for SHP. These insights could be used to inform investment and research strategies, policy, and other decisions that could promote economic growth and strengthen U.S. manufacturing capabilities.

The project scope included a design for manufacturing and assembly (DFMA) costs analysis and a levelized cost of electricity (LCOE) sensitivity analysis of modular, representative SHP turbines. A representative SHP system was chosen to be made up of two 5-megawatt (MW) turbines because these Kaplan-style turbines could be useable for many non-powered dams (NPDs) across the United States. The sensitivity analysis used the Integrated Design and Assessment (IDEA) tool, which has helped highlight the impact of the turbine equipment cost on the potential capital expenditure (CAPEX) and LCOE of the installed, representative system. In addition, the project team analyzed international tradeflows (e.g., export and import of hydropower turbines and the parts used in hydropower systems). As part of this project, hydropower stakeholder interviews were undertaken to help identify insights related to hydropower manufacturing opportunities for U.S. players in SHP, the manufacturing advantages in the United States and potential threats from other countries, and key factors behind manufacturing location decisions made by the SHP industry.

Key findings from this report include the following:

Section 2—U.S. Hydropower Market

- Nearly 82 gigawatts (GW) of hydropower and pumped storage capacity has been added from 1950 to 2000. Since then, hydropower growth has plateaued domestically (DOE 2016).
- Only 3% of U.S. dams presently generate electricity. The remaining NPDs represent a substantial market opportunity, and there is the potential by 2050 to add 4.8 GW of new electricity generation capacity by repowering NPDs, utilizing advanced technologies and low-cost financing (DOE 2016).
- Hydropower manufacturing for each of the six main hydropower components (gates, valves, generators, penstocks, transformers, and turbines) exist in the United States. The U.S. hydropower supply chain is distributed across the country with denser concentrations near manufacturing centers such as the West Coast, Midwest, Great Lakes, and Northeast.

Section 3—U.S. Hydropower Tradeflows

- In the foreign markets, there is excellent potential for the export and supply of SHP (e.g., <10 MW) equipment and components.
- When comparing the 2.0–4.8 GW of domestic U.S. SHP potential for NPDs to international countries, several countries have potential gigawatts of capacity remaining for SHP due to large untapped SHP resources. When the top five countries with the most potential are considered (Chile, China, Columbia, India, and Japan), there could be nearly 71,795 MW of SHP capacity <10 MW where SHP could be installed.

Section 4—Representative SHP Manufacturing and Costs

- ORNL and NREL have worked together on selecting and defining a representative system for NPDs made up of two 5-MW Kaplan-style turbines (referred to in this report as 2x5 MW turbines). For this representative system, a detailed manufacturing cost analysis was created. It was found that the SHP industry values such a reference, as few representative systems are easily available.
- The manufacturing cost of one representative system (i.e., 2x5 MW turbines) is approximately $510,000, with a total assembled cost of approximately $550,000.
- The tooling cost for 10 modular turbines is approximately $1.75 million.

Section 5—Insights into the State of U.S. SHP Manufacturing and the Impact of Turbine Equipment of LCOE

- A key strength in the U.S. hydropower manufacturing sector is the significant experience and availability of a skilled workforce, which can be leveraged by the SHP manufacturers to meet the domestic and foreign potential.

- The primary factors affecting manufacturing decisions for SHP systems include clustered areas of the country with regional strength in SHP, skilled labor availability, product quality, proximity of suppliers to excellent resource, existing supply chains, and existing or growing markets—all of which exist in abundance in the United States.
- The United States has capabilities for manufacturing and exporting hydropower components, and a deep and diverse range of potential suppliers are available to the hydropower industry and spread across the country.
- LCOE is sensitive to the overall electro-mechanical equipment cost, but civil works are the biggest driver for SHP LCOE. Electro-mechanical equipment contributes 8%–30% of the total LCOE for NPDs, while civil works constitute between 18% and 58% of the project LCOE. The remainder is from the balance of plant (~25%) and the operations and maintenance (~20%).
- Cost reductions in the turbine and other powertrain equipment (e.g., through volumes of scale) are important, but to make low-head SHP cost-competitive through manufacturing alone will be difficult. This is due to the civil works contribution needed to repower NPDs, even though infrastructure is present. However, manufacturing advances that allow for fundamentally new designs with reduced civil works could help transform the SHP industry.
- To decrease the overall cost of SHP, modular designs and decreased civil works will be vital to allow SHP to compete with other renewable sources.

Section 6—Composites and Additive Manufacturing in Hydropower Applications

- There is significant potential with new materials and advanced manufacturing technologies, such as composites and additive manufacturing (AM), but for the adoption of new technologies by the hydropower manufacturers, newly designed, validated, and tested systems will be essential, as well as competitive costs to today's components and systems.
- Composites and AM components could provide turbine, powertrain, and decreased civil works costs. Through the design of new, corrosion-resistant, lightweight components and integrated structures, system-level impacts could result on the installation of SHP systems.
- Comparing a 3D-printed turbine hub with a steel cast hub showed that steel cast hubs are less costly at low volumes (e.g., 10 produced hubs) because of the AM toolset investment. For 3D-printed hubs to be cost competitive to current sand cast mold hubs, approximately 188 turbines per year are needed to amortize the AM toolset.
- There is potential to use AM for SHP components. AM has significant potential for printing complex parts, molding to then produce carbon fiber (CF) components, rapid prototyping of scale-models for testing, and decreasing the innovation and cycle time to get products to market.

Section 7—Opportunities

- Foreign export markets, such as Chile, China, Columbia, India, and Japan, have an estimated 71,795 MW of technical potential that could be serviced with SHP installations. Utilization of existing manufacturing capacity and expertise, along with economies of scale benefits, could result in increased global competitiveness through lower investment requirements and component costs, which could lead to increased U.S. export strength for SHP systems.
- Technology advances such as modular turbine designs, standardized units for conduit systems, precast systems, and improved powertrain technologies could help reduce costs, particularly for manufacturing a small number of units. DOE is also exploring modular hydropower designs, which would integrate standard independently produced components, validated to meet multiple specifications. Using modules in product design simplifies manufacturing activities, such as inspection, testing, assembly, and purchasing, and may increase economies of scale to lower total system cost.
- There are significant opportunities for the use of composites and AM for hydropower components when design changes are made to hydropower systems. By taking advantage of the corrosion resistance, light-weighting, and structural benefits, composites and AM could help significantly alter hydropower cost structures and installations.

Table of Contents

List of Figures

List of Tables

1 Introduction

The Clean Energy Manufacturing Analysis Center (CEMAC), sponsored by the U.S. Department of Energy (DOE), conducts credible, objective, industry-relevant, recurring, and consistent analyses of clean energy technologies. In this project, the National Renewable Energy Laboratory (NREL) and the Oak Ridge National Laboratory (ORNL) collaborated on a hydropower manufacturing and supply chain analysis of U.S. small hydropower (SHP) to provide insights on supply chain constraints, manufacturing cost, location factors, and opportunities for hydropower using advanced manufacturing technologies. These insights could be used to inform investments, research, policy, and other decisions that could promote economic growth and strengthen manufacturing capabilities.

The goal of the project is to improve understanding of the manufacturing opportunities in the hydropower supply chain, U.S.-specific competitive advantages, and factors for manufacturing location decisions for SHP. This work has addressed some of the challenges in determining the current, baseline manufacturing processes and costs of key mechanical components in a representative modular SHP system. It is understood that for the majority of SHP projects, each site uses mostly custom turbines and systems. For hydropower, as in geothermal plants, custom turbines and systems are heavily used due to the variations in flow rates and head between different sites. The use of custom turbines in SHP also stems, as in geothermal, from the desire to maximize electricity generation from costly assets and installations because, generally, custom SHP turbines and systems benefit from increased electricity production compared to more modular turbines and systems (Akar et al. 2017).

Non-powered dams (NPDs) were chosen as the focus for this project because of the significant resource availability and market growth opportunity in repowering NPDs. For example, in the United States today, up to 97% of NPDs are dams used for purposes such as irrigation and water management and do not produce power (DOE 2016). It is expected by the DOE Water Power Technologies Office (WPTO) in the *HydroVision* study (DOE 2016) that by 2030, with the utilization of advanced technologies, 3.6 gigawatts (GW) of new electricity generation capacity could be installed in repowering NPDs. In the *HydroVision* scenarios (DOE 2016), NPDs were found to have the greatest potential for development and growth, compared to upgrades to existing facilities or new stream-reach developments (NSDs). It is worth highlighting that an advanced technology for SHP innovation and development refers to, for example, the use of alternative materials or manufacturing processes, pre-cast concrete structures, and modular SHP turbines and systems. Other key areas for research and development (R&D), analysis, and commercialization efforts to help decrease costs for SHP include the use of low-cost financing, and changes in environmental legislation (DOE 2016).

Work from this project can help drive R&D decisions, such as what advanced technology choices and investments can be made and the impacts on the long-term goals of decreasing SHP installed costs and increasing performance, to increase project viability. From the baseline manufacturing costs and processes in this project, composites and additive manufacturing (AM) can be understood in terms of the cost targets needed to be adopted by the SHP industry and suitable component selection.

ORNL and NREL have worked collaboratively to select and define a representative system for NPDs made up of two 5-megawatt (MW) turbines (referred in this report as 2x5 MW turbines) and perform manufacturing analysis on this representative system. Prior to this project, it was found in discussions with hydropower manufacturers and project developers that there were no easily accessible or available estimates of representative SHP systems to benchmark against; thus, there is value in performing this manufacturing analysis.

The Kaplan representation was chosen for two main reasons: firstly, these Kaplan-style turbines could be useable for many NPD sites across the United States; and secondly, to provide insight into the manufacturing challenge that most repowered dams use custom turbines for each site versus much more modular components and turbines. This work has created a 2x5 MW representative system to help determine baseline manufacturing estimates for modular 5-MW turbines that could then be utilized at multiple sites. For custom turbines, the tooling investment can only be split over a few units, while increased production volumes for modular turbines allow the tooling investment to be amortized over many more units, and benefits from economies of scale.

This report primarily looks at the components and supply chain of SHP and does not look in detail into the larger hydropower components or supply chain, so it focuses on a potential growth area in the U.S. hydropower industry. Also, components of a representative SHP system for NPDs were modeled to determine the manufacturing costs, and as such, other SHP systems such as NSDs have not been considered. A key assumption of this work is that modular turbines can be used at multiple similar NPD sites in the United States, and focus was given to the cost impacts of increasing the modularity of the system. The question of whether lower-cost, and potentially lower-performance, modular turbines (due to the turbines running at off-design points) can offer competitive long-term benefits [e.g., cost and levelized cost of electricity (LCOE)], when compared to using more expensive, one-off custom turbines (i.e., increased generation due to the custom design) (Akar et al. 2017), is saved for future SHP work and analysis.

Section 2 of this report gives an overview of the U.S. hydropower market, potential for SHP both in the United States and globally, and a snapshot of the U.S. hydropower manufacturing sector. Section 3 covers the U.S.-centric tradeflow (i.e., exports and imports) of the SHP turbines classed at 1–10 MW, and Section 4 highlights the manufacturing cost of the representative SHP system, which consisted of 2x5 MW Kaplan-style turbines. Section 5 covers the state of the U.S. SHP manufacturing industry, including insights from the stakeholder interviews and the ORNL cost model to understand the techno-economic and LCOE impacts from key constituents of the capital expenditures (CAPEX) and LCOE, such as the civil works and electro-mechanical equipment. Section 6 provides some opportunities and benefits for the use of composites and AM for hydropower components, including the use of the CEMAC AM tool to determine potential costs of an AM-printed hub. Section 7 highlights key opportunities for SHP, and Section 8 provides conclusions. Recommendations can be found in Section 9.

2 U.S. Hydropower Market

2.1 Hydropower Market Status and Trends

Hydropower resources exist in nearly every U.S. state and have been a key U.S. renewable energy resource for over a century. In 2016, hydropower provided approximately 44% of all the U.S. renewable electricity generated, which represented 6.5% of the net U.S. electricity generation (Uría-Martinez, Johnson, and O'Connor 2017). The cumulative installed electricity generation capacity of hydropower and pumped storage across the United States in 2015 was approximately 101 GW, which made hydropower the single-largest source of renewable electricity in the United States (DOE 2016). The trend in cumulative installed capacity for hydropower and pumped storage in the United States can be seen in Figure 1.

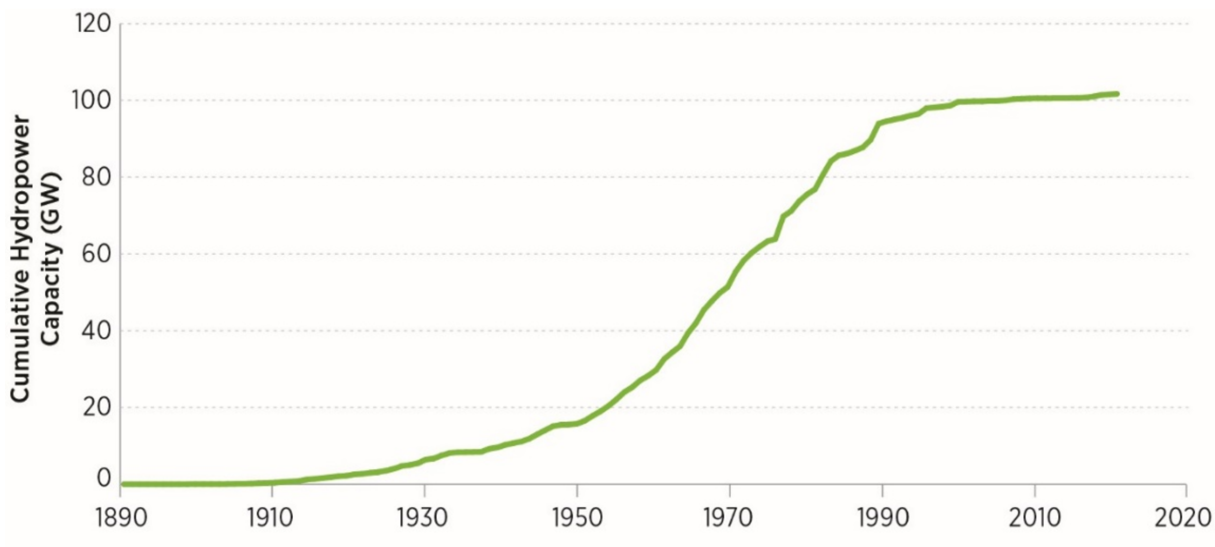


Figure 1. U.S. hydropower and pumped storage cumulative capacity, 1890–2015 (DOE 2016)

As seen in Figure 1, nearly 82 GW of hydropower and pumped storage capacity were added from 1950 to 2000. Since then, hydropower growth has plateaued domestically. New hydropower construction has declined in recent years because of a rebalancing of water-use priorities, a reduction in the cost of competing energy sources, and reduced incentives for domestic hydropower investments. Also, increased regulation for hydropower plants (e.g., from the 1980s) and the significant environmental impact of new large-scale hydropower plants (e.g., >50 MW) have made hydropower more costly and risky to develop (Uría-Martinez, O'Connor, and Johnson 2015).

While the U.S. hydropower generation capacity is plateauing, SHP (e.g., NPDs) represents a strong domestic and international growth opportunity. For example, only 3% of U.S. dams presently generate electricity (DOE 2016). The remaining NPDs represent a substantial market opportunity for capacity expansion and the U.S. SHP manufacturing sector. Therefore, NPDs are the focus of this study. As seen in Figure 2, NPDs by 2050 could add nearly 4.8 GW of new capacity (DOE 2016). Advances in technology (e.g., the use of alternative materials for turbines, pre-cast concrete structures, and modular SHP equipment) could help decrease costs for SHP and potentially increase the likelihood of installing a greater percentage of the potential.

