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## **Technological Cost-Reduction Pathways for Axial-Flow Turbines in the Marine Hydrokinetic Environment**

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## **Abstract**

This report considers and prioritizes potential technical cost-reduction pathways for axial-flow turbines designed for tidal, river, and ocean current resources. This report focuses on technical research and development cost-reduction pathways related to the device technology rather than environmental monitoring or permitting opportunities. Three sources of information were utilized to understand current cost drivers and develop a list of potential cost-reduction pathways: a literature review of technical work related to axial-flow turbines, the U.S. Department of Energy Reference Model effort, and informal webinars and other targeted interactions with industry developers. Data from these various information sources were aggregated and prioritized with respect to potential impact on the lifetime levelized cost of energy. The four most promising cost-reduction pathways include structural design optimization; improved deployment, maintenance, and recovery; system simplicity and reliability; and array optimization.

## **Acknowledgements**

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# Executive Summary

## Purpose

Under the direction of the U.S. Department of Energy (DOE), Sandia National Laboratories has produced this whitepaper to identify the most promising technological research and development cost-reduction pathways for lowering the levelized cost of electricity (LCOE) for axial-flow tidal turbines in order to accelerate development of the renewable marine hydrokinetic (MHK) energy resource in the United States. For some well-defined issues, recommendations for specific research programs can be made. In the case where an issue is not well defined, the recommendations outline the problem as clearly as possible and the authors suggest promising avenues for investigation. No single entity, including DOE, is likely or is expected to address all of these paths. However, particular paths are likely to align with the diverse strategic goals of individual companies, institutions, and government agencies. It is hoped that these recommendations can be productively pursued by collectively employing the strategic goals of the community at large.

## Issue

In recent years, the nascent marine hydrokinetic industry has seen tremendous interest and progress in device development and deployments, including axial-flow turbines; however, there is still significant improvement needed to make axial-flow turbines cost-competitive with other forms of power generation. Technological advancements are needed to lower the lifetime LCOE for large-scale deployments of axial-flow turbines so that this technology can effectively compete in the marketplace.

## Approach

This whitepaper includes information from three main sources:

- Literature review
- DOE Reference Model effort
- Industry webinars and questionnaire feedback

The information from these sources was aggregated and categorized so that cost-reduction pathways were of similar scope. The cost-reduction pathways were prioritized based on:

- Impact on LCOE (most significant factor)
- Potential for progress in this technology area (addresses technology maturity)
- Potential for success in the 2030 timeframe (significant improvements will not take 20+ years)
- Confidence in success (experience from other industries and new technology availability)

For the purposes of this analysis, relatively large deployments (approximately 100 devices or more) and a target timeframe of the year 2030 were assumed. While it is recognized that environmental barriers are significant to developers today,<sup>1</sup> this report focuses on cost-reduction pathways related to the device technology research and development rather than pathways related to environmental monitoring or permitting.

## Results

The cost-reduction pathways were separated into three tiers, with the first two tiers listed below.

### ***Most promising cost-reduction pathways***

- Structural Design Optimization
- System Simplicity and Reliability
- Improved Deployment, Maintenance, and Recovery
- Array Optimization

### ***Second tier cost-reduction pathways***

- Improved Power Take Off
- Reduce Grid Connection Costs and Increase Grid Connection Component Reliability
- Advanced Controls
- Materials and Coatings Utilization and Development
- Design for Manufacturing
- Common Components

# Motivation and Background

## Purpose

The purpose of this whitepaper is to utilize existing information regarding axial-flow turbines for the marine hydrokinetic industry to identify the most promising technological cost-reduction pathways leading to a lower LCOE. By identifying these cost-reduction pathways for axial-flow turbines, greater and more economical opportunities are made available for converting water flow energy into a renewable source of electricity. These cost-reduction pathways will help move water flow energy conversion from a relatively immature renewable energy source to a more developed form, in line with wind and solar.

For some well-defined issues, recommendations for specific research programs can be made. In the case where an issue is not well defined, the recommendations outline the problem as clearly as possible and the authors suggest promising avenues for investigation. No single entity, including DOE, is likely or is expected to address all of these paths. However, particular paths are likely to align with the diverse strategic goals of individual companies, institutions, and government agencies. It is hoped that these recommendations can be productively pursued by collectively employing the strategic goals of the community at large.

For the purposes of this analysis, utility-scale deployments (approximately 100 devices or more) and a target timeframe of the year 2030 are assumed. These assumptions tend to diminish the importance of product development costs and siting issues in favor of technological improvements that scale with the size of an array deployment.

## Terms and Definitions

### ***Annual Energy Production (AEP)***

The net annual energy produced by a device. By definition, this value captures the effects of availability and capacity factor.

### ***Capital Expenditures (CAPEX)***

Those investments in physical property, plant, and equipment – all fixed assets.

### ***Commercial Off the Shelf (COTS) components***

Commercially available components are frequently used by the MHK industry. These components were designed for another industry but meet or exceed an immediate MHK design specification.

### ***Cost Driver***

A cost driver is a relatively large contributor to the LCOE. A device component cost that constitutes 20% of the LCOE might be considered a cost driver. A component that constitutes 2% of the LCOE would not.

### ***Cost-Reduction Pathways***

These are proposed directions for research, development, investment, and/or policy that will have an impact toward reducing the LCOE of a technology.

### ***Levelized Cost of Electricity (LCOE)***

This is the price-rate at which electricity must be produced (cents per kilowatt-hour) for an electricity-generating venture to break even over its lifetime. In short, it is an economic value to compare and contrast various electricity producing projects per given resource.

### ***Marine Hydrokinetic (MHK) Technologies***

MHK technologies convert wave motion, free-flowing ocean, tidal, and river currents, and marine temperature changes into energy.

### ***Operational and Maintenance Expenditures (OPEX)***

Those investments involved in the day-to-day operation and maintenance of an electricity generating venture – the ongoing costs.

### ***Power Take Off (PTO)***

The power take off system converts the wave motion into electrical energy. The drivetrain first converts the wave motion to mechanical energy, which is then transformed to electrical energy by a generator. For axial flow turbines, the flow of fluid propels a turbine which is coupled to a generator.

### ***Technology Readiness Level (TRL)***

Measure of maturity of technologies: <sup>2</sup>

- TRL 1 – 3: Innovation and Basic Technology Research – Characteristic proof of concept
- TRL 4: Scale Model Validation - Basic components are integrated to validate design predictions.
- TRL 5 – 6: System Model Demonstration - Prototype in a relevant environment and at a scale relevant to full scale.
- TRL 7 – 8: Integration of Technology into Commercial Type System - Actual system completed and qualified through test and demonstration in an open water environment. Testing includes extreme conditions.
- TRL 9: Technology and System Ready for Full Commercial Deployment

## **Sources of Information**

Three main sources of information were used for the determination of cost-reduction pathways:

- Research and academic literature regarding axial-flow turbine technologies and their energy resources
- The DOE Reference Model effort <sup>1</sup>
- Discussions and questionnaire feedback from companies involved in the development and deployment of axial-flow turbines

The three sources are described below.

### ***Source of Information – Literature Survey***

A literature survey was performed to investigate research advances presently being performed, both nationally and internationally. The results point to current gaps in research that are not addressing present, or future, needs of the MHK industry. While industry hurdles may be alluded to in individual papers, the literature survey was used to broadly investigate those issues discussed in the industry webinars and spreadsheets and to then aid in determining those cost-reduction pathways that would have the most significant impact on reducing LCOE and the most success if pursued. Throughout this whitepaper, literature citations are placed in support of industry and SNL expert assertions.