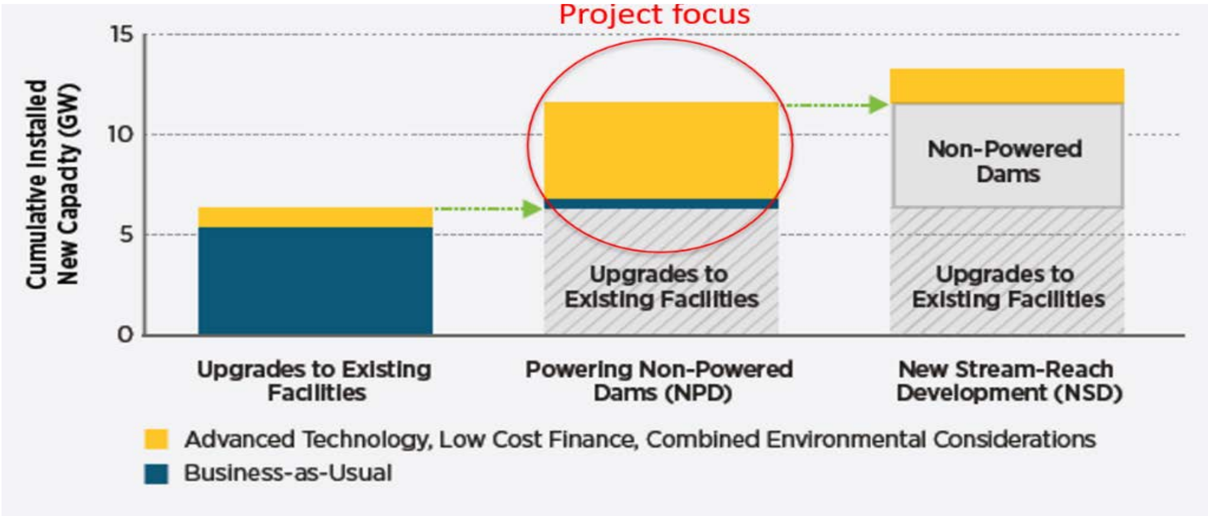


Figure 2. Cumulative 2050 deployment of new SHP generation capacity by NPDs and NSDs, as modeled by the Regional Energy Deployment System (DOE 2016)

The United Nations International Development Organization (UNIDO) estimated that, as of 2016, approximately 64% of the world's 217 GW of SHP potential (at <10 MWe) is still available for capacity expansion. Effectively, only 36% of the world's SHP has been realized as installed capacity (UNIDO 2016a). The domestic market for the consumption of U.S. SHP turbines for NPDs has slowed, and it is not expected to have significant growth in the next 5 years (DOE 2016). However, there is a significant market potential in the international markets, particularly for the United States to export SHP turbines as new markets open. Figure 3 shows the scale of the potential of SHP for the top 14 countries and illustrates how much could be theoretically available if all the technical potential could be realized (UNIDO 2016a).

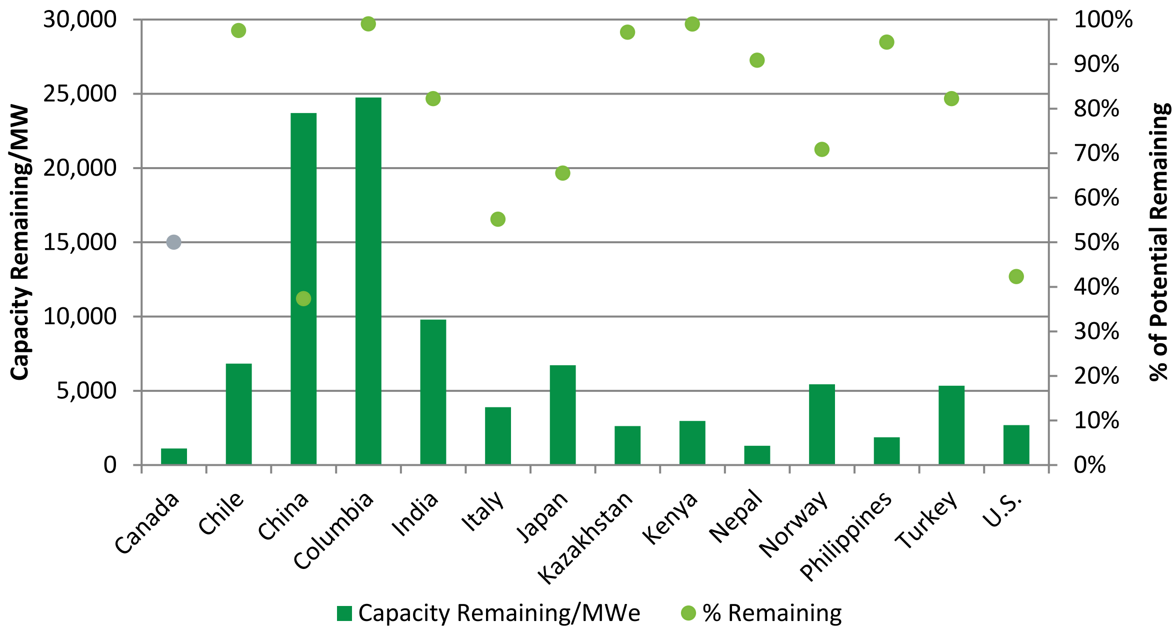


Figure 3. Technical potential of the capacity of SHP remaining by country (MW) and the percentage of the resource still remaining (UNIDO 2016a)

Figure 3 highlights both the capacity remaining that could theoretically be installed (i.e., technical potential—installed capacity for that country) and the percentage of the potential remaining relative to the technical potential of that country. In Chile, Colombia, Kazakhstan, Kenya, Nepal, and the Philippines, over 90% of the technical potential still available (i.e., each country has installed less than 10% of the technical resource potential) (UNIDO 2016a). Columbia could be a significant U.S. foreign export market for the future, as the UNIDO research indicates nearly 24,750 MW of capacity could be available for installations (UNIDO 2016a). When the top five countries with the most potential are considered (Chile, China, Columbia, India, and Japan), an estimated 71,795 MW of potential could have SHP installations (UNIDO 2016a). The data indicate that Brazil has an installed capacity of 1,023 MW of SHP (at <10 MW) and Canada has an installed capacity of 1,113 MW (<10 MW) (UNIDO 2016b). The data also indicate that Brazil has an unknown amount of <10 MW potential remaining, and Canada has at least 1,113 MW of potential capacity remaining (UNIDO 2016b). To note, Brazil and Canada have defined SHP as ≤30 MW and ≤50 MW, respectively, with little data being available for the <10 MW size range.

It must be noted that the global potential for SHP is highly indicatory, and a large part of it may not be installed, which could be for a variety of reasons, including uncompetitive cost for installing an SHP system, competition against other electricity generating technologies, and lack of knowledge to utilize the SHP resource potential. With the potential available for the export of SHP turbines and component parts (e.g., to Chile and Columbia), as global markets open further, there could be increasing demand and need for SHP systems. The United States can certainly also be active in the global markets and leverage existing SHP manufacturing to supply into these global export markets. While export potential exists, there will be country-specific barriers for each of the markets, which will need local project development to overcome the local barriers and realize some of these opportunities.

2.2 U.S. Hydropower Manufacturing

The U.S. hydropower supply chain is distributed across the country with denser concentrations near manufacturing centers such as the West Coast, Midwest, Great Lakes, and Northeast (Uría-Martinez, O’Connor, and Johnson 2015). The hydropower manufacturing hubs (such as the Northeast and the Great Lakes vicinities), which produce components for all sizes of hydropower generating equipment, can be seen in Figure 4. The major components for hydropower are the gates, valves, generators, penstocks, transformers, and turbines, and a representative hydropower plant with the major components is shown in Figure 5.

The manufacturing hubs, or clusters, have formed for many reasons. Key factors include the domestic capacity expansion of hydropower in the United States from the 1950s, the need for manufacturers to be proximal to the hydropower resources (e.g., areas of the country that in the past have required new projects due to excellent resource), and port access (Uría-Martinez, O’Connor, and Johnson 2015). Research in this project found there is sufficient existing capacity in the United States to manufacture and assemble hydropower generation equipment and all major components. A map of all the known manufacturing locations of hydropower components is shown in Figure 4 (Uría-Martinez, O’Connor, and Johnson 2015).

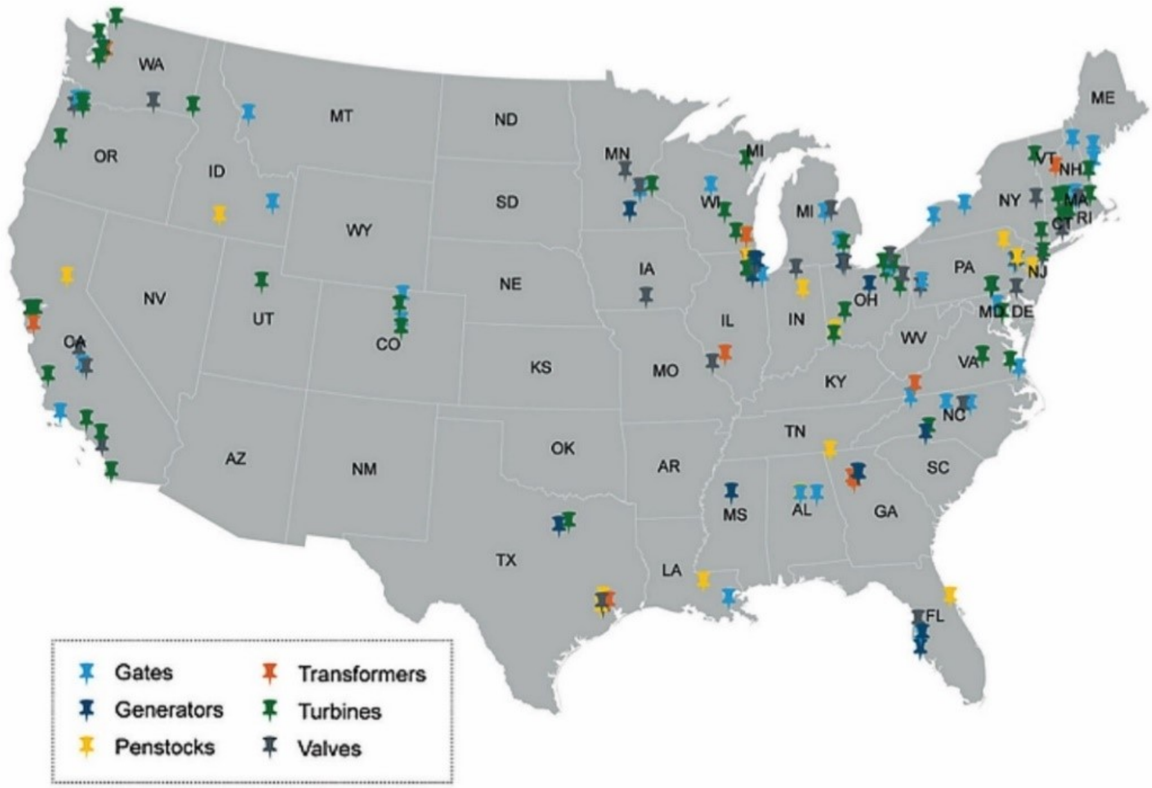


Figure 4. Map of U.S. hydropower manufacturing locations by state and components manufactured (Uría-Martinez, O'Connor, and Johnson 2015)

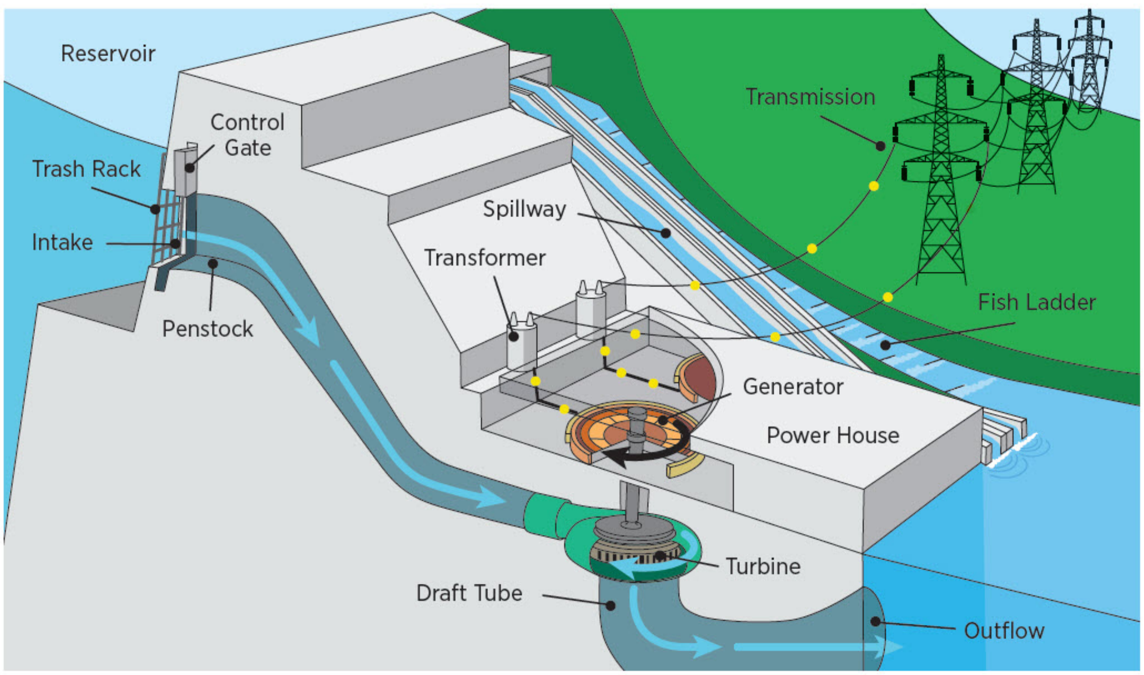


Figure 5. 3D cross-section of a representative hydropower plant and the major components (DOE 2016)

As shown in Figure 5, the flow of water from a contained reservoir through the gates, valves, and penstock allows the rotation of the turbine and generator for electricity generation. Transformers are generally needed to increase the voltage of the electricity transmitted from the hydropower plant through the transmission lines of the electrical grid (DOE 2016). The amount of power generated is based on the head (the difference in height between the upstream pool and tailwater) and the flow rate of water passing through a location (DOE 2016).

The production of reliable high-quality products for hydropower and SHP is a particularly strong competitive advantage for U.S. companies along the supply chain. Hydropower components are designed for long life operation, often in remote locations and under continuous operation.

Components manufactured to have high reliability are highly valued in such conditions. Four companies (Voith, Alstom, Andritz, and Weir) make up 94% of the recent large hydropower turbine market share (by capacity) in the United States for federal rehabilitation, new turbines, and expansion projects (Uría-Martinez, O'Connor, and Johnson 2015). While each of these companies also produces equipment for SHP, most of their focus is on the larger turbine and equipment markets. However, the number of manufacturers catering to the smaller turbine segment (e.g., <10 MW) is substantially larger. Companies such as Canyon Hydro, Hydro Green Energy, Gilbert, Gilkes & Gordon North America, and Wilson Power are supplying SHP parts, equipment, and turbines for domestic consumption and in some cases for foreign export.

There could be significant new SHP capacity and growth potential both for the manufacturers—both domestically and globally—of SHP equipment and the project developers. For example, in discussions with North East HydroPower, it was found that nearly 800 potentially viable projects in New England could use their Archimedes screw generators (100–250 kW per screw generator). The level of economic feasibility at these sites is unclear, as is whether North East HydroPower has assessed each site. This is worth further investigation in future studies. U.S. SHP suppliers can leverage international growth along with meeting domestic demands.

3 U.S. Hydropower Tradeflows

The U.S. International Trade Commission (USITC) monitors the exports and imports of hydropower components such as parts and turbines. Figure 6 shows the export and import tradeflow value in millions of dollars for all hydropower turbines by country/region per year from 1996 to 2015 (Uría-Martinez, Johnson, and O'Connor 2016). The USITC breaks up the U.S. hydropower component market by four Harmonized Tariff Schedule (HTS) trade codes, which represent three classes of hydraulic turbines and the parts needed for hydraulic turbines. These are (USITC 2017): turbines with capacity <1 MWe (HTS 8410.11); turbines with capacity >1 MW but <10 MW (HTS 8410.12); and turbines with capacity >10 MW (HTS 8410.13). The fourth code is for the "parts of hydraulic turbines, including regulators," (HTS 8410.90) and can include parts such as runners, couplings, stay rings, valves, and governors (ABF 2016).

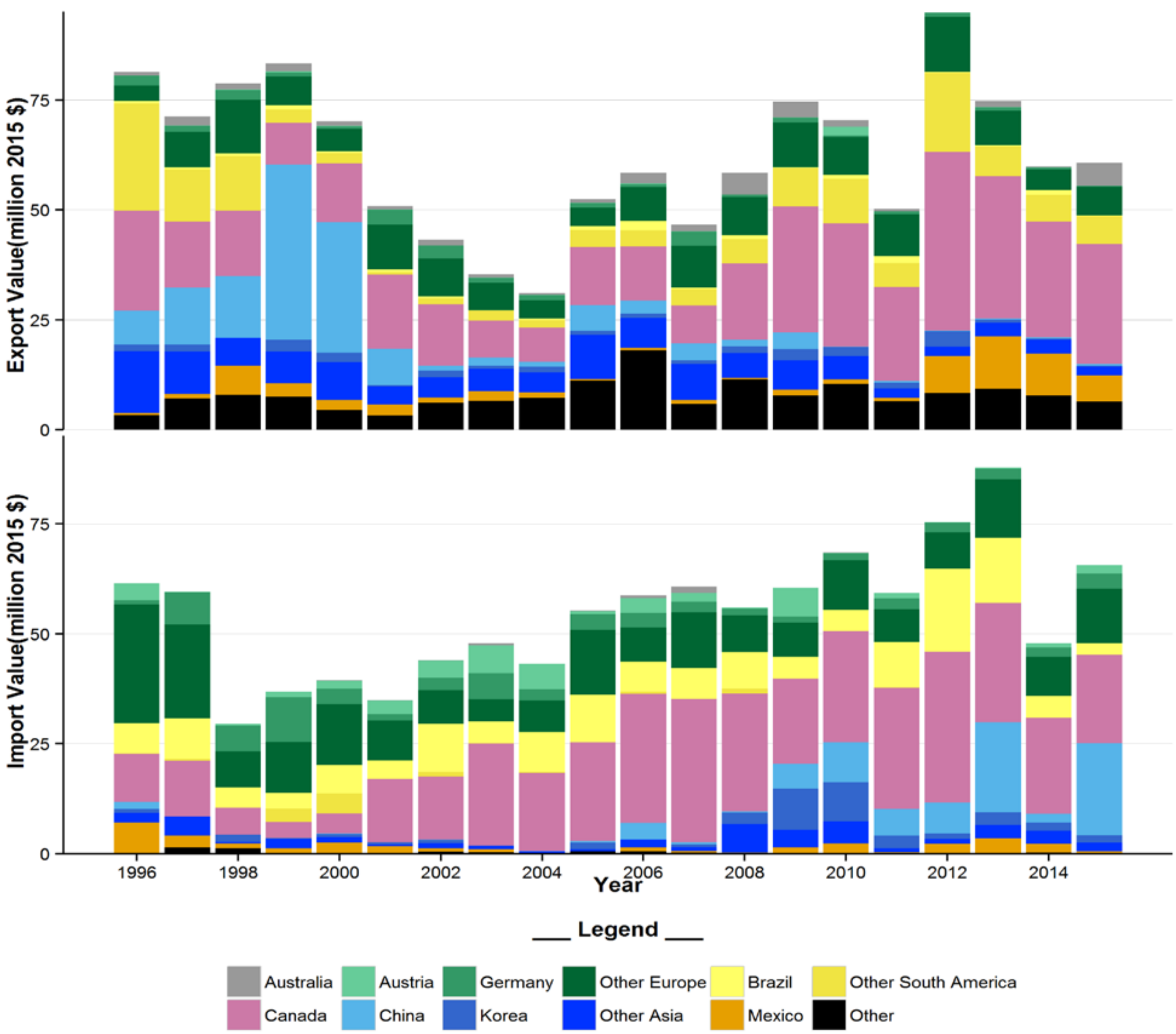


Figure 6. U.S. exports and imports for the hydropower turbine market (all turbine sizes) from 1996 to 2015 (Uría-Martinez, Johnson, and O'Connor 2016)

As seen in Figure 6, the United States exported approximately $62 million of hydropower turbines in 2015, with more than half of the export value coming from Canada, and imported slightly more than $66 million (Uría-Martinez, Johnson, and O'Connor 2016; United Nations 2017). Key export countries for the United States for hydropower turbines include Australia, Canada, and Mexico. Brazil, Canada, and China represented the largest importers for hydropower turbines between 2005 and 2015. As seen in Figure 6, China's import strength into the United States and the import value have increased and consolidated in the last few years, which could represent a manufacturing threat for the U.S. hydropower industry.

Looking at the tradeflow of the "parts of hydraulic turbines" for all sizes of hydropower systems (HTS 8410.90), it was found that the parts market can be comparable to the entire hydropower turbine market. For example, the United States exported approximately $46 million in hydropower parts (HTS 8410.90) in 2016, compared to an export value of nearly $68 million in hydraulic turbines of all sizes (HTS 8410) (USITC 2017). As can be seen, the parts market for U.S. hydropower manufacturers is valuable both for domestic use and global application.

To gain a true understanding of the manufacturing opportunities and value along the hydropower supply chain, it helps to also segment the U.S. hydropower turbine market. For this project, further data were extracted for the 1–10 MWe turbine range (HTS 8410.12). For the sake of simplicity, this 1–10 MWe turbine range is referred to as SHP in this report. Figure 7 highlights the U.S. export and import values (in dollars) for hydraulic turbines and waterwheels of SHP turbines, where the data are aggregated by country from 2005 to 2015.

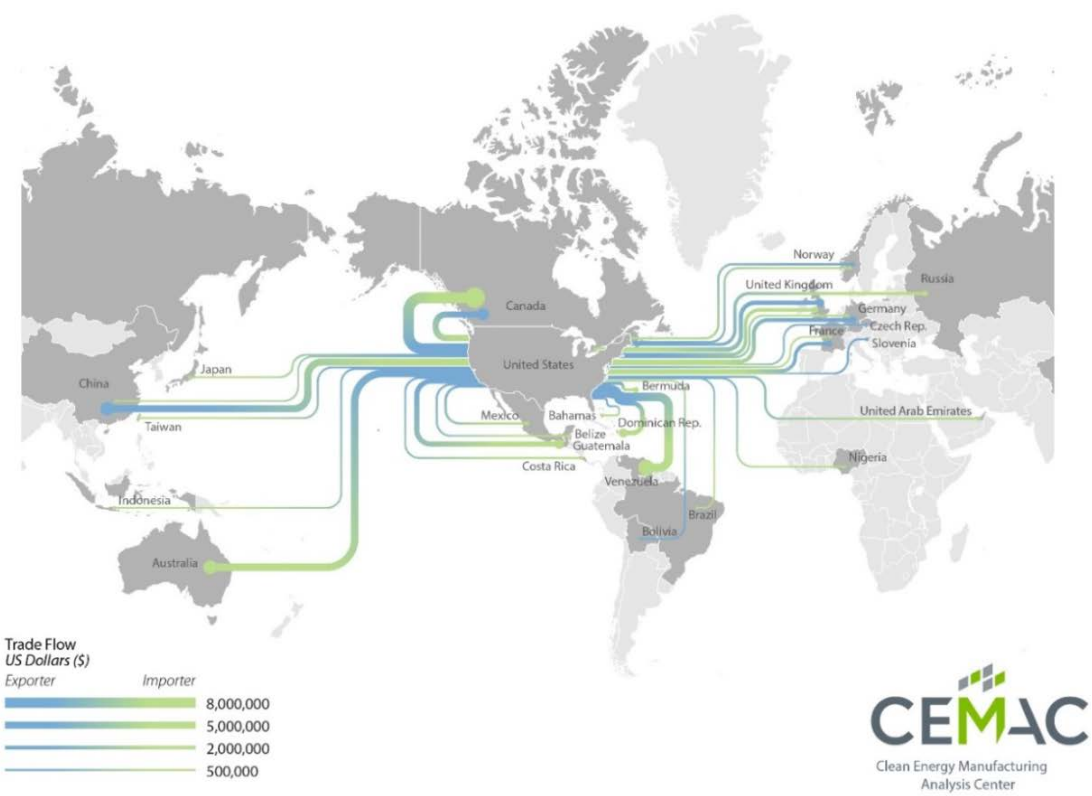


Figure 7. U.S. tradeflows for SHP turbines (1–10 MW, HTS 8410.12), 2005–2015 (USITC 2017)

The U.S.-centric map in Figure 7 illustrates how the United States interacted with other counties for SHP turbines with a capacity of 1–10 MW turbines from 2005 to 2015. It is worth noting, however, that the current data set does not show each country's total export or import data for the SHP turbines; it shows only the export and import values for the United States. The consolidated data from 2005 to 2015 were aggregated into a tradeflow map, where the blue lines represent export flow from the United States and the green lines represent imports. The thickness of the line indicates the value of the trade-in dollars, either as an export or import. Only countries with significant tradeflows or specific competitive interest to the United States are shown.

The data from 2005 to 2015 indicate the SHP turbine market (i.e., 1–10 MW) had an export value of approximately $35 million for the United States and approximately $16 million of SHP turbines by value were imported (USITC 2017). In this time period (2005–2015), the United States exported SHP turbines to 45 countries and imported from 13 countries (USITC 2017). When the same period is looked at for the U.S. export value of the "parts of hydraulic turbines" (i.e., HTS 8410.90), it was found that the export value for the United States was approximately $393 million (USITC 2017). This highlights that while the United States has a small export market for the SHP turbines, the parts and regulators for the overall hydropower turbine market is over 10 times in value. A key insight from an ORNL study is that the significance of the parts market is likely due to the rehabilitation and modernizing happening within the U.S. hydropower fleet, where since 2005, "approximately $3.6 billion has been spent to repair, replace, and refurbish U.S. hydropower facilities" (Uría-Martinez, O'Connor, and Johnson 2015).

Key countries that the United States has exported SHP turbines to include Australia, Canada, Germany, Norway, and the United Kingdom. Countries that the United States imports SHP turbines from include Canada, China, France, and Germany. The United States exported only approximately $60,000 of the SHP turbines to Brazil from 2005 to 2015, which could imply that Brazil's SHP turbine market is being satisfied by internal production and manufacturing.

4 Representative SHP Manufacturing and Costs

As part of this project, the manufacturing costs for a representative SHP turbine were estimated. The cost of hydropower manufacturing can be affected by a wide variety of factors, including the cost of labor, energy, raw materials, finance, and capital equipment costs. The project has focused on the manufactured component cost of some of the large pieces for a turbine system and the potential tooling investment. Finance costs (e.g., the cost of debt) have not been factored, nor were the costs of installing the system. Construction and civil works can be most of the CAPEX for SHP projects and in some cases up to two-thirds of the CAPEX (Chalise et al. 2016). The SHP turbine is normally less than one-quarter of the CAPEX (Chalise et al. 2016). The manufacturing cost analysis for this project focused on the main machining processes and costs for the rotor, blades, and hub and did not include additional turbine components (e.g., distributer/stay ring), the generator, and power electronics.

ORNL and NREL have worked together on selecting and defining a representative system for NPDs made up of 2x5 MW turbines. After a down selection of components that could be considered for detailed cost and manufacturing analysis, computer-aided design (CAD) models for the 5-MW turbine parts were made to provide the input for a design for manufacturing and assembly (DFMA) analysis. DFMA is a commercially available software tool from Boothroyd Dewhurst that can integrate product design, manufacturing processes, and the assembly of the components to then cost a product. DFMA produces the “should cost” for a product based on the material selection, machining, and assembly processes used.

The representative 5-MW Kaplan-style turbine with a variable pitch system can be seen in Figure 8. The pitch system (i.e., the linkages, collars, members, and actuator in Figure 8 right) allows pitch of the blade to be changed relative to the flow of water. Details about the 2x5 MW representative system are in Appendix A. For a sense of scale, the hub in Figure 8 is approximately 1.2 m (4 feet) in outer diameter, and the rotor diameter (which is the blade to blade span) is 3.5 m (11.5 feet). The representative Kaplan-style turbines have been considered suitable for 30 ft of head (approximately 9.14 m).

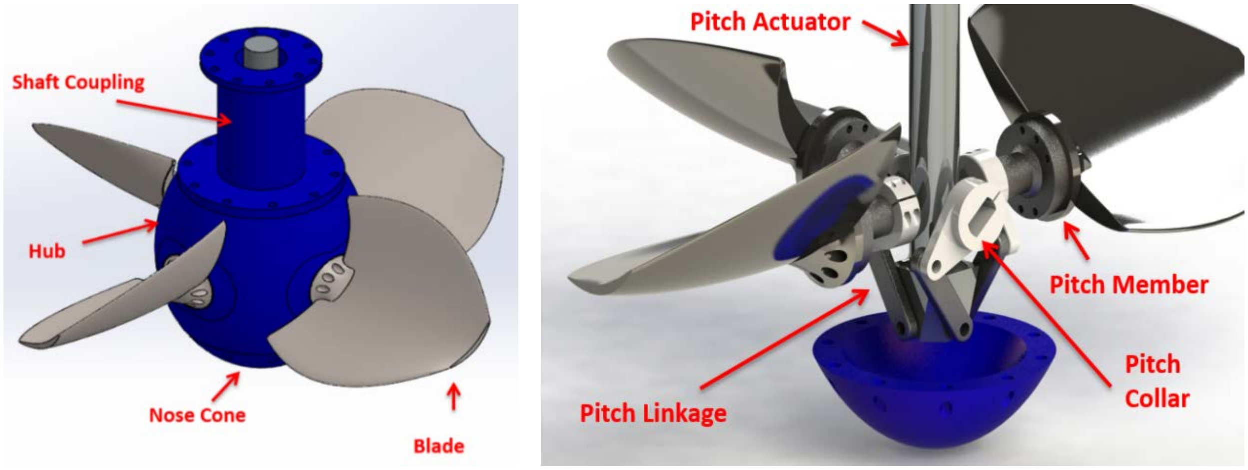


Figure 8. NREL CAD model of the components from the manufacturing analysis

A key assumption made in the analysis is that one representative system (2x5 MW turbines) would be manufactured five times per year. This means that 10 modular turbines in total are manufactured, and five different locations can use the 2x5 MW representative system. By using the same representative system at multiple sites with similar head and flow conditions, tooling investment can be amortized.

Table 1 shows each component of the representative turbine system and how each is manufactured. The manufacturing costs for each component of the representative system are shown in Table 2. The cost consists of the materials, setup, process, rejects, and tooling costs.

Table 1. Representative 2x5 MW SHP System and the Number for Each Component

Component Type	Number of Components	Description
Hub	2	Each hub is cast from steel and then machined using computer numerical control (CNC) machines.
Shaft Coupling	2	Each shaft coupling is made from plate steel pieces, machined, and then welded together to make the shaft coupling. Each shaft coupling consists of one upper flange, one thick pipe/tube, and one lower flange.
Nose Cone	2	The nose cone is cast and then CNC machined.
Blade	8	The blades are cast and then CNC machined.
Pitch System	2	Each pitch system shaft includes one pitch shaft made of forged high-strength steel that is CNC machined. Each pitch system includes one pitch mechanism, which consists of four linkages, four pitch collars, and four pitch members. The pitch system parts are CNC machined from blocks of metal.

Table 2. Representative Manufacturing Cost Breakdown by the Manufacturing Cost Factors

	Representative System Cost, with Tooling	Percentage of Total
Material Cost	$139,214	27%
Setup Cost	$3,978	1%
Process Cost	$15,331	3%
Rejects Cost	$2,592	1%
Total Tooling Cost per Representative System	$349,342	68%
Total Manufacturing Cost of Representative System	**$510,457**	—

The estimated total manufacturing cost of the representative system is approximately $510,000. This includes the allocated tooling cost or investment of approximately $349,000, which is nearly 68% of the total manufactured representative system cost. When the components in Table 1 are assembled into units, the representative assembled cost of the 2x5 MW turbines is approximately $550,000 and does not include installation.

For this analysis, the tooling investment has been estimated for the size of the components involved (e.g., sand molds for the hub into which the hub is cast) and for the main areas or processes where specific tooling was found necessary. All the components apart from the shaft coupling required some tooling investment, with the pitch system requiring the most due to the use of a forged shaft, which is more expensive than hot forged high carbon steel ($17.25/lb versus $0.8/lb). The material prices were from the DFMA databases in version 2.4.0.18 of the Design for Manufacturing: Concurrent Costing tool (Boothroyd Dewhurst Inc. 2017). Forged high-strength material was used for the shaft, as it is critical for the shaft to operate successfully for at least 25 years and in possibly corrosive environments. The use of a high-strength, corrosion resistant forged material and the manufacturing processes such as casting for the hubs was confirmed by the industrial discussions, though the material selection of the shaft would be project-dependent.

Figure 9 shows the breakdown of the representative system cost by component type, and it includes the tooling investment per 2x5 MW system. Each pitch system in Figure 9 includes the pitch shaft and the pitch mechanism. The two pitch systems for a representative 2x5 MW system made up nearly 75% of the manufactured cost, and the eight blades were the next largest proportion of the overall system cost at 13%.