## ***Source of Information - Reference Model Effort***

Through work performed primarily by its national laboratories, DOE is analyzing several MHK technology reference models – representative MHK device types – for the purposes of:

- Projecting cost of electricity with respect to a category of energy resource (e.g., tidal energy) and device type (e.g., axial-flow tidal turbine, cross-flow tidal turbines)
- Comparing and assessing respective innovations and technology development
- Determining and then suggesting improvements for both reliability and efficiency of each technology
- Evaluating environmental impacts and permitting costs

In total, four different reference models device types are under development. The first reference model is a dual-rotor axial-flow tidal turbine and the second is a dual-counter-rotating cross-flow turbine on a floating river platform.<sup>1</sup> The axial-flow model assumes a pile foundation and this design was analyzed for power performance and cost in a generic tidal resource based on physical and environmental data from the Tacoma Narrows region of the Puget Sound. More details regarding the Reference Model effort are provided in Appendix A.

While reference model efforts have focused primarily on the present LCOE rather than future cost-reductions, some cost driver and cost-reduction pathway information from the axial-flow reference model have contributed to this report. The cross-flow reference model is not included further in this report due to its technology device type, but the effort resulted in similar cost-reduction pathways as did the axial-flow reference model.

## ***Source of Information - Aggregated Information from Industry***

Over the course of approximately one week, three separate webinars were held with individual companies whose primary mission is the development of axial-flow turbines for converting underwater currents into electricity. The companies were:

- Dehlsen Associates – Ecomerit Technologies, LLC.
- Free Flow Power Corporation
- Verdant Power Inc.

The webinars were venues for information exchange in which companies shared information related to their cost-reduction pathways. It was important to address the various assumptions made during their determination of the device LCOE. Additionally, specific cost-reduction pathways which may be easily investigated due to little effort or resource requirements and more substantial cost-reduction pathways which are more difficult in terms of resource allocation were also discussed. The framework for the information exchange can be found in Appendix B.

In addition, each company received a cost-reduction spreadsheet that encouraged responses that provided quantitative insight into development and maintenance costs. This report gives emphasis to information acquired from the industry webinars.

# Overview of the Resource and Device Type Technology

## Resource Overview

The rise and fall of the sea level that induces tidal currents is due to the gravitational pull of the Moon on Earth's oceans. These currents, or tidal flows, are often magnified by oceanic features such as a narrowing of a strait or the shallowing of the continental shelf. Such magnified tidal flows create significant opportunities for renewable, emission-free electricity production by means of tidal turbines (also known as tidal stream turbines). An axial-flow turbine utilizes rotors, which rotate around an axis oriented in the same direction as the moving water, to capture the energy in tidal channel – the process is analogous to the way in which horizontal-axis wind turbines operate in air. An example of such a turbine is Verdant Power's Free Flow Kinetic Hydropower System shown in Figure 1.



Figure 1: Verdant Power's Free Flow Kinetic Hydropower System, an axial-flow tidal turbine, is lowered into the East River, New York. Photo credit: Verdant Power, Inc.

Several areas of high-mean tidal flow rates exist within the territorial waters of the United States. These high flow rate areas provide great potential for large tidal flow electricity production. An assessment of the coastal waterways of the United States was performed by the Georgia Tech Research Corporation.<sup>3</sup> Some of these high flow rate areas have been identified below with their corresponding available power, if available in the report:

- Northern Maine coast; mean current speed of approximately 1.40 m/s, 5.92 TWhr/yr (675 MW)
- Anchorage, AL (Cook Inlet); mean current speed of approximately 1.40 m/s, 159.88 TWhr/yr (18,239 MW)
- Tacoma Narrows, Puget Sound, Washington State; mean current speed of approximately 1.12 m/s, 4.04 TWhr/yr (461 MW)
- New York City's East River; mean current speed of approximately 1.00 m/s, 3.61 TWhr/yr (411 MW)

Interestingly, approximately 95% of the resource is concentrated along the Alaskan coast. In addition to the strong energy production potential of tidal flows, the resource occurs in a predictable manner.<sup>4</sup> This consequently makes tidal power a dependable form of energy, which facilitates its integration into the power grid.

River and ocean currents are also resources to be tapped as sources of electricity. River currents, like tidal currents, are also driven by gravity; however, as their velocities are dependent on the amount of precipitation and runoff upstream of a deployment, river currents are less predictable than tidal currents. An assessment of the river hydrokinetic resource

in the continental United States was recently completed.<sup>5</sup> The technically available resource for the continental U.S. is 120 TWh/yr, approximately half of the technical resource available from tidal power in U.S. coastal waters. Large-scale ocean currents (on the order of 1000km) are driven by wind stress, density differences, the Coriolis force and gravity. The continuous flow of major ocean currents is predictable though the velocity and location of the current 'core' (higher velocity region) shows significant variability at time scales from weeks to years. An assessment of the ocean current energy resource in the Florida Current (the highest power density current along the United States coast) was recently completed.<sup>6</sup> The theoretically available resource for the Florida Current is 45 TWh/yr. If a 30% conversion efficiency of flow energy to electrical power is assumed, the technically available resource is 13 TWh/yr from the Florida Current.

## ***Current State of MHK Turbine Technology***

There are presently many MHK turbine designs being considered for deployment in river, tidal, and ocean currents. Two reports require specific mention and will be referenced throughout this review: *A techno-economic analysis of tidal energy technology*<sup>7</sup> and *The ORECCA Project*<sup>8</sup>. Further overviews of ocean renewable energy and their development can also be found in Bedard et. al., Alldritt et al., Thresher et al., and Verbruggen et al.<sup>9-12</sup> Unlike the wind power industry, which has settled on an upwind, three-bladed, unducted, horizontal-axis turbine as the primary architecture, the preferred marine turbine design has not been chosen. The following are the most common differentiating characteristics:

- Number of blades
- Diameter of the turbine
- Fixed pitch or controlled pitch of blades
- Ducted or unducted
- Number of turbines per platform
- Foundation/mooring used to secure the platform to the seabed
- Flow directionality limits to power generation

The number of blades and desired operational characteristics, e.g. flow speed and rotational speed, will determine an optimal blade design for the turbine and loading balance. The turbine diameter is proportional to the power converted and will be chosen by resource limitations such as depth and any navigational and recreational uses. While commercial-scale ducted wind turbines have proven to be an inefficient use of material and cost, there are potential advantages to using a duct in the marine resource due to size and environmental restrictions. The number of turbines per platform will influence infrastructure costs and the diameter of the turbine, and is partially dictated by the type of platform being considered. A pile-driven foundation with a tower platform will most resemble wind turbines and may also leverage technology from the oil industry. However, neutrally-buoyant and surface-floating platforms are being considered as well and would be fixed to the bed or shore by mooring cables. These types of platforms have the potential to reduce costs and improve device serviceability.

A unique aspect of tidal turbines is the ability to operate in a bi-directional flow, flow which changes direction with the ebb and flood tides. In order to fully capitalize on the resource, this can necessitate, for an axial turbine: 1) a symmetric foil, which is not optimal for power production, 2) a blade that can rotate 180°, or 3) a mechanism to rotate the entire rotor, either passively or actively. The latter two increase the complexity of the design, the cost, and the potential for failure for a single device, but may yield improved array power production and efficiency (improved AEP), or the use of fewer devices for the same power production (potentially lower CAPEX). The bi-directional flow also has an effect on power production because of the periodic nature of the flow; this means the device will experience peak and zero velocities daily, with additional seasonal and extreme changes.

High-level design specifications for a selection of turbine technologies are presented below.

### **DOE Reference Model: Dual-Rotor Axial-Flow Tidal Turbine**

The DOE Reference Model effort is finalizing its initial investigation of an axial-flow tidal turbine as the first model.<sup>13</sup> It was designed as a hypothetical axial-flow tidal turbine for the Tacoma Narrows in Washington State. It was designed to be representative of the technology being pursued by industry developers, such as the ones presented below and has a TRL of approximately 3. The principal characteristics of this axial-flow tidal turbine are:

- 2 blades per turbine
- 20 meter diameter turbines
- Unducted turbines
- 2 turbines per platform
- Pylon driven foundation, tower platform
- The blades pitch, the turbines are fixed



Figure 2: An illustration of the dual rotor axial flow turbine assessed in RM1.

### **Ecomerit Technologies, LLC.**

Ecomerit Technologies, LLC. is developing an axial-flow turbine that will operate in uni- and bi-directional flows. The principal design is for ocean current environments and consists of two neutrally buoyant turbines affixed to a wing with mooring lines. The Aquantis turbine is still in the design stage. The design characteristics are:

- 3 blades per turbine
- Unducted turbines
- 2 turbines per platform
- Neutrally buoyant with mooring lines – other foundation platforms being considered
- Uni- and bi-directional flow acceptance – technology is not discussed

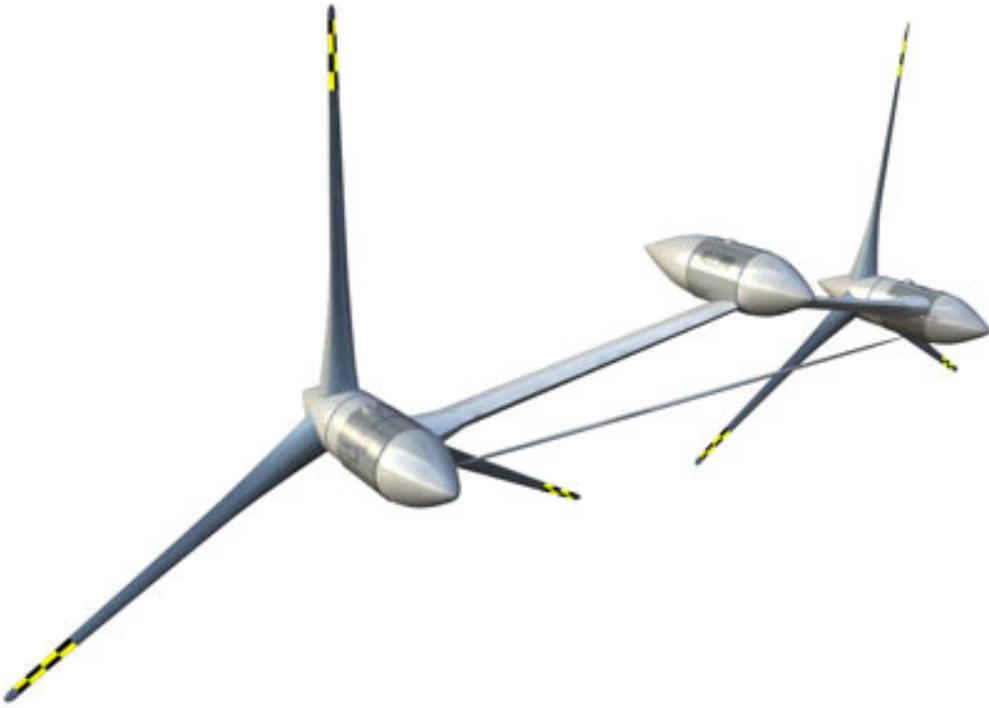


Figure 3: An illustration of the Ecomerit Aquantis turbine.

More information about the Aquantis Turbine can be found online at: <http://www.ecomerittech.com/energy.php>.

## Free Flow Power Corporation

Free Flow Power, Inc. prototyped and tested an axial-flow turbine within the Mississippi River. Free Flow Power leveraged the national laboratories to investigate performance and environmental impacts of array deployments near Scotlandville Bend, LA, consisting of 4, 23, and 112 piles, or 23, 112, 534 turbines, respectively. The principal characteristics of the Free Flow Power turbine are:

- 7 blades per turbine
- 3 meter diameter turbine
- Ducted turbines
- 2 turbines per platform – total number of pairs is depth dependent
- Pylon driven foundation, tower platform
- Unidirectional flow acceptance

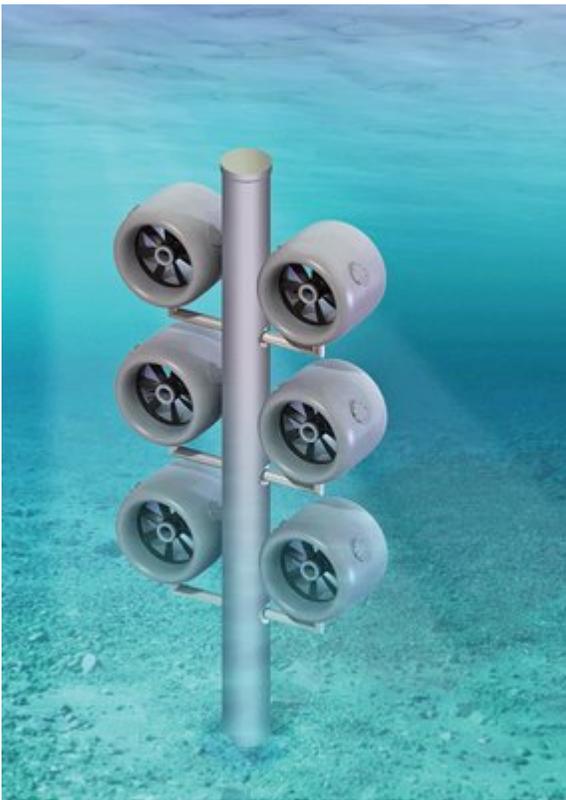


Figure 4: An Illustration of the Free Flow Power Turbine with three pairs of turbines on the tower.

More information about the projects pursued by Free Flow Power Corp. can be found online at: <http://www.free-flow-power.com/>.

## Verdant Power Inc.

Verdant Power, Inc. is one of the first MHK companies in the United States to be grid-connected. They demonstrated their axial-flow tidal turbine technology in an array arrangement of six stations within the East River, New York. The demonstration array was grid-connected and provided approximately 50 MWh of energy over the course of 6 months<sup>14,15</sup>. The principal axial-flow tidal turbine characteristics of Verdant Power's technology are:

- 3 blades per turbine
- 5 meter diameter turbine
- Unducted turbines
- 1 turbine per platform
- Pylon driven foundation, tower platform
- Bi-directional flow acceptance – nacelle pivot



Figure 5: An Illustration of Verdant Power's axial flow tidal turbine.

More information about Verdant Power can be found at: <http://verdantpower.com/what-initiative/>.

## Marine Current Turbines Ltd.

Marine Current Turbines Ltd. installed two axial-flow tidal turbines that generate a total of 1.2 MW of power for approximately 19 hours every day in the narrow straight between Strangford and Portaferry of Northern Ireland. This amount of electricity is tied to the Northern Ireland power grid. In this environment, the axial-flow tidal turbines operate in tidal flow velocities upwards of 3.5 m/s. The principal axial-flow tidal turbine characteristics of SeaGen are:

- 2 blades per turbine
- 16 meter diameter turbine
- Unducted turbines
- 2 turbines per platform
- Pylon driven foundation, tower platform
- Bidirectional flow acceptance – blades rotate 180 degrees



Figure 6: The SeaGen axial flow tidal turbine above water, ready for onsite maintenance

More information about Marine Current Turbines Ltd. can be found at: <http://www.marineturbines.com/>.