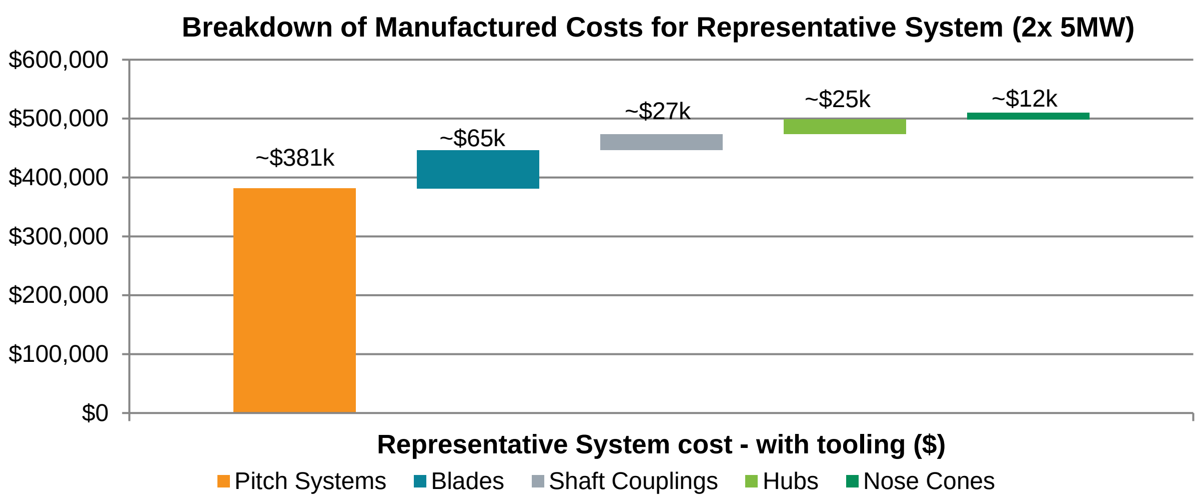


Figure 9. Breakdown of the representative system manufactured cost by main component type

As mentioned before, a key assumption in the DFMA analysis was that five representative 2x5 MW systems could be made, allowing for the tooling cost to be split over five sites. The overall tooling cost for the 10 SHP turbines was approximately $1.75 million. This includes the design of sand cast molds for the hubs, blades, and nose cones as well as the forging presses and hammers for the pitch shaft. If each site used different turbine designs (e.g., due to different heads and flow rates available at that NPD site), it could be expected that the castings needed for the hub, blades, and nose cones would be different at each site, which could increase the overall tooling investment per site or representative system.

The casting investment for a representative system is approximately $40,000 of the $349,000 tooling cost, which is approximately 13% of the overall investment cost, assuming that that five representative systems can be produced from the single set of molds. If the casting investment could not be easily amortized because each site needed radically different molds, the casting investment could be of the order of $200,000 for five sites instead of $40,000. It is worth noting that the total tooling cost does not include the cost of buying and setting up new CNC machines to undertake the work because it is expected that a manufacturing facility would have these types of key equipment. The tooling investment is only for the specialized tooling needed to manufacture the components of the representative system (e.g., specialized molds needed for the hub and nosecone) and does not include the CAPEX to purchase new casting and forging machines or to set up a new manufacturing facility.

The manufacturing processes used (e.g., castings and forgings) work well for the SHP scale and are well established and proven, but these processes could be more suited for larger volumes of production (e.g., 20 turbine hubs). This could help considerably decrease the tooling cost per representative system. This manufacturing analysis gives insight to approach SHP manufacturers, inform the industry, and continue to refine the models and assumptions. It would be worthwhile to test this assumption by analyzing the energy generation annually using custom turbines at one site and comparing that analysis to the energy generation of the modular turbines at other sites with similar head and flow properties.

Looking closer at the main manufacturing cost categories of the representative cost can give insight into the effects of the material and labor on the overall manufacturing cost. It is important to note that the labor cost (e.g., $/hr for a machine operator) affects the setup and process cost. The process cost is made up of an averaged operator rate ($/hr) + machine rate ($/hr). As seen in Table 2, the total representative manufactured cost of approximately $510,000 is broken down by the material, setup, process, rejects, and tooling costs allocated to the representative system.

The material cost of approximately $139,000 was ~27% of the representative system cost. The representative system is sensitive to the material used for each component (e.g., $/lb for steel for the hub). A ±10% change in material cost (e.g., from $139,000 to $154,000) has a ±3% change for the overall system cost. It is worth noting that certain high-strength materials (e.g., for the shaft and pitch system of the representative turbine) could be subject to price changes more than the cast steel. When the labor cost is extracted from the DFMA analysis as a percentage of the overall manufactured cost, it represents a small percentage of the overall cost to manufacture the system. DFMA has utilized U.S. labor rates of $25–$70/hr, depending on the skill and hourly rate of the skilled operation. The setup cost is 100% labor, and the process cost is estimated at 60% labor (where the remainder is the respective machine’s rate); this was only $13,000–$15,000 of the system cost or only 2.5% of the manufactured cost.

5 Insights into the State of U.S. SHP Manufacturing and the Impact of Turbine Equipment on LCOE

This section looks at: 1) a Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis; 2) key qualitative and quantitative U.S. SHP manufacturing and siting factors; and 3) the techno-economic impact of equipment manufacturing factors on the competitiveness of new SHP.

5.1 SWOT for the U.S. SHP Manufacturing Sector

A SWOT analysis for the U.S. SHP manufacturing sector has been undertaken by conducting a series of interviews with U.S. manufacturers for hydropower systems and components. To represent the breadth and depth of the U.S. SHP sector, both large and small hydropower manufacturers were approached to gather key details and insights. The most important elements and insights from the SWOT analysis are shown in Table 3.

Table 3. Key Elements of the SWOT Analysis for the U.S. SHP Sector

Strengths	**Opportunities**
Domestic capacity expansion of hydropower in the United States has stemmed from the need for manufacturers to be proximal to the hydropower resources, which can be leveraged by SHP as the markets (domestic and export) grow. The United States has historically had one of the lowest energy costs, which is beneficial for producing high-energy components. The U.S. manufacturing supply chain has "everything it needs" to manufacture SHP components and systems. Financial strength of the equipment vendors and quality of the products have been found to be key because they ensure operations and maintenance (O&M) can be undertaken over the long system life.	There are significant untapped markets (e.g., NPDs, canals and conduits, and NSDs) in the United States. Countries such as Colombia, India, and Vietnam have similar untapped NPD resources as the United States and could add to the U.S. export value of SHP turbines and components. Innovations and research in SHP systems could increase market demand through potentially decreased cost or system benefits. This could be a way of progressing U.S. SHP deployment, both domestically and internationally.
Weaknesses	**Threats**
SHP systems are currently produced and procured in small numbers (e.g., 1–2 turbines per site), and even with some relative standardized equipment offerings, these are typically limited in achieving benefits from manufacturing volumes and economies of scale. In SHP, one issue is an aging well-trained workforce. Manufacturers find it difficult to attract younger workers and keep them.	There is currently low market demand for SHP systems (e.g., utilities) because the overall *project* development barriers are high and the return on investment for SHP is low compared to photovoltaics (PV) and wind. The financial incentives for large-scale PV and wind make SHP projects uncompetitive. Consequently, the SHP manufacturing follows with decreased production. Foreign competitors in low-cost countries (e.g., China and Brazil) could compete further in the global manufacture of SHP turbines.

In the U.S. SHP sector, some key strengths have been built over time that have allowed the U.S. hydropower supply chain to be concentrated in certain areas such as the Northeast and near the Great Lakes but also in other areas (e.g., near the Mississippi River and in the northwestern United States). As highlighted, the manufacturing clusters that have formed produce components for all sizes of hydropower generating equipment, including the high value components such as the turbine, generator, and penstocks/localized constructions. The manufacturing hubs or clusters have formed for many reasons, though key factors include the domestic capacity expansion of hydropower in the United States from the 1950s, the need for manufacturers to be proximal to the hydropower resources (e.g., areas of the country that in the past have required new projects due to excellent resource), historically low energy costs (which are beneficial in manufacturing large parts such as hubs), and port access. The areas that have undertaken SHP (e.g., the Northeast) have proximity for lean manufacturing and can also readily service the systems in operation.

As one SHP developer highlighted, the United States "has everything it needs" along the supply chain, particularly in the manufacturing sector for SHP components and systems. This includes access to raw materials and the components that manufacturers can use to build SHP systems. Also, the U.S. workforce (especially in the Northeast) has the skills and tooling needed for SHP manufacturing. This includes historical experience in producing SHP components and other heavy manufacturing industries that can be leveraged in future SHP growth. Along with a strong manufacturing base, the innovation potential in the United States is high, which through universities, research institutes, and laboratories can help innovate new technologies to better use the remaining SHP resources. Another key strength is that U.S. SHP manufacturers have a good reputation for reliability and system quality and are expected to be able to fulfill the warranty claims over 30–40 years of operational service. For example, an SHP developer highlighted that "the financial substance of the (U.S.) equipment vendors is key and can negatively impact Chinese manufacturers," as municipalities and long-term investors want more certainty of the plant generating over a long period.

A few weaknesses in the U.S. SHP sector highlight where potential improvements could be made. For SHP, a key weakness is that SHP systems are currently produced in small batches and most sites use turbines that have some standardization, though they do not benefit from increased manufacturing volumes or economies of scale. If larger volumes of manufacturing could be leveraged (e.g., through modular turbines), the capital equipment needed for SHP systems could perhaps decrease in cost, helping SHP systems to be more valuable. Another weakness in the U.S. SHP sector is the lack of a robust pipeline of well-developed projects, which means producing larger volumes of equipment and turbines is difficult.

The next portion of the SWOT analysis considers the opportunities in the SHP market and related manufacturing. There are huge domestic and international markets where SHP systems and manufacturing could grow and expand to meet potential demands. While this project has focused on NPDs, there is also significant untapped potential in hydropower systems installed in canals and conduits and NSDs, as highlighted by DOE and the Army Corp of Engineers (Kao et al. 2014; DOE 2016). For example, it is expected that there could be 4.8 GW of NPD potential by repowering dams in the United States (DOE 2016). There are significant opportunities internationally for U.S. original equipment manufacturers, component manufacturers, and project developers to supply both knowledge and technologies. Countries such as Columbia and Vietnam, where most of the SHP technical resource potential is untapped, could allow U.S. suppliers to leverage existing SHP facilities and strengths to export SHP systems and components and to service those markets.

Coupling the strong innovation potential in the United States and the available manufacturing for SHP, the United States also has excellent opportunities to innovate and develop new SHP systems for NPDs and NSDs. The use of advanced materials and manufacturing processes (e.g., AM and composites) could lead to new equipment design. Changing the equipment designs to allow for lighter easier-to-assemble systems could be a path for decreasing turbine equipment and installation costs.

The last part of the SWOT analysis addresses the internal and external threats for the current U.S. SHP sector. The main internal threat for the capacity expansion of domestically installed SHP systems, which would utilize the significant resource potential available, is the current low market demand for SHP systems. Indicators of the lack of manufacturing demand for SHP systems can be seen, for example, through a key global manufacturer of hydropower turbines (of all sizes). It was found in discussions with one of the largest global suppliers of SHP systems that the SHP production in its flagship U.S. facility has decreased significantly to focus on R&D, manufacturing, and refurbishments of large turbine systems. Smaller SHP developers and manufacturers that have been part of the discussions have suggested the regulatory and economic struggles to develop, compete, and win projects are proving to be major barriers to SHP uptake. A key insight from the developers is that SHP is perceived as uncompetitive with PV and wind power in the United States. This is because the incentives such as the 30% federal investment tax credit for PV and wind are not applied to SHP systems (e.g., <10 MW). Without the right market conditions, the SHP manufacturers will have little incentive to produce SHP systems for the domestic market. Manufacturers of SHP systems will follow the demand, and SHP turbines are unlikely to be produced while waiting for projects to be environmentally assessed, bid, and funded.

The external threat for the U.S. SHP sector is the emergence of foreign competitors in low-cost countries (e.g., China and Brazil) that could compete further in the global manufacture of SHP turbines and, if they are significantly less expensive, could take U.S. SHP market share from the local producers. As highlighted earlier, China in recent years has consolidated and strengthened its import position into the United States for hydropower equipment (in all sizes), which indicates that the cost of equipment is an important factor to consider for U.S. competitiveness in the SHP sector. Going forward, the U.S. SHP sector must maintain and improve its strengths to utilize the opportunities present (e.g., the potential number of NPDs that could be repowered in the United States), both in the domestic and international markets.

5.2 Key Qualitative and Quantitative Factors for U.S. SHP

This project has determined some of the key qualitative and quantitative factors for locating or siting SHP manufacturing facilities and for helping inform DOE and the SHP industry. This has been through market research, industrial engagement of SHP manufacturers, and cost analysis.

The cost of manufacturing components in the United States for a representative SHP system has been highlighted, and this is an important step in helping understand the cost of production in the United States. The main factors considered in this project are shown in Table 4.

Table 4. Key Qualitative and Quantitative Factors for U.S. SHP Manufacturing Location Decisions

Qualitative Factors	Quantitative Factors
The availability of skilled, experienced labor (e.g., workers skilled and experienced in SHP and machining) is a benefit for the United States.	The labor rate for skilled workers needed in SHP manufacturing will vary by occupation and region in the United States.
Material supply chain and constraints for the SHP components and raw materials will affect the location decision.	Raw material and component costs will impact the SHP system costs. Regional areas may have different cost structures and taxes affecting the manufacturer.
Availability of capital and financing/loans for setting up plants (e.g., due to desire by a state to revitalize an area) will determine whether companies are willing to set up new facilities.	The cost of energy (e.g., cost of electricity) is vital for manufacturing plants, and low electricity cost areas, especially the Northeast, are likely to attract manufacturers.
Domestic and international demand for SHP systems is essential in siting SHP manufacturing facilities. Proximity to local customer base is likely to change an SHP manufacturer's mind in siting a new facility (at least domestically).	The cost of financing and debt, especially in setting up capital-intensive manufacturing facilities such as those for SHP, will be key in determining a new SHP manufacturing location.
Availability of port access and transport logistics relative to the serviced markets are key. Without good port access, transporting the heavy large SHP components will be difficult.	Cost of equipment and machines (e.g., large five-axis CNC machines) will affect the manufacturing location.
The United States has a significant R&D and innovation environment for hydro and SHP, and there is focus from DOE to help increase the penetration of SHP within the United States.	Exchange rate costs will affect where the manufacturer wants to create a base (and therefore receive components) to serve a specific market.

5.2.1 Qualitative Factors

An important qualitative factor in SHP manufacturing siting has been the clustering of U.S. SHP manufacturers that can supply different components such as the turbine, generators, and valves so that suppliers can supply equipment locally near SHP resources or refurbish existing systems.

In effect, the demand of previously unexploited available resources has helped ensure the growth and expansion of hydropower systems, as well regional uptake. Once SHP systems are set up, because of the very long life involved, O&M is required over time and so provides steady demand for the manufacturers to produce goods for the refurbishments and upgrades locally. For international markets, SHP will require port access to manufacture and then export the components.

The proximity to a customer base (especially with heavy transport and port access needed) has likely influenced SHP manufacturers to form in areas together as well. Having U.S. regions with specific skills and workers that are heavily part of the hydropower industry would certainly affect other manufacturers in considering the availability of skilled labor for their operations. Another important qualitative factor for the United States is the involvement of DOE in fostering an innovation environment, utilizing resources such as the national laboratories and universities to then help penetration of SHP in the United States, through design and process changes. Locating manufacturing clusters and innovation centers close together can help improve the product design and the manufacturing processes that are then needed for the new technologies and designs (Hill and Engel-Cox 2017). It has been found that innovation centers situated near manufacturing regions can then help the manufacturing sector become more innovative and can act as a tool for economic and regional growth (Hill and Engel-Cox 2017).

Another qualitative factor that has likely impacted the SHP manufacturing sector has been the availability of capital and financing/loans for setting up plants (e.g., due to desire by a state to revitalize an area). This project has not gone into the financing or the availability of financing for SHP manufacturers, but that could be a path for further analysis.

5.2.2 Quantitative Factors

To determine a baseline for the manufactured cost of a representative system, this project has focused on manufacturing cost for some of the larger pieces of the turbine. For a full representative turbine and complete SHP installation costs, further analysis would be needed (e.g., to include the generator and civil works). The current manufacturing cost analysis though has highlighted the importance of the material costs and the labor costs (e.g., due to regional variation of different plants in the United States, on a representative system). For international supply of SHP systems, the exchange rate will also be an important quantitative factor for location decisions.

While detailed analysis has not been done on the cost of debt for manufacturers to purchase and set up new equipment, or on the high CAPEX needed for setting up a manufacturing facility, it is expected these would be key determinants on manufacturing location. CEMAC has undertaken detailed manufacturing location analysis for other clean energy technologies, such as carbon fiber manufacturing siting, which identified the key role of debt and CAPEX needed in siting new facilities (Cook and Booth 2017). Further analysis will be required to connect potential future growth either in domestic or international SHP markets to potential areas for U.S. SHP manufacturing capacity expansion.

As part of this, further investigation will be needed on the level of capacity currently in the U.S. SHP sector (e.g., how much could U.S. manufacturers produce to changes in demand) and from that where new locations could be needed to satisfy both domestic and international demand, if demand were to increase.