## Cost Drivers and Cost-Reduction Pathways

The following is a compilation of key cost drivers and cost-reduction pathways derived from all of the sources of information listed above: the DOE reference model effort, the industry webinars, and the literature review.

### Key Cost Drivers

Of the many costs and expenditures associated with the research, development, and deployment of axial-flow tidal turbines, the subsequent, unprioritized list indicates specific cost drivers whose role has been determined to play a significant part in the technology's overall expense.

- Acquisition of resource assessment and information
- Data acquisition systems
- Device deployment
- Device production
- Device structural components
- Drive train components
- Frequent maintenance and operation

- Hardening device systems for the marine environment
- Lack of task specific tooling and equipment
- Marine operations
- Mooring and anchorage
- Overly complex design and sub-system assembly tasks
- Power take-off
- Replacement parts
- Research and development for device scaling – commercialization
- Testing and lab expenses
- Weight of axial-flow turbine device and structure – weight to generated power ratio

## Cost-Reduction Pathways

Cost-Reduction Pathway data from all of the sources of information were aggregated and analyzed; similar concepts were combined and concept scope was normalized. The resultant cost-reduction pathways are shown below (divided into CAPEX and OPEX). Reference Model information regarding cost-reduction pathways can be found in Appendix A.

### *Capital Expenditure Cost-Reduction Pathways*

- Alternative foundation concepts
- Array design and optimization
- Better and easier deployment, recovery and maintenance
- Better resource assessment
- Cost-reduction as fundamental part of development process
- Design for manufacturing
- Device architecture flexibility
- Exploit larger devices
- Improved alloys or composite material choices
- Improved power take-off
- Improved understanding of failure rate distributions and failure modes
- Optimized structural design
- Purpose-built systems (avoid COTS components)
- Reduce grid connection costs and increase grid connection component reliability
- Reduce mooring costs
- Standardized data acquisition systems
- System simplicity and reliability
- Utilize advanced control schemes

### *Operational and Maintenance Expenditure Cost-Reduction Pathways*

- Better and easier deployment and maintenance (including custom vessels)
- Better resource assessment
- Exploit larger devices
- Materials and coatings utilization and development

- Purpose-built systems
- Reduce grid connection costs and increase grid connection component reliability
- Standardized data acquisition systems
- System simplicity and reliability

## Prioritization of Cost-Reduction Pathways

The cost-reduction pathways were separated into three tiers to aid in the selection of those that would have the largest impact toward lowering the LCOE and most success in being achieved. Prioritization of the cost-reduction pathways was based principally on the quantitative information provided by the industry webinars and the experience and engineering judgment of the authors, followed by the results of the DOE Reference Model effort, and trends determined from the literature survey. All the data were then used to rate each of the cost-reduction pathways in four categories:

- Impact on LCOE
- Potential for progress in this technical area (Is the technology already mature?)
- Potential for success in given timeframe (Will it impact deployments in 2030?)
- Confidence in success (Is this needed progress likely to happen?)

The first category was weighted most heavily, roughly equal to the other three combined, and the total ratings were used to order the cost-reduction pathways into three tiers.

It is important to note that these cost-reduction pathways were evaluated through a long-term lens (year 2030+) in which utility-scale deployments of approximately 100 devices are assumed. This approach reduces the impact of product development costs because these costs are amortized over a large number of production units.

## Most Promising Cost-Reduction Pathways

These cost-reduction pathways were determined to have the largest potential impact on lowering the LCOE with the highest chance of success.

### *Structural Design Optimization*

#### Definition

An optimized structural design seeks to improve both device performance and component characteristics in order to increase the energy-capture-to-weight ratio and to minimize the safety factors used at the component and system levels. Lowering safety factors through more accurate and reliable models indicates that there is greater confidence in the numerical solution and implies a more reliable device. Though not dependent on the introduction of new structural materials, optimized structural designs are complimented by material improvements, in that better materials offer the opportunity to further improve power-to-weight ratios and can positively impact deployment and maintenance through weight reduction. To properly utilize new structural materials, structural design optimization should be combined with accurate prediction of loads.

#### Justification

This area was identified by both developers and the Reference Model effort as a significant path toward lowering cost of energy and directly impacts both CAPEX and OPEX. Additionally, wind experience, once adapted for the marine environment, can be leveraged to make initial gains in this area. As demonstrated in the aerospace industry, a more complete knowledge of the system allows significant reductions in material weight and safety factors, while also improving performance and reliability. Efforts to increase the power-to-weight ratio through structural optimization are a fundamental method for lowering the LCOE. Because this pathway topic encompasses both capital and operational expenses over the life of the turbine system, it is reasonable to assume it will have a significant impact.

## Research Paths

The goal of this research effort is to optimize the structural design of axial-flow turbines in order to improve performance, reduce deployment and maintenance costs through reduced weight, and reduce excess margin in safety factors.

This goal can be achieved through multiple paths, including:

- Hydrodynamic performance models and experimentation: High-fidelity computational fluid dynamic (CFD) simulations provide detailed information of flow around a device or small array.<sup>3,16–22</sup> These simulations are essential to accurately predicting the loads that will be applied to structural models. Stall and turbulence transition models are active areas of CFD research that will have large effects on the performance and loading results.<sup>23,24</sup> Currently, these solutions are too costly for modeling even a couple of days of simulation time in a constrained domain. Any resource model also relies on experimental measurements to provide an accurate validation of the model, with turbulence and velocity profiles being critical for device optimization.<sup>25–27</sup> Site specific measurements may be necessary for accuracy.
- Improved composite material models: Unlike metals, composite structures and their response to strains and fatigue are not well understood. Material defects cause greater variation and uncertainty in strain and fatigue response and also are not easily detected. Crack propagation models are still in their infancy. Improved models will be necessary for higher accuracy finite element analyses (FEA).<sup>28,29</sup>
- High-fidelity fluid-structure interaction (FSI): Coupling CFD and FEA will yield time-accurate solutions for the loading and performance of a deforming rotor. This will be required to provide a fully optimized material layout and design with a minimal safety factor; however, this will be very computationally expensive, and significant effort will be required to build and validate such a capability.
- Survivability modeling: To minimize the number of maintenance operations and increase the reliability of a device, life-cycle analyses under survival conditions should be performed. This will have one of the largest impacts on operational expenses.
- Low-order models: Low-order tools such as WTPerf,<sup>30</sup> FAST,<sup>31</sup> and CACTUS<sup>32</sup> can be used to provide approximate loading and performance values and allow large design space optimization in order to narrow down a design in a time-efficient manner. While not as accurate as their high-fidelity counterparts, the short computation times will allow designers to investigate performance and cost trends prior to moving forward with an advanced prototype design. The high-fidelity tools described above are necessary for developing the most-optimal design and validating these lower-order models.
- Material and coating selection: Material and coating choices will impact the structural design and maintenance schedule. Another pathway, “Materials and Coatings utilization and development”, covers this topic.
- Platform design: Platform (e.g., foundation, tower, moored pontoon) design can also be optimized. Design choices will impact turbine serviceability, performance, and loading, e.g. tower-wake effects. Multiuse platforms are another possible consideration that may reduce resource crowding and duplication of infrastructure<sup>10,33</sup>. Platforms could also be shared with desalination plants, marine aquaculture, or serve as a breakwater.
- Design for Maintenance: Design for maintenance is a new paradigm for minimizing the time and expertise required to maintain a device and repair faults. This topic is a developer design process and is not proposed as a direct area of research.