5.3 Techno-Economic Impact of Equipment Manufacturing Factors on the Competitiveness of New SHP

As seen in the SWOT analysis, key challenges face SHP development in the United States and, ultimately, the decisions to locate manufacturing capabilities domestically (and the resultant economic and employment benefits). To provide context to this challenge, this section explores the extent to which the ultimate cost of hydropower generating equipment influences the techno-economics of developing SHP—and by extension—the potential for manufacturing cost decreases to address the overall cost-competitiveness barrier to development. To note, 80% of an SHP's CAPEX can be from equipment and civil works (Chalise et al. 2016). The initial capital cost remains a major barrier to development for small low-head hydropower (Zhang et al. 2014).

The Integrated Design and Economic Assessment (IDEA) model for SHP is used to generate component-level cost estimates for the reference project and other NPDs. The IDEA model (O'Connor et al. 2017) combines a collection of rule-of-thumb, statistical, and engineering-based design approaches and cost estimates for conventional small, generally lower-head hydropower projects. It combines these cost and design elements with operational simulation to generate cost, performance, and economic metrics such as the LCOE.

As a reference against the cost of manufacturing (and its sensitivity to major inputs such as labor and material prices), the IDEA model is used to generate cost and LCOE estimates for a generic NPD project that would use the representative turbine configuration (2x5 MW Kaplan-style turbines rated at 30 ft of head), which was analyzed in the DFMA analysis. This analysis assumes the NPD would use horizontal-type Kaplan units (an "S-Type" configuration) in a powerhouse constructed in the abutment of an existing dam.

Unlike the cost estimate of the DFMA analysis, this cost estimate from the IDEA model includes all powertrain equipment (including components such as the generator, power electronics, and additional turbine components such as the governor, wicket gates, stay ring, and seals) as part of the electro-mechanical equipment.

As seen in Figure 10, the estimated capital cost of this potential NPD project could be approximately $3,400/kW, of which the biggest contributors were civil works and the electro-mechanical equipment. As shown, the electro-mechanical equipment (which includes the turbines) is the second-largest contributor to the capital cost at 35% ($1,176/kW, or $11.76 million) compared to the civil works at 37% of the capital cost. For this representative project, the cost of equipment is a major—but not the most determinative—cost category.

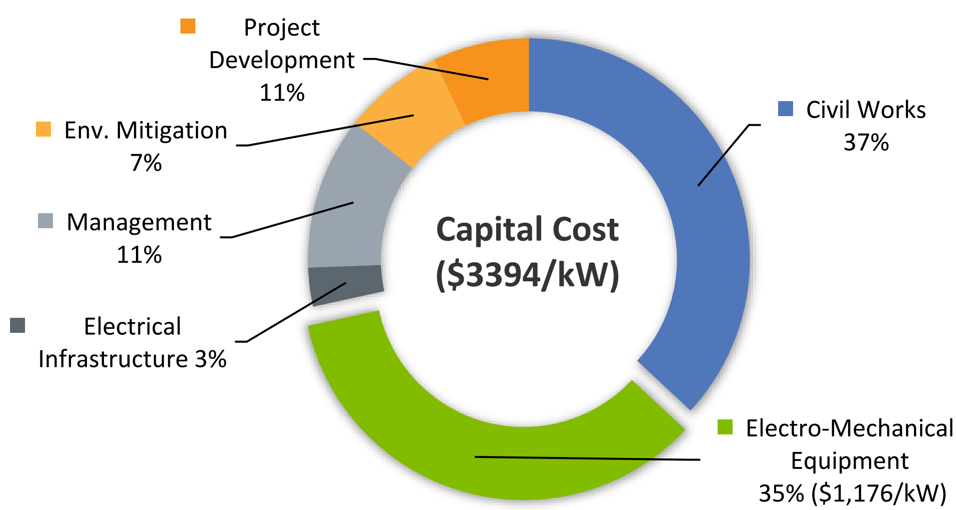


Figure 10. Capital cost breakdown ($/kW) of a potential NPD site using the representative 2x5 MW turbines

Figure 11 shows the LCOE impact of the CAPEX for the overall potential project. Assuming a 60% capacity factor, the electro-mechanical equipment contributed approximately $23/MWh of the total $81/MWh of the project LCOE (i.e., 28% of the total LCOE).

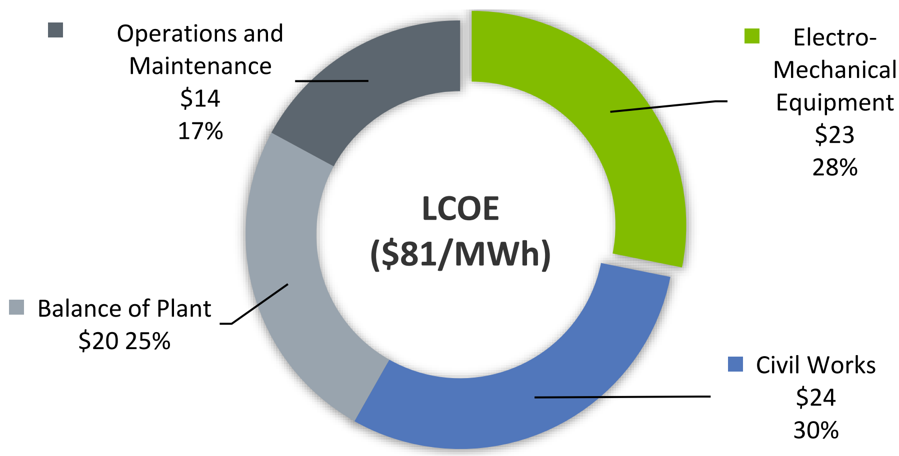


Figure 11. LCOE breakdown for prototypical NPD plant with the 2x5 MW representative turbines

As with the capital cost in Figure 10, again the civil works for a potential NPD project using the 2x5 MW turbines represents the single-largest contribution to the LCOE (as shown in Figure 11). However, the magnitude of the equipment contribution to the project cost and LCOE is a useful indicator of how manufacturing factors might influence broader SHP feasibility. Projects on the margin of financial viability may elect to sacrifice long-term reliability by sourcing less expensive (typically non-U.S.) equipment to justify moving forward with construction.

To gauge the overall sensitivity of the U.S. SHP resource potential to the manufacturing cost beyond the reference system, LCOE and cost were modeled for approximately 1,600 NPD projects (between 100 kW and 30 MW and low to medium head between 7 and 100 ft), totaling over 2 GW of potential. The modeled LCOE results from 100 kW to 2 MW of cumulative NPD plant capacity are shown in Figure 12.

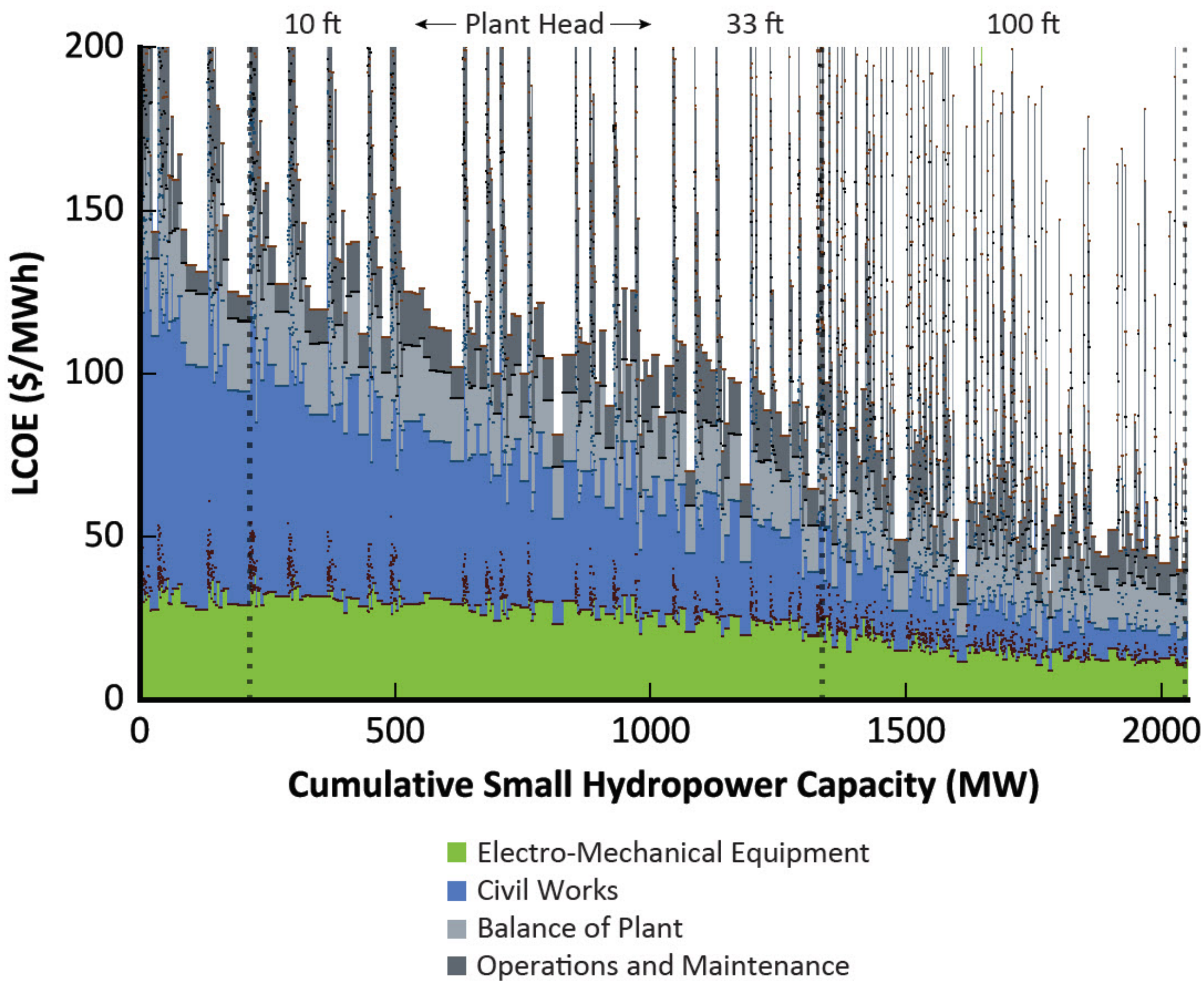


Figure 12. Modeled LCOE for NPD projects between 100 MW and 2,000 MW

Projects are sorted from lowest to highest head.

The range of the LCOE from 100 kW to 2,000 MW was from $33/MWh to $200/MWh. The average LCOE based on the span of projects and capacity was approximately $112/MWh. To better understand the impact of the constituents on the LCOE (such as civil works and electro-mechanical equipment), Figure 12 has been normalized by the proportion of each constituent on the overall LCOE. Figure 13 shows the breakdown of the LCOE as a fraction of the key constituents (i.e., the O&M, balance of plant, civil works, and electro-mechanical equipment).

The analysis has found that the electro-mechanical equipment contributes 8%–30% of the total LCOE, or on average, approximately $25/MWh for NPD plants. This is for the whole range of sizes of NPDs, from 100 kW to 30 MW. As seen in Figure 11, the potential NPD project using the representative 2x5 MW turbines had a LCOE contribution of $23/MWh from the electro-mechanical equipment compared to $25/MWh average. Civil works are the largest LCOE component, constituting 18%–58% of the project LCOE, and the average civil works LCOE contribution was $44/MWh (39% of the average LCOE).

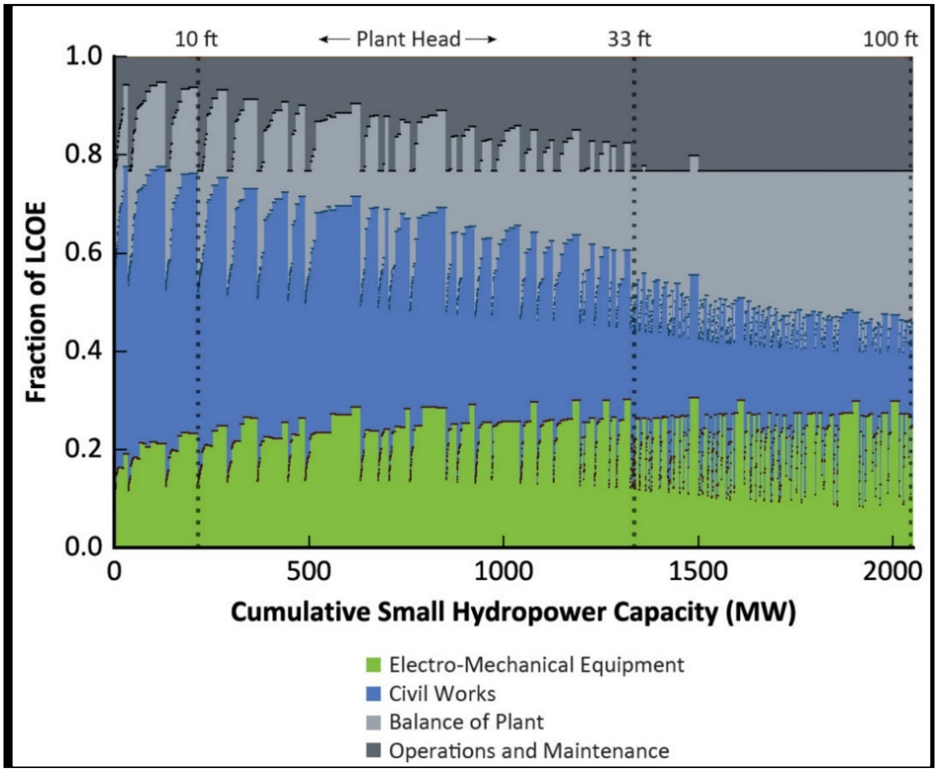


Figure 13. Fraction of LCOE and breakdown of the LCOE for NPDs between 100 MW and 2,000 MW

Projects are sorted from lowest to highest head.

There is significant variation between NPD projects, owing to differences in both plant capacity and design hydraulic head. For a given capacity, a turbine designed to a lower head must be physically larger and will rotate at lower speed, requiring a larger generator or the expense and efficiency losses associated with a speed increaser. Larger equipment sizes also exponentially increase the volume of the powerhouse necessary to house them. These kinds of differences are evident in Figure 13, as projects are shown in order of ascending head. Due to significant differences between sites and NPD locations, not all projects are created equal, and while low-head (<30 ft) projects have higher equipment LCOE (as seen in Figure 12), equipment represents a lower fraction of the overall project LCOE than it does for projects with higher heads. Civil works are the major driver of this outcome, and those costs increase dramatically for low-head projects at <30 ft. On average, the civil works LCOE contribution is $57/MWh (43% of total LCOE) for low-head projects versus $18/MWh (25% of LCOE) for those at heads >30 ft.

Cost reductions in the turbine and other powertrain equipment (e.g., through volumes of scale) are important, but to make low-head SHP cost-competitive through manufacturing alone will be difficult. This is due to the civil works contribution needed to repower NPDs, even though infrastructure is present. However, manufacturing advances that allow for fundamentally new designs with reduced civil works could help transform the SHP industry. In aggregate across the United States, the modeled value of small NPD equipment is greater than $3 billion. Equipment cost reductions along with civil works cost decreases are essential to help deploy systems that repower NPDs and thus help capture as much of the potential $3 billion equipment value as possible.

6 Composites and AM in Hydropower Applications

The development of new materials, advanced manufacturing technologies, and manufacturing processes provides exciting opportunities for the hydropower industry. As highlighted, the current hydropower technologies have utilized very established materials and manufacturing processes, such as casting and forging. There is significant potential with advanced technologies, but for adoption of new technologies and processes by the hydropower manufacturers, there is the continued need for analysis and research to determine best fits and suitability of advanced manufacturing technologies for hydropower components and systems.

Section 6.1 highlights two advanced technologies, composites and AM, and the general benefits of each technology. The potential hydropower applications are given in Section 6.2. A cost analysis of the representative 5-MW turbine hub is shown, where an AM hub (without design changes), is compared to the cast hub in Section 6.3.

6.1 Benefits of Composites and AM in Hydropower

Through the design of new, corrosion-resistant, lightweight components and integrated structures that utilize composite or AM components, system-level impacts (e.g., decreased transport costs, quicker assembly and installation) could result for the installation in SHP systems. This section looks at the benefits of composites and AM components.

6.1.1 Composites and Carbon Fiber Benefits

As the term composites covers many materials, focus here has been given mainly to carbon fiber (CF) and fiber reinforced polymers. CF is a material, normally manufactured in filaments, which has a high carbon content (e.g., greater than 92%) and is a high strength-to-weight ratio material (Das, Warren, and West 2016). Applications of CF currently include high performance automobiles, aircraft sections, wind turbine blades, and gas pressure vessels. Depending on location and sourcing of the precursors and raw materials, the manufactured cost can be $10–$25/kg for industrial grades of CF (Cook and Booth 2017). Figure 14 shows how multiple CF filaments, through precise automation and machinery, can be wound rotationally around symmetrical parts such as shafts, pipes, beams, and vessels/containers (Connova 2017).

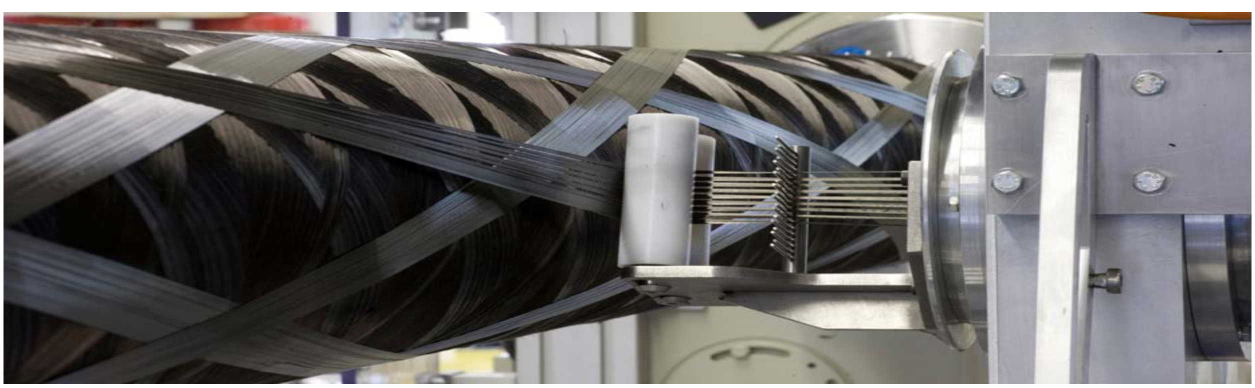


Figure 14. Rotary CF filament winding around a symetrical object (Connova AG 2017). Photo credit: Connova AG.

Fiber reinforced polymers (e.g., glass fiber and epoxy composites) are common in many industries such as wind turbine blade manufacturing (James and Goodrich 2013) and could provide benefits for hydropower components as well. CF and other composites can be engineered, for example, to be flexible, strong, and simultaneously lightweight, tough, durable, and long lasting (DOE AMO 2015, 2014). Composites such as CF, particularly for hydropower applications, give the potential for increased corrosion resistance compared to metals that would need corrosion protection against the environment (Das, Warren, and West 2016).

6.1.2 AM Benefits

The AM market is currently dominated by metals and polymers (over 90% of the produced parts globally) and has many variants in terms of the technologies [e.g., extrusion, powder bed, fused deposition material, selective laser melting (SLM), and metal laser sintering] (Müller and Karevska 2016). AM both in metals and polymers is now moving away from prototyping into commercially useable parts. AM gives incredible design flexibility in both metals and polymers. As shown in Figure 15, one-piece metal turboexpanders (left) can be produced or similar complex polymer shapes for a potential new runner (right).

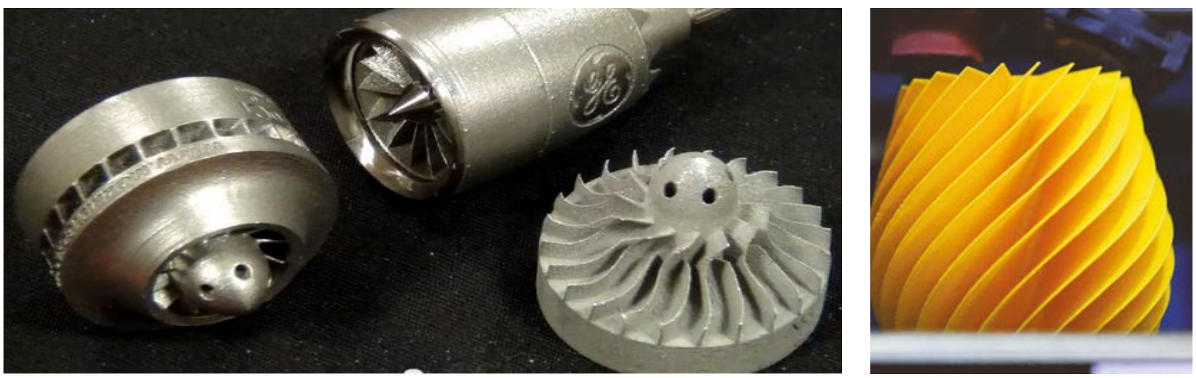


Figure 15. General Electric printed metal turbine representations [left (GE 2013)] and polymer printed part [right (Müller and Karevska 2016)].
Photo credit left: GE Global Research Center. Photo right: iStock 67120779.

AM in metal is also reaching maturity, whereby even structural members can be produced. As seen in Figure 16, the original steel structural member made up of seven individually welded components is re-designed and printed in steel, into a single integrated piece, and then optimized further, but can hold the same loads as the original member.

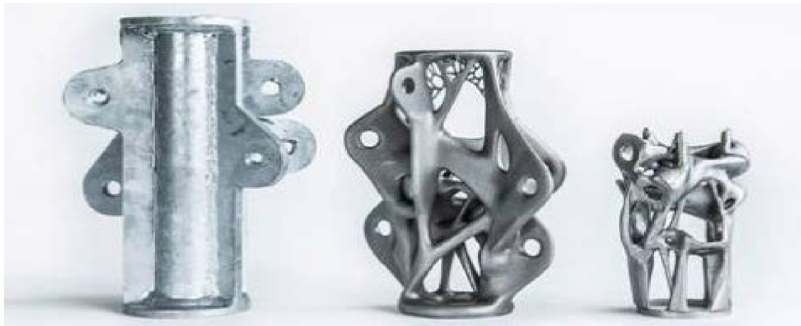


Figure 16. Arup steel structural member in original form (left) and AM (center and right) (Protocam 2017). Photo credit: Davidfotografie.

AM could be used alone or in conjunction with conventional established manufacturing technologies to build innovative hybrid structures such as for the hub, runner, or even penstock. A key limitation for metal and polymer parts is the size of the part that can be built based on the process used. However, advances in the Big Area Additive Manufacturing (Kunc 2017) and the next generation Wide High Additive Manufacturing (Alec 2016) polymer toolsets have addressed this limitation. The maximum build volume of the Big Area Additive Manufacturing toolset is approximately 60 ft x 60 ft x 60 ft (Post et al. 2017). Due to size limitations of metal AM parts (e.g., a maximum build volume of 500 mm x 280 mm x 365 mm) in today’s high-volume AM toolsets (SLM Solutions 2017), SHP systems such as NPDs, NSDs, and conduit systems could show immediate suitability for prime metal targets with current AM toolsets.

The use of AM for hydropower components could have several benefits including the potential to reduce costs in the long run (e.g., due to printing lightweight, integrated parts and then having system-level benefits such as decreased civil works to install the system). AM could also reduce transportation costs because of the reduced weight of 3D-printed parts (i.e., less fuel is used to transport the loads), and the printing of parts onsite could potentially allow little or no transport from manufacture to assembly. Due to the freedom offered through AM, changing the components could also improve plant performance (e.g., by having multi-material combinations printed together to reinforce certain areas and allow for mass customization of parts). A key area that this report will highlight is the use of AM for tooling replacement.

6.2 Applications of Composites and AM in Hydropower

Research is ongoing within the DOE WPTO portfolio and at other institutions to innovate and utilize the potential of advanced manufacturing technologies such as composites and AM toward the applications of hydropower to potentially decrease the installed CAPEX cost of systems, increase modularity in turbines and installations, lead to performance improvements, increase the deployment of hydropower technologies, and help meet the goals set out in the WPTO *Hydrovision* study (DOE 2016). By 2030 with the utilization of advanced technologies, DOE estimates that 3.6 GW of capacity could be installed in repowering NPDs (DOE 2016). A highlight of some key activities and areas where composites and AM are being researched and utilized in the hydropower is highlighted subsequently.

6.2.1 Composites

Significant research is ongoing, funded by the DOE WPTO to begin identifying the components that composites can be utilized for in hydropower systems. DOE WPTO has identified that while composites hold potential to decrease the weight of components and systems, and potentially overall project cost, composite materials for the hydropower industry have yet to gain acceptance as a viable, long-term solution. The research that DOE WPTO is funding is helping to de-risk the use of composites and manufacturing methods for SPH systems. A key reason for the investigation of composite materials is that composite materials have the potential to be significantly lighter and a reliable, economic alternative to current runner metal materials (Hipp 2017). Feasibility studies on 2-MW Francis turbines found that a composite turbine could be 50%–70% less weight than current steel versions (Whitehead and Albertani 2015).

Examples where WPTO-funded research is helping to improve the understanding and the use of composite components include the development of a composite Archimedes screw turbine and a composite runner (Straalsund 2017; Hipp 2017). The stress distribution on a low-head prototype composite screw can be seen in Figure 17.

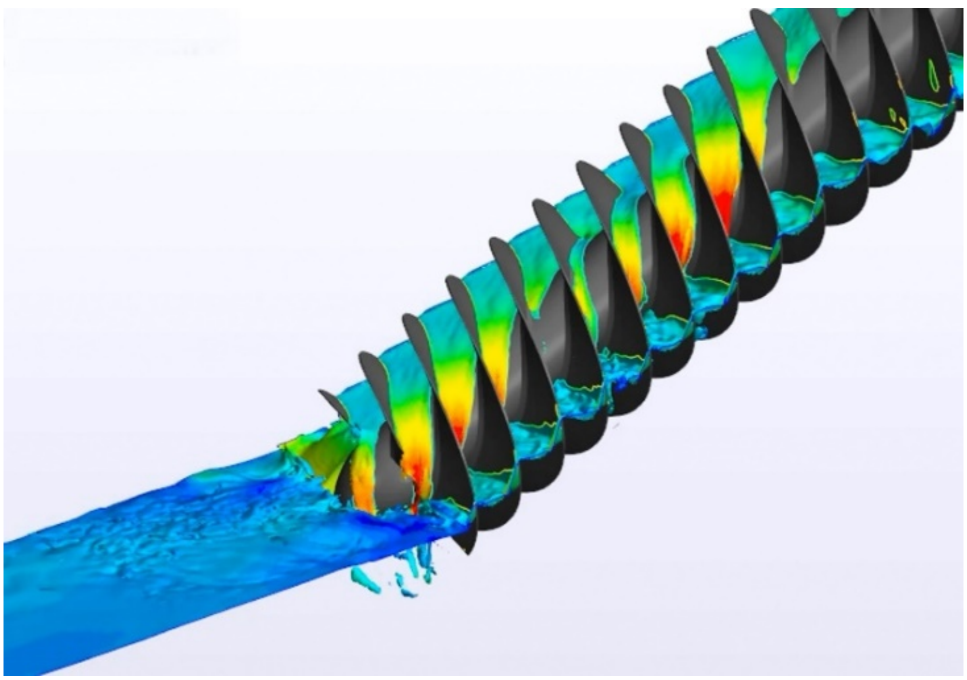


Figure 17. Stress distribution on a composite Archimedes screw turbine (Straalsund 2017)
Photo credit: Image courtesy of Pacific Northwest National Laboratory.

The left image in Figure 18 shows the current metal runner that could be redesigned with composites, and the right image shows the wire mesh of a composite blade that could be utilized instead.

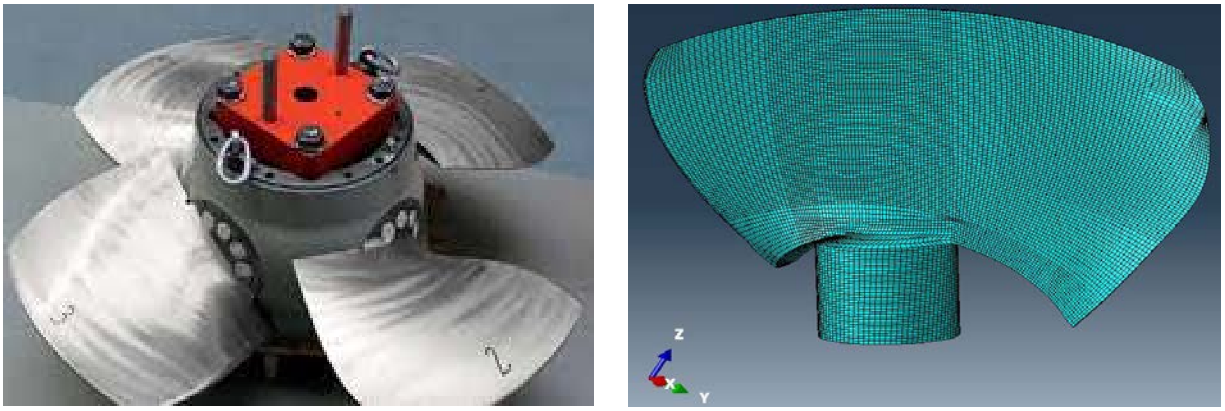


Figure 18. Original runner (left) and wire mesh of composite blade for new runner (Hipp 2017) Photo credit: Composite Technology Development (CTD).

Both the composite Archimedes screw turbine and the composite runner are looking to meet DOE WPTO goals of lowering costs of hydropower components and civil works (Straalsund 2017; Hipp 2017). The use of composites for the Archimedes screw and the runner is with the objective of developing more efficient, lighter (compared to the current steel parts), potentially environmentally friendly components and structures, which are then likely to have system-level impacts for SPH systems and existing low-head U.S. sites. System-level effects that can significantly affect the overall project CAPEX include decreased site installation and civil works, which, as shown earlier, can be up to 35% of the overall CAPEX for SHP projects.

Composites can become a viable option for runners, vanes, and secondary structures and screw turbines, as the composite materials tend to show excellent corrosion resistance, fatigue resistance, and resistance to cavitation compared to steel runners and components.

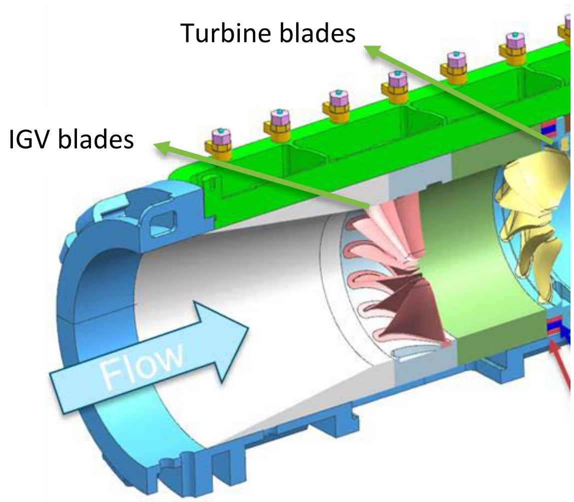
Polymer and composites use for hydropower components in the flow path (e.g., the runner and draft tube) are still early-stage research, though polymers and composites are already utilized for other areas in hydropower systems. The corrosion and cavitation resistance and ease of application of composites onto blades and runners for repairs make them a valuable alternative rather than replacing entire damaged blades (Belzona 2017). Composites in hydropower systems have also been found to be utilized for "environmentally friendly, self-lubricating bearings and wear pads," as a replacement and refurbishment option for a variety of turbine designs including repowering NPDs (CIP Components 2017).

Future, composite blades (e.g., with CF) and components for hydropower systems could effectively incorporate such corrosion mitigation through the composite and coatings applied, and thereby potentially avoid costly repair compared to the current metal turbine components. The current, metal turbines and components also have significant downtime for service and repairs, which leads to large decreases in generation revenue during the repairs.

6.2.2 Additive Manufacturing

The use of AM, for either metal or composite/polymer hydropower components, is an area of significant WPTO-funded research and is considered part of the advanced technologies that could help implement the DOE Hydrovision goals toward 2030 and 2050, particularly for SHP systems. While there is incredible potential for the use of AM components in hydropower (and for similar reason such as lightweight structures as in composites), the design freedom to print complex parts for commercial application still requires significant research. The DOE WPTO research into the use of AM for hydropower components again is to de-risk the use of AM and increase the deployment of SHP systems "to grow and modernize the U.S. hydropower fleet and promote U.S. leadership in hydropower" (Halal and Parundik 2017).

An example where WPTO-funded research is helping to improve the understanding and use of AM components in modular low-head turbines can be seen in Figure 19. In the left image in Figure 19, the fish-friendly design can be seen at the inlet guide vane (IGV) and the turbine section of the modular system, and in the right image shows test turbine blades produced via metal AM.



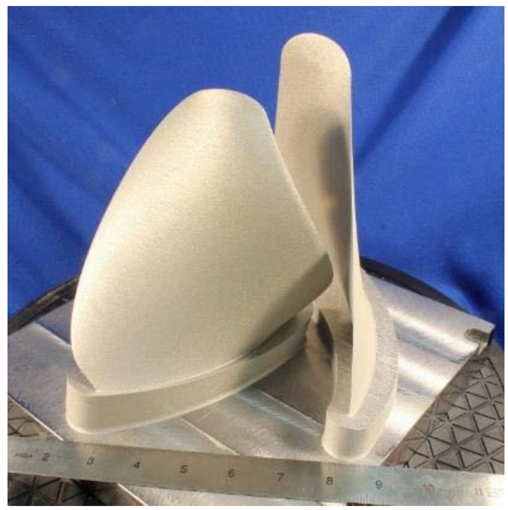


Figure 19. Design of modular section showing the IGV and turbine sections (left) and ½ scale turbine blades produced via metal AM (right) (Fontaine et al. 2017)
Photo credit: Arnold Fontaine/Penn State.