## *Improved Deployment, Maintenance, and Recovery*

### Definition

Every developer or operator will need to deploy, maintain, and recover their devices. However, because of the challenging operational environment and uniqueness of each technology, the costs of interacting with the devices over their lifetime will be substantially more than has been seen in the land-based wind industry. While efforts can be made to minimize the amount of interaction required, these devices must be accessed at regular intervals for routine maintenance and for required repairs.

## Justification

This pathway was selected for the first tier due to the potential enormity of its costs; this selection was echoed by the developer webinars, mentioned in the Reference Model effort, and in the literature survey. Because the subject matter encompasses a large range of topics and has seen little research in the area of axial-flow turbines, minor improvements will realize significant gains in cost-reduction. Wind history indicates vast improvements can be made in lowering operational costs. Although lessons learned from wind should be leveraged, due to the operations unique to working in the marine environment, there is opportunity to further advance this pathway to impact LCOE.

## Research Paths

The goal of this pathway is to investigate a range of topics that can positively impact the associated costs of lifecycle interaction. An un-prioritized list of promising avenues is given below and is, in part, a collection from the three sources, but, due to the infancy of the technology, it is also derived from the engineering judgment of the whitepaper team.

- Standardized (and submersible) power electronics and instrumentation: Standardizing these packages will improve the quality and reliability of the power generated and the accuracy of the data collected. Improved wet-mate connectors alone would simplify maintenance and recovery efforts. Wet-mate connectors have high failure rates and dry-mate connectors require the removal of any connection from the water. Weiss et al.<sup>34</sup> has proposed a dry-mate connector that allows subsurface connection and evacuates the seawater before removing the protective cover; other solutions should also be investigated.
- Improved fault controls and instrumentation/sensors to facilitate prognostics management: Fault controls and monitoring determine if a device needs to be serviced. Reducing the number of false-positives will prevent extraneous costs and can only be accomplished with reliable instrumentation of the device.
- Logistics best-practices: Providing an evolving document that provides developers and operators a guide that incorporates best practices from design considerations through recovery of their device. This type of effort can leverage prior work such as Sandia National Laboratories' CREW (Continuous Reliability Enhancement for Wind) database.
- Lighter weight: Device weight will determine the requirements of the maintenance vessel, with a lighter device being serviceable by a larger number of vessels and with a smaller crew. Another cost-reduction pathway, "Structural Design Optimization", covers this topic.
- Coatings: This will impact the frequency of maintenance visits and potential failure modes. Another cost-reduction pathway, "Materials and Coatings utilization and development", covers this topic.
- Design for deployment and recovery: Incorporating design practices that promote ease of deployment and recovery of the device. This can include improved locking/unlocking mechanisms, standardized methods of attachment for custom vessels, task-specific tooling and equipment, and lighter weight.
- Design for maintenance: Incorporating design practices that promote this philosophy will reduce the time, costs, and requisite expertise associated with maintenance and repairs. This can include use of common components, ready accessibility to high-priority sections, and use of "plug-and-play" components.

- Common components: Bulk manufacture of a component is the only way to reduce component costs and ensure a ready supply is available when needed. Another cost-reduction pathway, “Common components“, covers this topic.
- Custom vessels: Designing and building ships or barges specifically for deployment, on-site maintenance, and recovery of marine hydrokinetic turbines (or more broadly, offshore renewable devices) would be significantly lower in cost than purchasing and converting a multi-use vessel for the same purpose.

## ***System Simplicity and Reliability***

### **Definition**

Though improved methods of maintenance can have a positive LCOE impact, the fundamental key to reducing OPEX is enhanced system reliability. System simplicity and reliability is the engineering of systems that need minimal maintenance or replacement of parts so that OPEX may be minimized. This effort is not about improved methods of maintenance, but rather about eliminating as much maintenance as possible. This effort to achieve system robustness may negatively impact efficiency; thus an effective cost model will be required to evaluate the LCOE trade-offs between efficiency and reliability. Some of this work should be able to leverage wind and marine industry reliability efforts.

### **Justification**

Though not specifically called-out in the reference model effort as “system simplicity and reliability,” that effort does suggest that LCOE reductions can be achieved with PTO hardening and a better understanding of failure rate distributions and failure modes. The industry webinars indicated that system simplicity and reliability is the top cost-reduction pathway. Finally, the literature review indicates that device simplicity, reliability, and survivability are paths to reduced LCOE.

### **Research Paths**

The goal of a system simplicity and reliability research effort is to drastically reduce the axial-flow tidal turbine OPEX by reducing the need to perform maintenance or replace parts.

To achieve this goal, multiple research paths are required.

- System and Component Simplicity: This effort will evaluate both the entire device and major components to determine if the same or better functionality can be achieved with reduced complexity and/or fewer parts. By definition, this type of effort is dependent on a thorough understanding of the entire system, the detailed interaction of the various components, and how OPEX is affected by subtle component or system configuration changes. Potential reduced complexity will be evaluated against the LCOE metric. In some cases, reduced efficiency may be tolerated if reliability is significantly increased (reduced OPEX). While this effort may use known component requirements, achieving reduced system complexity will be less straightforward and will require detailed system models.
- Reliability: This effort should focus on the reliability of the current component configurations comprising an axial-flow tidal turbine. Again, possible increased component costs to achieve increased reliability must be weighed against reductions in OPEX. Wind reliability experience in the areas of blades, generators, and drive trains, coupled with simulation and validation testing for various components will lead to increased reliability. Premature wind turbine blade and gearbox failures have a significant impact on wind plant operations and cause lengthy periods of downtime and considerable cost to repair due to the need for specialized equipment and expertise. Sandia National Laboratories leads the Blade Reliability Collaborative (BRC) which is a collaborative

framework among academia, research institutions, and industry, that addresses the issues related to the premature failures of wind turbine blades delivered to the field.<sup>35</sup> The project solicits the advice of industry partners for evaluation of manufacturing processes, full-scale blade testing, and inspection techniques. The National Renewable Energy Laboratory (NREL) initiated the Gearbox Reliability Collaborative (GRC) to identify areas for improvement in the reliability of gearboxes.<sup>36, 37</sup> The project combines field testing, dynamometer testing, analysis, modeling, condition monitoring, development of a failure database, and operations and maintenance research in a multi-pronged approach to determine why wind turbine gearboxes do not always achieve their expected design life (<http://www.nrel.gov/wind/grc/projects.html>).

- **System Reliability Analysis:** Results and approaches from several wind energy focused reliability programs sponsored by the U.S. Department of Energy can be leveraged to improve axial-flow MHK turbine reliability. The Continuous Reliability Enhancement for Wind (CREW) Database and Analysis Program is a national reliability database that enables detailed reliability analysis of entire wind plants.<sup>38</sup> This enables the characterization of operating performance at a system-to-component level and identification of technology improvement opportunities. The annual publication of the Sandia CREW Wind Plant Reliability Benchmark (<http://energy.sandia.gov/crewbenchmark>) allows the industry to self-assess and thereby identify targeted improvement activities in their O&M programs.
- **Design to Minimize Failures:** Many design modifications have been proposed to reduce device downtime. In order to minimize the disruption of power due to the impact of floating debris, e.g. seaweed, to enhance accessibility, and to increase reliability, it has been suggested that axial turbines should be designed for high speed with swept-back blades and mounted on a pontoon.<sup>39</sup> Marine propulsors are designed with anti-singing trailing edges to reduce the chance of a high-frequency noise source caused by structural vibrations, which could lead to premature failure of the trailing edge.<sup>40,41</sup> The tips of many propulsors are also unloaded to reduce the potential for cavitation, although this would negatively impact the turbine efficiency, as the outer portion of a turbine blade is where the majority of power is produced. As device designs become finalized, high-fidelity CFD and finite-element analysis can be performed to provide the most accurate flow and structural analyses of the turbine and components.

## Array Optimization

### Definition

Array optimization refers to the spacing and orientation of axial-flow tidal turbines within a large deployment of devices. This optimization must be on a LCOE basis rather than on strictly array power performance. The optimization includes many variables such as power performance, structural loads, cabling costs, mooring/foundation costs, installation and maintenance costs, and environmental considerations such as sediment transport and changes in the tidal climate. Energy storage could potentially be part of array optimization.

### Justification

The Reference Model effort, and specifically RM1, determined that array optimization is one of the best paths to significant reduction in the LCOE. Industry webinar participants were asked to assume utility-scale array deployments and were asked to primarily focus on issues relating to individual device improvements. Even with this guidance, however, array effects were considered important. Based on experience of the axial-flow reference model project and the wind industry and the significant impact that array design can have on performance, loads, infrastructure costs, installation, maintenance, and environmental issues, the Sandia whitepaper team also rated array optimization highly. Lastly, the literature mentioned the importance of array effects for both power and environmental considerations.

Research shows there is a physical limit to the amount of power that can be extracted from a tidal system<sup>42</sup>. As the number of devices in a channel increases, the maximum flow rate through the tidal channel will decrease; power generation will peak when the un-restricted flow rate is reduced by 42%. This level of flow-rate change could have significant environmental and water-usage implications. Moreover, generating power in a location that is fed by a tidal network results in much more complex flow dependencies than generating power in a single-inlet bay. Polagye *et al.* demonstrated the need for site-specific models, as the location of peak power moves once devices provide an obstruction.<sup>19</sup> It is anticipated that flow will accelerate around an array of turbines; this may necessitate the need to utilize three-dimensional flow models and to optimize array layouts with respect to more criteria than just the distance between individual devices.

## Research Paths

The goal of this research path would be to minimize the LCOE of large deployments of axial-flow tidal turbines through the development, public dissemination, and use of a robust array optimization tool.

- Robust array optimization tool: This tool would include many parts that could be combined into a single framework, including but not limited to:
  - Optimization shell – primary user interface, communication with modules, optimization engine
  - Power performance module – complex flow through array and determination of power production
  - Loads module – static and fatigue loads on structures
  - Mooring and foundation module – mooring/foundation costs
  - Power infrastructure module – costs for cabling, substations, interconnects
  - Environmental module – sediment transport and changes to wave climate
  - Installation module – cost effects due to array layout
  - Maintenance module – array effects on access and maintenance
  - Navigation Module – effects on navigation

## Second Tier Cost-Reduction Pathways

These pathways also lead to lower LCOE but were not considered as impactful as those in the previous list.

### *Improved PTO*

Power take-off systems comprise a significant portion of the capital expenses and require regular maintenance. Because the PTO is responsible for converting the mechanical energy of the rotor into electrical energy, any efficiency losses will impact the total power generated. Failure of a PTO results in zero power production and may coincide with failure or damage to the other turbine components, further increasing operations and maintenance costs. The goal of this pathway is to improve the efficiency and reliability of the PTO. The PTO was highlighted by the three sources as being a top focus area. Gearboxes are commonly used in wind because they are easily built and require less-expensive generators (lower torque, higher speed). However, gearboxes may be prone to failure and have high OPEX.<sup>36,43</sup> Direct-drive PTOs reduce complexity by directly attaching the rotor shaft to the generator but require high torque, low speed generators.<sup>8,34,36</sup> These generators require improved controls and are more expensive due to the size, efficiency and cost of permanent magnets used. Other PTO systems may provide advantages not realizable in the wind industry.<sup>36</sup> Improving the device performance (annual energy) may even justify more expensive PTO systems than those currently employed.

## ***Reduce Grid Connection Costs and Increase Grid Connection Component Reliability***

The power electronics and cabling required for transforming and transmitting power from a device or array to the grid are expensive and have efficiency losses. Lower-cost alternatives do not have proven reliability in the marine environment and increase the complexity of the system. The goals of this CRP are to improve the reliability of grid connection and investigate methods to lower its costs. One of the largest cost drivers is cabling; improved array models that also incorporate this expense into an optimization framework are potentially the most effective way to understand cost versus performance tradeoffs. Wet-mate connectors have proven unreliable and dry-mate connectors require additional maintenance and recovery considerations that can increase infrastructure and maintenance costs. Similarly, common components for power electronics that have been ruggedized for the marine environment, together with best practices for deployment, could reduce complexity and costs.

## ***Advanced Controls***

As arrays of turbines are deployed, they must be operated as systems in order to reach peak efficiency through all operating conditions while minimizing adverse device interactions (e.g. turbine-wake ingestion). Advanced controls will make use of device and inflow measurements to improve array performance by proactively controlling each turbine appropriately for inflow conditions. This strategy is in contrast to present wind operations that reactively respond to the resource on a turbine-by-turbine basis. Advanced control of turbine arrays will also allow operators to select various objective functions, such as peak efficiency or increased lifespan strategies.

## ***Materials and Coatings Utilization and Development***

This cost-reduction pathway includes both structural materials and coatings for durability and anti-bio-fouling. Improved lightweight structural materials can have a cascading beneficial effect on the system: better performance, reduced mooring loads, smaller (less expensive) maintenance vessels to deploy and maintain, and others. Material selection will be a critical part of the success of the marine hydrokinetic power industry, as water provides a unique environment, with many challenges, within which to operate. Wind experience can still be leveraged to help identify and characterize low-cost structural materials. Investigation on the current state of the art for materials and coatings in the naval or oil and gas industries could help address current needs. Durability and anti-biofouling coatings exist for these and other industries, but may not be economical or durable enough for a marine renewable energy application. Structural models that incorporate representative material defects will help to improve material reliability and optimize structural design. The Composite Material Fatigue Database, developed at Montana State University, is being updated to include fatigue response for composite coupons that have been submerged in water.<sup>44,45</sup> Researchers there have shown that significant water uptake can occur; this increases material weight and reduces its strength. Metal blades and components can be manufactured, but will result in high material and fabrication costs, and corrosion of metal in a marine environment is inevitable. Corrosion “prevention” techniques, including cathodic protection and coatings, are available but they do not provide a permanent solution. Coatings may provide another stopgap method for improving device reliability and productivity by preventing corrosion, water infiltration, soiling/erosion, and bio-fouling.<sup>46</sup>

## ***Design for Manufacturing***

Design for manufacturing is a common paradigm implemented throughout the entire design process to minimize costs associated with complicated fabrication and/or assembly and to optimize use of standard material forms. Implementation of this paradigm may allow automation of certain processes or parts creation, but is ultimately used to

reduce cost and time of device manufacture. Designing for manufacture requires significant understanding of the system so that trade-offs between manufacturing, structural integrity, hydrodynamics, and cost can be made.