This project, which is developing a design for AM-manufactured IGV and turbine blades, is looking to design, develop, and print components for testing in the overall prototype design. Through the use of AM, the project is looking to develop low-cost, highly efficient designs that could become modular and decrease the cost of installation (Fontaine et al. 2017).

Another AM application suited for NPDs is the use of AM for turbine component optimization, undertaken as a collaboration between DOE and the power management company Eaton. The use of AM is looking to "help innovate hydro turbine technology to improve economics in small-scale hydropower applications and make renewable power more accessible to developers" (Halal and Parundik 2017). This 4-year project has been focused on turbine design, analysis, and optimization to establish component sizing for AM and viability at NPD sites.

A key area suitable for commercial hydropower application is the use of AM for tooling replacement. AM as highlighted can be used with metal and polymers, and a developing area for AM is the printing of incredibly complex sand casts for use with traditional metal casting. As highlighted, AM could be used to form hybrid processes where traditional manufacturing is combined with the design freedom AM can offer. This then allows for potentially decreased tooling and mold requirements. For example, ORNL collaborating with Emrgy Hydro found that 3D-printed sand casts could be made to then allow rapid testing and prototyping of variations in complex aluminum gearbox parts (Shoemaker 2017). A key benefit of the use of AM in hydropower is to hybridize the current manufacturing process and reduce cycle times of manufacture and innovation before commercially ready parts can make it to the market. As identified by Emrgy Hydro's CEO, in an ORNL news article, with AM "we're able to test and make adjustments quickly, which reduces our cost and lead time in designing and making components" (Shoemaker 2017). Figure 20 shows the final aluminum parts produced via the novel AM sand casting technique.

Figure 20. Aluminum gearbox parts produced using 3D-printed sand casts (Shoemaker 2017) Photo credit: Brittany Cramer/Oak Ridge National Laboratory, U.S. Dept. of Energy.

This novel application of printing sand casts with AM has also been utilized directly in commercial SPH applications. Figure 21 shows the sand cast mold made with Voxeljet technology (left) and the finished turbine runner (right) that was cast from the printed mold.

Figure 21. Sand cast made via AM [left] and the resulting runner [right, (Voxeljet AG 2015)] Photo credit: Voxeljet & Wolfensberger.

This runner was for a rural Ethiopian hospital, where the turbine failed, and it was found that replacing the defective turbine wheel would have been too costly for the hospital (Foundry Planet 2013; Chemets 2015). Had the conventional route been used, the production of the wheels would have been “an extremely cumbersome, labor-intensive, and expensive process because it requires the manual production of several sand core segments and complicated undercuts” (Foundry Planet 2013). The complicated sand cast mold was separated into two, the internal and external molds. It was possible to 3D print in one piece the entire internal geometry, which was finished in 5 hours and was found to be a tool-less and economical production of a complex mold (Foundry Planet 2013). Had conventional sand casting been used, several months may have been needed for the sand casts, and it was found that the AM sand cast mold was 75% cheaper than the conventional option (Voxeljet AG 2015). The exterior of the mold utilized the conventional molding technique because it was found that the economics of a hybrid process for a one-off were better than producing the internal and external molds in one 3D-printed mold (Foundry Planet 2013).

6.3 Cost Analysis of a Representative 3D-Printed Hub

NREL, in collaboration with ORNL, has developed a CEMAC AM modeling tool that can determine potential costs of AM components. The CEMAC AM models seek to utilize the global indices compiled across projects to understand the cost sensitivity for different manufacturing locations including Brazil, China, and the United States. This CEMAC AM tool was used to specifically explore the benefits and potential of manufacturing up to 50-m polymer wind blade molds with AM (Post et al. 2017). This report was published by ORNL and includes the CAPEX of today’s and potential future AM toolsets and improvements and shows that, under certain conditions, the costs of an AM mold could be comparable to current, traditionally manufactured wind blade molds (Post et al. 2017). As a potential indication of the application of polymer AM on the representative turbine, a cost analysis has been done using the CEMAC AM tool for the 5-MW turbine hub. Figure 22 shows the Kaplan-style turbine hub, as used in the manufacturing analysis earlier, and has four blade ports as part of the original casting. The sizes indicated are based on estimations and not a specific design. The hub was chosen to demonstrate the use of AM on large pieces; however, this does not consider the likely increase in volume of an Acrylonitrile Butadiene Styrene (ABS) hub due to the reduced mechanical properties of ABS compared to steel.

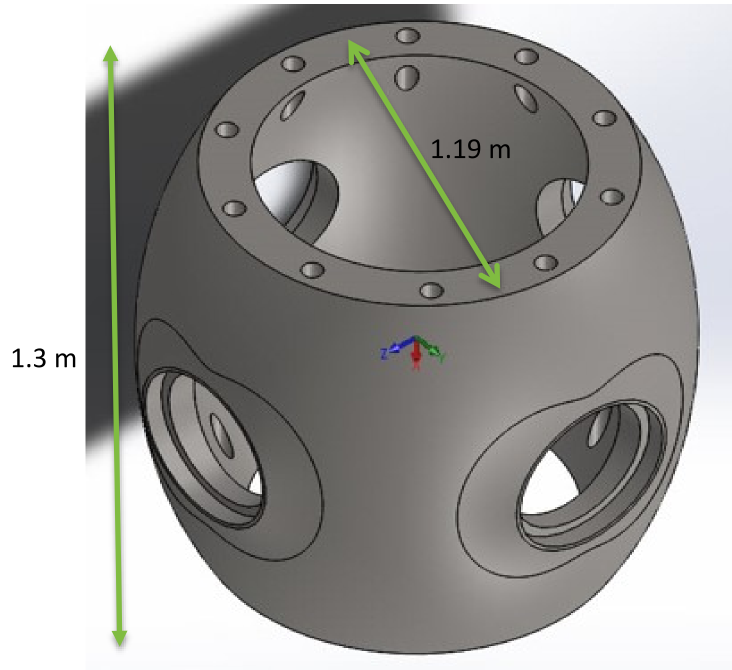


Figure 22. CAD of representative 5-MW hub used for manufacturing and AM analysis

The manufacturing analysis using DFMA had originally used complex sand casting and the associated moldings to produce the cast steel alloy hub. The hub was approximately 0.1 m in thickness. The DFMA analysis has shown if 10 cast steel hubs could be produced from the same molding in modular SHP systems, then the tooling investment per hub for the sand cast molds could be ~$6,600 each (i.e., ~$66,000 in total). If, as in most cases currently, 10 different hubs would be needed due to customization at each site, then ~$66,000 would be needed for each site, leading to a total of ~$660,000 of tooling investment just for the hubs.

Table 5 highlights key details used for the representative AM hub analysis. Importantly, the AM hub used the same volume as the steel cast hub. No design changes have been made to the AM hub. This is done only to show a potential cost for a component of similar size to the steel cast hub. ABS with chopped fiber was used, and the density of the composite is 1,190 kg/m^3 (Post et al. 2017). The current cost of the ABS composite material is $9.55/kg, and today's AM toolset available at ORNL is used for the analysis (Post et al. 2017). The deposition rate of the extruded polymer is approximately 36 kg/hr (~80 lb/hr) (Post et al. 2017). Future AM polymer toolsets could be of the order of 1,000 lb/hr (Alec 2016; Post et al. 2017). Today's AM toolset has a CAPEX of approximately $1.5 million (Post et al. 2017).

Table 5. Key Parameters Used for the AM Hub Compared to the Steel Cast Hub

	Cast Steel Alloy	Unit	AM Polymer Component	Unit
Volume of component	0.334	m3	0.334	m3
Finished mass	2,440	kg	398	kg
Density of component	7,500	kg/m3	1,190	kg/m3
Total internal and external surface area	8.221	m2	8.221	m2
Average thickness	0.1	m	0.1	m
Max thickness	0.125	m	0.125	m

For a similar comparison between the AM hub and the cast steel hub, 10 AM-printed hubs were modeled. The depreciation for the AM toolset is over 7 years, and the yearly amortized cost of the tool is split over the number of parts printed per year (i.e., 10 AM hubs). At a printing speed or deposition rate of 36 kg/hr, a 398 kg AM hub could take approximately 11 hours to print. This does not include the design time for creating the computer models needed to print the hub, the setup time for the tool, or the processing of the final part if needed. The maximum build volume of the AM toolset is approximately 60 ft x 60 ft x 60 ft (Post et al. 2017), and due to this, the AM hub can be printed in one piece without sections.

It is assumed that based on a 40-hour regular work week for a manufacturing facility printing the AM hubs, approximately 3.6 hubs could be printed per week. This then results in the 10 AM hubs taking approximately 3 weeks to be printed. Clearly an AM toolset that is used for 3 weeks in a year is heavily under-utilized. For full utilization of the AM toolset (i.e., where it is used as much as possible), it is estimated that 188 AM hubs could be printed per year, based on a 52-week working year and each week being a standard 40-hour work week. Due to the large CAPEX needed for the AM toolset, the ideal is to amortize the cost of the AM toolset as quickly as possible over the most number of parts per year.

The CEMAC AM model accounts for each step from design to processing of the AM part and includes factors such as labor, energy, and equipment at each step to determine the manufactured cost. Table 6 summarizes the comparison between AM-printed hubs and cast steel hubs for a production volume of 10 hubs (under-utilized AM toolset) and 188 hubs (full-utilization of the AM toolset).

Table 6. Comparison of AM Hubs and Cast Hubs for Production Volumes of 10 and 188 hubs/yr

	Investment cost	Investment cost
Investment cost	$1.5 million for polymer toolset	$66,000 for sand-cast moldings
Hub material	ABS polymer	Cast steel
Cost of two hubs *(production volume of 10 hubs per year)*	~$87,000 for two hubs	~$25,000 for two hubs
Cost of two hubs *(production volume of 188 hubs per year)*	~$19,000 for two hubs	~$125,000 for two hubs

As seen, when 10 hubs are produced per year, the AM-manufactured cost could be approximately $87,000 for two hubs, compared to approximately $25,000 for two steel cast hubs. There is significant difference in the costs, as the AM toolset is not being utilized for the majority of the year. When the number of printed parts is increased, the cost difference between the AM and cast steel hubs is much smaller. When 188 hubs are printed (i.e., the AM toolset is fully utilized), the manufactured cost is approximately $19,000 for two AM hubs, compared to approximately $125,000 for two steel cast hubs. As shown, large AM parts are sensitive to the number of parts produced per year.

Considering that today's AM materials (due to the palletization or energy intense processing) can be expensive, AM parts are sensitive also to material cost per kilogram. As mentioned, the cost of $9.55/kg has been used for the ABS polymer, though indications from ORNL highlight that this material cost could be decreased significantly to $4.33/kg within the next few years and lower in the mid-term (e.g., 5 years) (Post et al. 2017). When $4.33/kg is used, and 188 hubs are printed, the manufactured hub cost for two hubs drops to approximately $155,000. This is very similar in cost compared to the approximate $125,000 for two steel cast hubs when 188 are cast. Comparing the steel hub and the AM hub, the cost is likely to increase in the AM case, particularly at the low volumes associated (e.g., 10 hubs/yr). When the volume of manufacturing is increased to fully utilize the AM toolset, the cost could be comparative to the current costs. This is without the system impacts (e.g., decreased transportation costs of shipping polymer hubs instead of steel hubs).

The use of the ABS polymer for the hub will have reduced mechanical and strength properties compared to the steel, and as such, the volume and amount of ABS polymer is likely to increase significantly based on the design changes. When the volume of the AM hub is doubled (i.e., to 0.668 m^3) due to increasing hub thickness, the AM hub mass would be approximately 796 kg. When 10 of these increased volume hubs are printed, the manufactured cost for two hubs is approximately $95,000 instead of $87,000. Effectively by doubling the mass of AM material printed, the increase in cost for two hubs is only $9,000. For low production volumes, the major cost driver for the printed part cost is the CAPEX of the AM toolset and the number of parts printed. This analysis has assumed that only hubs would be printed from the AM toolset, and it is highly unlikely any company would buy a large AM polymer toolset only for one specific component. It is realistic that a company investing in the AM toolset would utilize the AM toolset to produce many different types of components at significant quantities to ensure the toolset is well-utilized and to make the investment worthwhile.

It is worth highlighting that large AM hubs may not necessarily be the best choice for low volumes due to the straightforward nature of the component. Other low simple volume parts (e.g., the nose cone) may also not be suitable for direct printing. There is potential once AM is used to produce complex parts and AM has significant potential for printing molds to then produce CF components, rapid prototyping of scale-models for testing, and decreasing the innovation and cycle time to get products to market.

It is important to highlight that the use and power of AM stems from changing designs for components and integrated structures rather than simply printing equivalent parts (e.g., AM hubs without design changes), as current manufacturing practices like casting have been proven successfully for over the last century. The use of topology optimization and lattice structures are ways that AM offers completely new designs not possible with conventional manufacturing processes. Topology optimization refers to the movement and optimization of material dependent upon the design conditions the component needs to meet. Traditional manufacturing of components (e.g., CNC machining) cannot place material in preferential locations. The component meets the design and life conditions but typically has more material than needed. This is illustrated in Figure 23, where the original Sentinel satellite antenna bracket through topology optimization is completely altered to produce an AM design suited to the conditions but is over 40% lighter than the original part (EOS GmbH 2017).

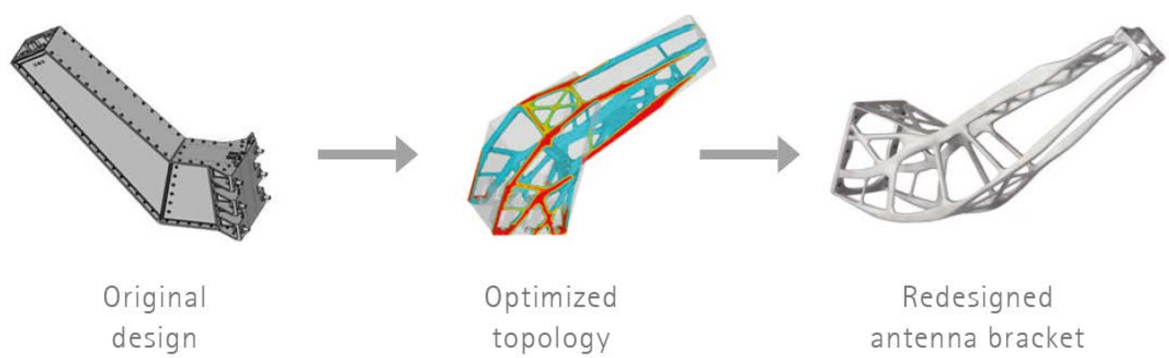


Figure 23. Topology optimization for a Sentinel satellite antenna bracket, from the original (left) to the AM (right) (Jensen 2017). Photo credit: EOS GmbH.

Another important way AM design of components can be used to increase the strength of components while simultaneously decreasing the weight is through lattice structures. This is a critical advantage over traditional manufacturing. Utilizing design changes that are possible with AM could incorporate biomimicry, improved aerodynamics, and increased strength or corrosion resistant properties, depending on the custom metal alloy or polymer powder used.

As can be seen in Figure 24, the internal lattice structures possible with metals such as titanium could allow for completely new hydropower components. Aluminum lattice structures can also easily be produced using the current AM metal processes and would be a more cost-effective option than titanium. To ensure the same material strength, rigidity, and durability, these new structures could be made in metal, but as highlighted, the AM build volume for metal is more suited for SHP components, such as the runner and IGVs. Polymer and composite AM materials, if suitable for hydropower, can be printed at much larger size than current metal applications.