## **Common Components**

Common components would be specifically designed for use in the spectra of offshore renewable energy devices and conditions. As a result of offshore renewables being a relatively new technology, there are few commercial off-the-shelf (COTS) components that are applicable or reliable for this industry. This results in developers designing custom components for their technology. Consequently, the only two alternatives for the repair of a device are to 1) stockpile parts, which requires an initial investment that may be wasted, or 2) manufacture replacements as necessary, but this results in a long lead-time. Bulk manufacture of a component is the only way to reduce component costs and ensure a ready supply is available when needed.<sup>9</sup> The goal of this cost-reduction pathway is to leverage commonalities across the range of offshore renewables in order to design common components that are reliable when submerged and are easily manufactured and procured. Potential components are bearings, seals, power electronics and connectors; and instrumentation and sensors for data acquisition. A survey could aid in determining which classes of components to target with recommendations for incorporation of critical MHK needs. However, market forces will determine which components industry chooses to optimize and manufacture for sale. Common components may eventually become COTS if the offshore renewables industries become large.

## **Third Tier Cost-Reduction Pathways**

For numerous reasons, the following pathways were not included into the two prior tiers, but still promise potential benefit.

- Alternative foundation concepts: Foundation costs can be substantial, but at present advancements in this area are not expected to achieve significant cost-reductions in the assumed timeframe. The majority of axial-flow turbine deployments are presently considering pile foundations in river and tidal systems.
- Better Resource Assessment: Better resource assessments may aid in selecting sites for a technology deployment, but research in this area is best conducted in combination with array performance and optimization modeling.
- Cost-reduction as fundamental part of development process: This refers to an approach in which LCOE is an active topic during each phase of the development process. This cost-reduction pathway is already employed to various degrees by existing manufacturers; a research program to support this is not considered to be of highest potential at this time.
- Device architecture flexibility: This cost-reduction pathway was defined by a developer as becoming too firmly attached to a single architecture at an early design stage. Flexibility early in the design process has the potential to reduce costs and should be encouraged. Development of and access to design optimization tools will help ensure developers are able to make the best design decisions.
- Exploit larger devices: As seen in the wind industry, larger-diameter devices will generate more power; however, as indicated in the literature survey, there may be an upper design limit enforced by environmental considerations.
- Improved understanding of failure rate distributions and failure modes: This will be a fundamental means to reducing the operational expenses for a device; however, until a large number of technologies are deployed this will remain predominately device- and developer- specific. Using common components and leveraging a common instrumentation and sensing platform will provide the necessary data to make progress in this

pathway. A database allowing for meta-analysis of failure rate distributions and failure modes can then be constructed. The DOE/SNL CREW database (developed for wind energy) is an example of how this can be accomplished. A new modeling tool for incremental wear and thermal response shows that the transient temperatures in the bearing cannot be ignored, even under water<sup>47</sup> and will aid in design selection and lifespan prediction.

- Purpose-built systems (avoid COTS components): One solution to the lack of applicable off-the-shelf components is to design components specifically for a MHK technology. This provides the best performance, and the components can be redesigned as necessary; but this path will lead to high-cost devices. Emphasis may be better placed in a longer term solution: the CRP that will establish a common components supply line for MHK applications.
- Reduce mooring costs: As deployments of neutrally buoyant devices increase, this technology will be able to leverage mooring advances from offshore wind and wave energy converters for cost saving techniques. Novel material development may provide cost effective solutions for traditional mooring lines. A combined elastomeric and thermoplastic tether has been proposed by Mc Evoy<sup>48</sup> that permits unconstrained motion during normal operations, but becomes stiffer in extreme loading. This reduces tension loads on the cables and device, while also requiring a smaller footprint. The reduced loads and decreased footprint could result in lower CapEx.
- Standardized data acquisition systems: Data acquisition systems are not a large overall cost driver for axial-flow turbines, but their quality and capability will determine the quality and reliability of data being returned from the device/array. This cost-reduction pathway will be partially covered by the “Common components” and “Reduce grid connection costs and increase grid connection component reliability” pathways. It should be noted that data acquisition systems are distinct from power electronics and instrumentation. Instrumentation of a turbine and accurate, real-time measurement of the meteorological and marine environment and the resultant turbine performance, loading, and response in the marine environment will be critical for acquisition of model validation data that can eventually lead to efficient and cost-effective turbine operation. Standardizing the instrumentation, connectors, and data logging hardware and software is crucial to reducing the instrumentation costs and acquiring high quality data. The National Renewable Energy Laboratory has developed an adaptable instrumentation package for marine hydropower applications<sup>49</sup> that can serve as a prototype for such a system. Characterization of extreme and normal operating conditions will aid in the development and implementation of advanced control systems to further optimize performance and increase reliability and survivability.

## Conclusions

A prioritized list of technical cost-reduction pathways, with potential research avenues to pursue, has been presented to lower the LCOE of axial-flow turbines. These cost-reduction pathways were identified as the most promising technological opportunities that would have the highest chance of success by 2030 and the greatest impact on the LCOE. These were compiled from the reference LCOE model, developer input, literature review, and research and engineering judgment. The analysis assumed utility-scale deployments (approximately 100 devices or more) in the 2030 time frame in order to focus on technological improvements that would have a positive impact on the entire industry.

The future of axial-flow turbines looks relatively bright, even though the current LCOE is noncompetitive with other sources of energy, as the potential for LCOE reduction for this technology is still high. The most promising cost-reduction pathways identified in this study have both the potential for high impact on LCOE and high confidence in success within the timeframe (2030) of this analysis. Improvements in simulation capabilities and the accumulation of data from deployments will lead to the development of more axial-flow turbine-specific technology, which will lead, in turn, to a lower LCOE. As an example, wind turbines started with standard airfoils and aluminum blades but progressed to wind-specific airfoils and renewable energy appropriate composites.

The primary cost-reduction pathways identified for axial-flow turbines will be relatively universal for marine and hydrokinetic devices. Any immature technology, including axial-flow turbines, will benefit greatly from device structural optimization. This optimization is necessary to improve energy capture and utilization of materials. The marine environment is very harsh and device deployment, maintenance, and recovery are quite costly. Thus, any avenue which reduces these costs will have a large positive impact on LCOE. Both the “Improved Deployment, Maintenance, and Recovery” and the “System Simplicity and Reliability” cost-reduction pathways are aimed directly at reducing these costs. “Array Optimization” is another cost-reduction pathway that will be relatively consistent among MHK technologies. While there may be some ability to leverage array optimization efforts from wind energy, axial-flow array optimization may be even more important due to the fact that foundations are more likely to be part of the optimization. Finally, due to the ability to borrow technology from the wind industry, the “Advanced Controls” cost-reduction pathway does not score as highly for this technology as it likely will for wave energy convertor devices; the “Advanced Controls” cost-reduction pathway for axial-flow turbines is primarily related to array optimization.

Based on the input and analysis performed for this effort, all of the primary and secondary cost-reduction pathways identified are high LCOE impact and actionable in terms of viable research efforts. The research elements of the Structural Design Optimization; Improved Deployment, Maintenance, and Recovery; and Array Optimization cost-reduction pathways are presented in detail above. For the System Simplicity and Reliability cost-reduction pathway, reliability efforts could be modeled after similar efforts in wind energy and other industries while the system and component simplicity portion would require an emphasis on system characterization. The secondary cost-reduction pathways are also all viable research efforts although the Common Components research path should be market driven. While survey efforts might identify previously unseen component commonalities, there is a strong market aspect of this work which does not necessarily lend itself to a traditional research effort.