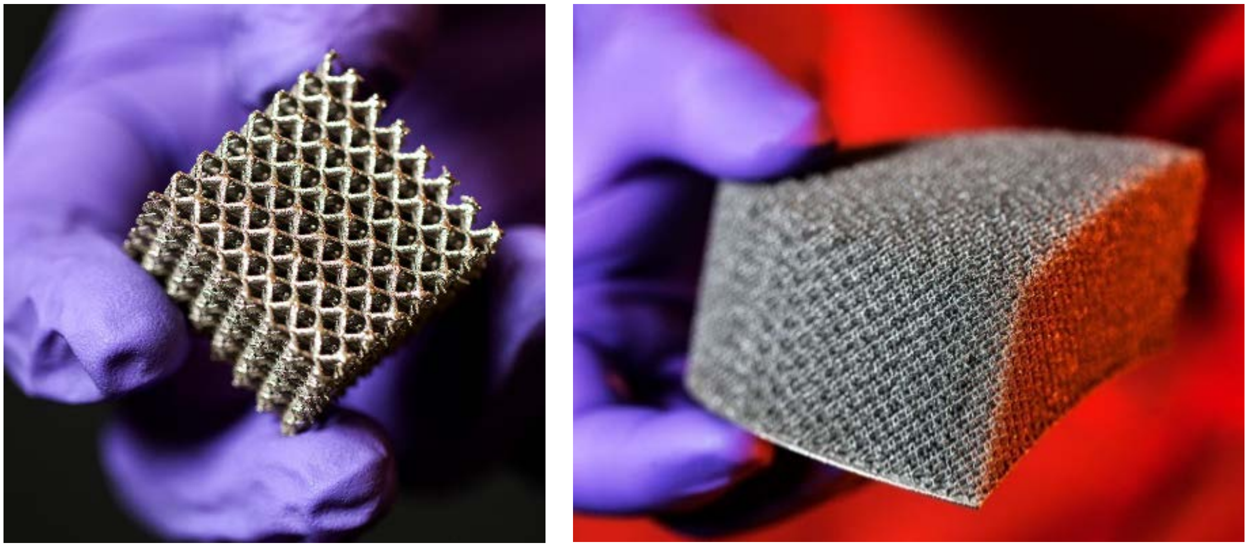


Figure 24. AM titanium lattice structures (LLNL 2014)
Photos credit: George Kitrinos/Lawrence Livermore National Laboratory.

Both topology optimization and lattice structures will be needed in future studies to determine the suitability of polymers and metals, to re-design components, and to benefit from AM.

7 Opportunities

Although new hydropower construction has declined domestically in recent years, opportunities exist in the domestic SHP industry in the mid- to longer-term, especially in powering NPDs and developing NSDs. However, the relatively small manufacturing volumes, coupled with a lack of strong demand for SHP in the United States, may domestically limit manufacturing investments and then could contribute to higher capital costs for SHP systems. Existing U.S. SHP manufacturers, however, could utilize opportunities to export to foreign markets to meet potential demand. As highlighted, Chile, China, Columbia, India, and Japan, have an estimated 71,795 MW of technical potential that could be serviced with SHP installations (UNIDO 2016a). Utilization of existing manufacturing capacity and expertise, along with economies of scale benefits, could result in increased global competitiveness through lower investment requirements and component costs, which could lead to increased U.S. strength in the export of SHP systems and components.

Although substantial export opportunities exist, Brazil and China could emerge as potential low-cost suppliers and competitors to the United States to supply these regions. Increasing U.S. turbine manufacturing volumes (e.g., through more modular turbine designs), advanced manufacturing technologies, and new materials that could reduce cost and enable new system designs will be important to maximizing U.S. hydropower manufacturing in these markets. As highlighted, the export of parts (HTS 8410.90) for U.S. hydropower suppliers and manufacturers in 2016 had a value of $46 million (USITC 2017). Manufacturing of certain components (e.g., turbines) could be strategically important along the hydropower value chain.

Technology advances such as modular turbine designs, standardized units for conduit systems, precast systems, and improved powertrain technologies could help reduce costs, particularly for manufacturing a small number of units. An additional cost reduction opportunity identified by DOE and the national laboratories is the possibility of using emerging advanced manufacturing technologies, such as large-scale AM with novel low-cost materials for the largest capital items such as civil works (DOE 2016). Additionally, assembly of composite hydropower turbines could reduce labor costs and lead to weight reduction of the final unit (Whitehead and Albertani 2015). DOE is also exploring modular hydropower designs, which would integrate standard independently produced components, validated to meet multiple specifications (DOE 2016). Using modules in product design simplifies manufacturing activities such as inspection, testing, assembly, and purchasing and may increase economies of scale to lower total system cost.

Discussions with SHP manufacturers have highlighted an opportunity for DOE to be involved with the workforce training and retention of skilled labor for the SHP industry. An issue or weakness present for the SHP manufacturing sector is an aging workforce skilled in SHP manufacturing and retaining the younger manufacturing workers. Workforce training and retention are key for the United States to maintain strength in the domestic production of SHP systems, and offices at DOE such as the Water Energy Technology Office and the Advanced Manufacturing Office could be well placed to help support workforce training in new SHP developments.

Strengthening the competitiveness of the domestic medium and large hydropower supply chains and the component suppliers could then be leveraged for SHP. Incentives or subsidies/tax rebate from local government entities or the federal government, in partnerships with DOE, could be used to offset the capital of large hydropower equipment and help manufacturers stay or enter as new players into the SHP market.

There are significant opportunities for the use of advanced manufacturing technologies such as composites and AM for hydropower components when design changes are made to hydropower systems. By taking advantage of the corrosion resistance, light-weighting and structural benefits, composites, and AM could help significantly alter hydropower structures. Changing the hydropower components itself may not decrease the LCOE of hydropower systems immediately but more likely there would be overall system changes such as decreased civil works to install lighter SHP systems. Composite materials can become a viable option for runners, vanes, and secondary structures (Hipp 2017). AM is being investigated for the IGV and rotor blades for SHP modular turbines (Fontaine et al. 2017). AM can be very significant in hybridizing the manufacturing processes used for today's hydropower components and for printing the tooling and molds.

8 Conclusions

The United States has considerable domestic hydropower and SHP manufacturing clusters, skilled workforce, and domestic market potential, which could be used to reach significant untapped resources such as NPDs and low-head/in-stream sites. Within the United States, the NPDs that could be repowered by 2050 could be nearly 5 GW (DOE 2016), though recent slowdown in NPDs being deployed in the United States suggests manufacturing volumes could be increased by manufacturers dependent on the demand from projects ready to use the SHP equipment and components. Stable higher-volume manufacturing is important, and as a result, both domestic and foreign markets are important to the U.S. supply chain. Without stable orders for SHP systems (i.e., fully bid and funded domestic projects), manufacturers of SHP systems are unlikely to make turbines without projects to use them. It is important to identify in the future the amount of capacity that is available for U.S. medium and large SHP manufacturers that could be leveraged for SHPs dependent on demand changes for either exported or domestically used SHP systems.

From 2005 to 2015, the United States exported SHP turbines with a value of approximately $35 million, which is about half the 2016 export value of hydraulic turbines of all sizes (HTS 8410) at $68 million (USITC 2017). The SHP turbine manufacturing sector is important and could increase in value for the United States, as there are substantial export opportunities existing in North America, Central and South America, Asia, and Australia. The global markets may represent a larger market potential than the domestic U.S. market due to the current low level of competitiveness of SHP with PV and wind. China and Brazil (as potentially lower-cost competitors) are notable threats to U.S. domestic manufacturing of SHP systems. As highlighted in Figure 6, for the hydropower turbine imports into the United States, China has in the last 5 years increased and consolidated its imports into the United States. The drivers of the cost of manufacturing SHP in different countries could be investigated in future cost comparisons to identify opportunities to leverage U.S. strengths for meeting international demand.

In this project, a representative 2x5 MW turbine system was analyzed. A publicly available cost estimate for the manufactured costs of a representative system was found to be valuable, especially for the SHP manufacturers and developers, who did not have such a reference before. The representative system has helped create a baseline for reference by the SHP industry. With most SHP systems being custom turbines, the industry did not have an available system for understanding the aspects of a more modular turbine design where the system is produced for multiple sites. Further development will be needed to (1) include more of the manufactured cost of other key parts of a SHP system, such as the generator and the penstock and (2) test and refine the assumptions. Systems could be added for further bottom-up analysis (e.g., standard conduit systems or precast solutions). Increasing turbine manufacturing volumes could be important to U.S. SHP system innovation and exports. The use of more standard, modular turbines at each site (rather than the mostly custom turbines used today), and the increased volume of production could allow some of the turbine cost to benefit from economies of scale.

Both AM and composites have potential value for hydropower systems and could be significantly beneficial if future costs can be decreased. However, these emerging advanced manufacturing technologies have not yet been comprehensively assessed or demonstrated for use in commercial hydropower components, nor is it understood what size of parts could be printed using today's AM toolsets or materials. With AM advancing for metals and polymers, hydropower components could benefit from research into whether changing the materials used (e.g., metals, polymers, and CF) and the process of manufacturing (e.g., AM) could benefit the overall design and cost and provide system-level impacts such as reduced civil works requirements.

AM has a high potential to reduce the time needed to manufacture complex components, either through direct part printing or hybridization of the manufacturing process of today's parts. This is shown by both the AM hub analysis (e.g., printing an AM hub in approximately 11 hours) and for printing the AM sand cast mold in approximately 5 hours (Foundry Planet 2013). The AM analysis in this report has shown that the AM-manufactured cost is strongly sensitive to the AM toolset CAPEX, and to a lesser degree, the material cost. With rapid development in AM for metals and polymers, it is very likely that CAPEX and material costs will fall sharply in the next 5 years (Post et al. 2017) and thereby decrease component costs.

This project has successfully identified some of the manufacturing opportunities in the U.S. hydropower supply chain, key U.S. competitive advantages, and some of the qualitative and quantitative factors for manufacturing location decisions in SHP. Decreased CAPEX on SHP turbine and power train equipment, alongside decreased civil works and installation will be needed in the United States to help capitalize on the nearly $3 billion domestic market for SHP equipment, for example, when applied to adding approximately 2.0-4.8 GW of new installed SHP capacity for repowering NPDs.

9 Recommendations for Additional Research

1. Data gaps have been identified that could be beneficial for the SHP industry if further information can be gathered and analyzed. Typically, SHP systems and components are not well captured in the US ITC trade codes. It is recommended that further analysis and data collection is conducted to collate data on tradeflows, production capacities, and manufacturing facilities in the United States that can produce SHP components and systems.
2. The initial manufacturing analysis of the representative 2x5 MW system has determined cost benefit of modular turbines, compared to one-off designs (e.g., the amortization of tooling investment over multiple units). The question of whether lower cost, and potentially lower performance, modular turbines can offer competitive long-term benefit (e.g., simpler installation and lower LCOE) when compared to using more expensive, one-off custom SHP turbines is still outstanding. This is a key next step to determine not only the cost but the performance of modular SHP turbines and systems and continue to refine the cost models.
3. A representative system for the manufacturing analysis was created, but this is an initial baseline, and much more depth is needed if understanding of these SHP systems is desired. The future analysis of representative systems could be extended to NSDs, conduit systems, and the other equipment in a NPD system (e.g., generators and wicket gates). The recommendation for further detailed component and system-level cost analysis for modular representative systems would allow the LCOE and performance of modular systems to be compared to custom turbine systems.
4. It is important for DOE WPTO to continue to develop understanding of the supply chain of SHP components and raw materials. This is because it can help direct R&D efforts and develop understanding where along the manufacturing value chain benefits from federal funding to then increase U.S. competitiveness.

   Much deeper supply chain analysis and analysis of the manufacturing location factors and decisions could be undertaken and could include policy and financial incentive/support and impacts. This extension of the supply chain activities, through further R&D, could then help identify parts of the hydropower supply chain for further focus and where there is added economic value in investing in that area. Further supply chain data could be collected in five broad categories: supply and demand, price and value, supply chain flow, manufacturing, and other regional influences.
5. As part of future manufacturing analysis, the manufactured cost of the SHP representative turbines could be extended for example by determining the minimum sustainable price for turbine equipment, which includes the cost of energy needed to produce the equipment. As part of further analysis, a comparison for the costs of producing the representative turbines in different countries could be done, for example, by the Brazil, China, and the United States. This should be undertaken to help provide further insight into areas for increased U.S. competitiveness.
6. This initial research into the potential opportunities for advanced manufacturing technologies in SHP (e.g., AM used for printing the complex sand cast molds or changing

the innovation cycle times for production parts) could help the DOE WPTO in identifying and understanding potential benefits and appropriate R&D opportunities for further developments. For AM components to be suited for commercial applications in SHP, investigation is needed into the potential costs, design changes needed, and the prototyping of components. Future work can undertake much more detailed investigation, where new components are selected and could be redesigned either in metals of polymers or to utilize the power of composites and AM. Additional supply chain and impact analysis could be undertaken to investigate how AM could potentially impact capital costs, innovation cycle time, combined AM, and traditional manufacturing, mass customization of production designs, and tooling impacts. Such analysis would highlight important cost drivers and research opportunities.

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Appendix A. Representative System and Details

This appendix highlights the steps taken to determine and select the most suitable components for detailed manufacturing analysis and the bill of materials for the representative 2x5 MW turbine system.

Figure A-1 shows the down selection of the components, which then led to the DFMA analysis.

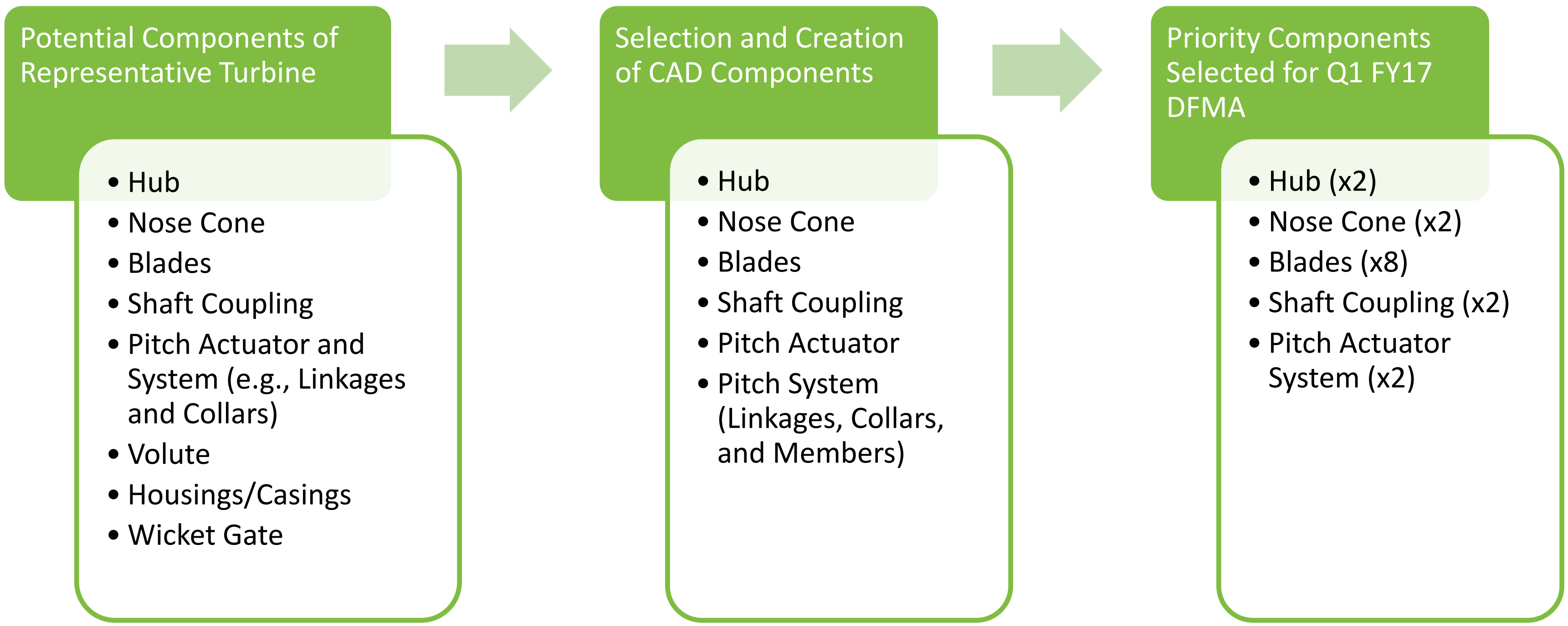

Figure A-1. Down selection of the potential components for more detailed manufacturing analysis

Table 7 shows the number of parts in a representative system (middle column). Each representative system is made up of 2x5 MW Kaplan-style turbines and is used for NPD application. With the life volume produced (i.e. 10 turbines), five representative systems can be manufactured.

Table 7. Bill of Materials for the Component Types and the Manufacturing Volumes Used for DFMA Analysis

Number	Component	Number in Single Kaplan Unit	Number in Representative System	Life Volume Produced
1.00	**Hub**	1	2	10
2.00	**Blade**	4	8	40
3.00	**Nose Cone**	1	2	10
4.00	**Shaft Coupling**	1	2	10
4.01	Top Flange	1	2	10
4.02	Tube	1	2	10
4.03	Bottom Flange	1	2	10
5.00	**Pitch System**	1	2	10
5.01	Pitch Member	4	8	40
5.02	Pitch Collar	4	8	40
5.03	Pitch Shaft	1	2	10
5.04	Pitch Linkage	4	8	40