While this effort focused on axial-flow turbines and incorporated input from axial-flow turbine developers, most of the cost-reduction pathways would apply similarly to cross-flow turbines. “Structural Design Optimization” would certainly apply to cross-flow turbines and the support structures for these devices. Similarly, the cost-reduction pathways of “Improved Deployment, Maintenance, and Recovery”; “System Simplicity and Reliability”; and “Array Optimization” would apply to cross-flow turbines; the research paths to achieve these cost-reduction pathways would be analogous to those specified here for axial-flow turbines. One significant difference might be the greater need for improved and

validated hydrodynamic simulation capabilities for cross-flow turbines – the vertical-axis wind turbine (VAWT) research area has not received nearly the attention that the horizontal-axis wind turbine (HAWT) research area has received in the last couple of decades. Thus, the HAWT technology, which is readily transferable to axial-flow water turbines, is more advanced than the corresponding VAWT technology, which is transferable to cross-flow water turbines.

This work is intended to help identify the most promising routes to a lower and more competitive cost of energy for axial-flow turbine devices. It is hoped that this work can productively support the research direction decisions of many in the MHK community; developers can compare their own research priorities against those outlined here, government funding agencies can use this information as one input to their research prioritization for MHK technology, and academics and researchers at other institutions can use this information to help identify long-term research directions.

The authors fully acknowledge that this process, by definition, can be imprecise. Many of the cost-reduction pathways influence and have consequences for other pathways, and an argument can always be found to “slice” the data a different way. This report represents the authors’ best engineering judgment to distill all of the data in a meaningful and constructive manner to support future research decisions.

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# Appendix A – Reference Model 1

## Reference Model Overview

The objective of the U.S. Department of Energy’s Reference Model effort is to establish baseline cost of energy (COE) numbers for four MHK device designs that cover the primary wave and current resources.<sup>1</sup> As part of this task, a comprehensive cost model has been constructed for each of the four devices analyzed in the Reference Model effort. Each reference model focuses on simple, robust designs that lead to conservative and defensible performance and COE benchmarks for DOE. In many cases, the Reference Model device designs are generic versions of designs pursued by MHK developers. Reference Model resource definitions are generic such that different design concepts can be evaluated and compared in similar resource types.

The Reference Models achieve a Technology Readiness Level (TRL) of 3 and are not sufficient to reproduce exact full-scale replicas. Since full-scale deployment of the reference models is not planned, analogues were used for design (i.e., mooring and anchors), installation, and operation and maintenance aspects of each model. The initial results will be verified and improved through subscale device model testing and data-correlation from large-scale deployment projects. Through this validation and correlation process, key cost drivers will become apparent and cost-reduction pathways will be identified.

While the primary objective of the Reference Model effort is to inform DOE, public release of the results will support additional benefits including:

- Benchmark reference resource sites allow developers to assess their device performance at documented generic sites with transparent, detailed resource data, site attributes, and environmental risk characterization.
- Developers can compare their own COE predictions to the Reference Model baseline cost estimates. In many cases, developer estimates may be lower than Reference Model cost estimates due to more advanced designs.
- A cost modeling methodology demonstrated with the Reference Model can be followed by industry to strengthen industry cost predictions.
- Developers will be interested in the public experimental data sets and numerical models to use as benchmarks for their “in-house” design and performance tools.
- Developers will have a basic outline for determining environmental issues and cost as they assess design-resource metrics for potential deployment.
- Greater investor confidence will result from the use of this independent Reference Model.

# Reference Model 1 – Tidal Turbine

## Overview

Of the four different devices modeled as part of the Reference Model effort, the first one (RM1) is a dual-rotor axial-flow tidal turbine, as illustrated in Figure A-1, with a pile foundation. This design was analyzed for power performance and cost in a generic tidal resource based on physical and environmental data from the Tacoma Narrows region of the Puget Sound. Performance analysis for this design demonstrated an annual output of 2700 MWh with a 1.1 MW rating for a single turbine. Cost analysis based on the performance of the design and resource characteristics resulted in an estimate of 18.1 ¢/kWh (cents per kilowatt hour) for 100 units of installed capacity, which was considered as a commercial operation evaluation. Figure A-2 shows the cost of energy results as a function of installed capacity and cost components.



Figure A-1. Dual-rotor axial-flow tidal turbine

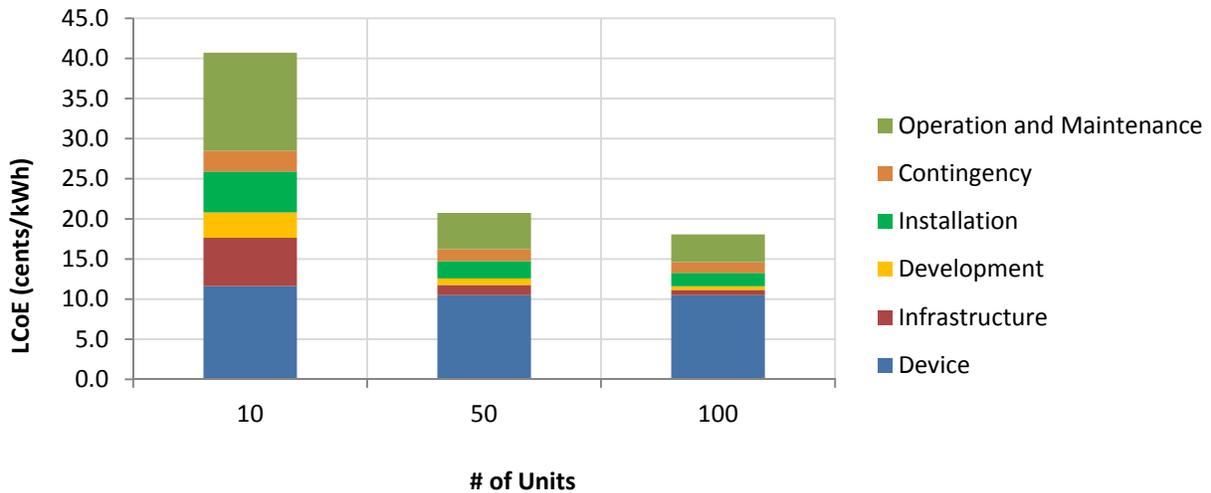


Figure A-2. High-Level LCoE Breakdown — Tidal Reference Model Technology

## Cost Drivers

Though the initial Reference Model effort does not specifically list or prioritize cost drivers, it does present certain cost data versus deployment scale (1 unit, 10 units, 50 units, 100 units). Focusing on the 100 unit deployment scale, RM1 cost drivers appear to include:

- Power Take Off
- Device Structural Components
- Marine Operations
- Replacement Parts

## ***Cost-Reduction Pathways***

Though the subscale device model testing and data-correlation from large-scale deployment projects has not yet been completed, some suggestions for cost-reduction pathways have emerged from the initial Reference Model 1 effort.

These preliminary cost-reduction pathways include:

- Improved understanding of Failure Rate Distributions and Failure Modes
- Array design/optimization
- PTO hardening or redundancy
- Alternative foundation concepts
- Improved device recovery and redeployment
- Improved alloys or composite material choices

## Appendix B – Question List for all industry webinars

To ensure consistency regarding interaction with industry participants, all webinars used the same question set (below).

1. What are your assumptions when determining the LCOE of your utility-scale project?
2. What are the most promising cost-reduction pathways for your company to pursue?
3. What are potential areas for improvement that would require an incremental improvement or smaller investment (i.e., the low hanging fruit)?
4. What are potential game-changing improvements that could significantly reduce the LCOE but would require significant resources to achieve?
5. Have you generated economic or performance data that can inform DOE and help DOE meet its data and analysis requirements (e.g. identification of components with significant technical headroom for targeted R&D and LCOE reduction; techno-economic assessment). Which of these requirements would you be willing to provide to DOE?
6. What areas have the most uncertainty in your cost predictions?

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