Progress Report on the Development of Design Tools for Wave and Current MHK Devices

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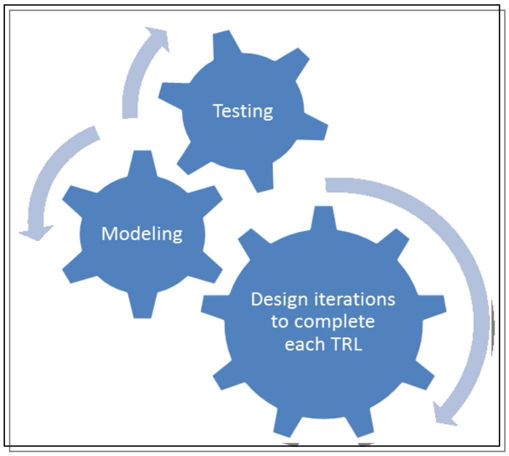
1. Purpose, Objectives and Recommendations

The purpose of this report is to provide DOE:

- A snapshot of the current state of the art of tools available to the MHK industry
- An overview of the National Labs MHK modeling activities funded under the FY09 Lab Call
- A description of the modeling tools used by the Reference Model team and the relationship between those efforts and FY09 Lab Call work.
- A preliminary assessment of the MHK industry's modeling needs

The objective is to collect the information and conduct the initial assessments necessary to inform DOE's prioritization of investments in modeling tool development such that the areas of greatest impact can be targeted to more rapidly advance MHK technologies. For the purposes of this report, a need refers to the lack of a particular modeling tool that would accelerate the design process and lead towards more rapid commercialization. Hence, when needs are discussed, they refer specifically to industry needs. A modeling tool is a computer design/analysis code that allows the user to simulate the operation of an MHK device and output performance data. A comprehensive cost model can use this data as input and predict the cost of electricity (COE) for a given device. In order for DOE to effectively utilize available funds to advance the state of the MHK industry, efforts to develop modeling tools must be well coordinated and based on careful consideration of the capabilities that would most benefit device developers. The report takes an initial pass at delivering a prioritized list of modeling tool needs; however, it does not intend to take the place of an in-depth modeling needs assessment.



The report includes a discussion of the design process in order to provide context for modeling tool development recommendations. In addition, there are a number of assumptions that help to frame the high level recommendations. First, one must take into consideration the maturity of the industry. The MHK industry is not yet mature, and a single device type for each resource has not yet emerged; therefore, investments made at this stage should be as device agnostic as possible. Second, it is clear that MHK tidal, river, and open-ocean current device modeling capabilities are more advanced than their wave energy counterparts because they leverage tools originally developed for the wind industry. Third, potentially convertible resource estimates for wave energy are significantly larger than tidal and river current. These final two points indicate that Wave Energy Converter (WEC) modeling tool development should be of higher priority. The specific needs listed in section 3 of the report include present device modeling gaps given the understanding that MHK devices hold significant near term promise as a cost competitive energy source.

In moving forward with improved modeling capabilities for the MHK industry, it is evident that DOE National Labs have relevant experience and skill sets to play a large role and perhaps lead the effort. However, there is a benefit in leveraging existing expertise in the commercial and academic sectors as well. First, partnerships with DOE funded industry demonstration projects will leverage lessons learned by industry and can help generate valuable model verification data. Secondly, to ensure a high quality product, the depth of experience in some areas of industry and academia cannot be excluded.

	Gap or Barrier	Impact of Gap or Barrier on MHK Industry	Priority
1	Comprehensive, Wave to Wire, Device Agnostic WEC Modeling Software Package	• Longer development time to reach commercialization and higher cost for developers • Increased investor risk	High
2	Mid-Fidelity Computational Code	• Higher risk for TRL 4-7 design products • Inaccurate performance predictions throughout preliminary and final design	High
3	Life Cycle Cost Modeling Tool	• Results in higher COE for MHK devices • Cost is often not used as a key driver in the design process	High
4	Open Source Versions of Hydrodynamic Modeling Tools	• Developers must pay higher costs for commercial code licenses • Many commercial codes were developed for oil and gas and need to be adapted to WEC operation for more accurate results	High
5	High Fidelity Survival Modeling With Prediction of Extreme Conditions	• Must overdesign and deploy a more expensive device • Results in higher COE for MHK devices	Medium
6	Fatigue Modeling Capability and Design Databases	• High risk of failure for TRL 7-9 deployments creates barrier to private investors • Offshore oil and gas industry cites fatigue as #1 challenge and source of failure	Medium
7	Simulation of Turbines on a Moored or Floating Structure	• Risk of inaccurate predictions of performance and operation in extreme conditions for tidal, open-ocean, and river current devices	Low
8	Simulation of Multiple WEC's on a Single Structure	• Reduced capability to optimize design of modular WEC arrays which have potential for significant COE reduction	Low
9	Test Data for Verification of Modeling Tools	• Lack of verification data results in greater uncertainty for device performance predictions and subsequently reduced confidence in COE estimates • Verification data is essential to all model development efforts	Applies to all modeling efforts (high priority)

2. Modeling Tools

2.1 Existing Codes

Codes related to MHK turbine development have a significant advantage over codes related to WEC development due to the fact that turbine codes have the ability to leverage existing wind turbine codes. Thirty plus years of wind technology development has enabled the validation of wind modeling codes. As a result, turbine modeling codes tend to be more mature than wave modeling codes. There are several available codes that have either been developed for marine and hydrokinetic (MHK) technologies or have been adapted to be used with MHK technologies. Some of the work being performed by the National Laboratories is to adapt or improve existing codes to make them more applicable to MHK modeling. While there are many more codes in existence than could be applied to MHK devices, Table 1 and Table 2 list the codes commonly used for the modeling of MHK technologies. More codes can be found on the National Renewable Energy Laboratory's (NREL) website.

Table 1 - Existing Wave Codes

Type	Code	Specific Behavior/Interaction	Open Source or Commercial
Marine Dynamics	ANSYS AQWA	Boundary Element Method (BEM) for device & mooring dynamic loads in frequency & time domains	Commercial
	OrcaFlex	Mooring dynamics evaluations	Commercial
	WAMIT	Dynamic loads of moorings and occasionally devices	Commercial
	MultiSurf	Creates complex geometry models	Commercial
	aNySIM	Commercial code for sharing MARIN hydrodynamic software	Commercial
	HydroD	Performs hydrostatic and hydrodynamic analysis	Commercial
	SIMO	Simulates time domain for multibody systems and allows non-linear effects to be included in the wave-frequency range	Commercial
Mooring	MIMOSA	Calculates wave frequency and low frequency vessel motions and mooring tensions	Commercial
	WADAM	Hydrodynamics of wave/structure interactions	Commercial
	MOOROPT-2	Finds values of design variables that give minimum system cost while satisfying a specified set of constraints	Commercial
	AQWA with Coupled Cable Dynamics	Fully coupled device and mooring loads in frequency & time domains	Commercial
Wave Response	DIFFRAC	Calculates wave diffraction due to units in waves	Commercial
Computational Fluid Dynamics	STAR-CCM+	Commercial computational fluid dynamics code	Commercial
	LS-Dyna	Commercial computational fluid dynamics code	Commercial
	CFX	Commercial computational fluid dynamics code	Commercial
	Storm (CFD2000)	Models erosion, sediment, waterways, channel flow and water vehicle performance	Commercial
Arrays	SWAN/SNL-EFDC	Computes random, short-crested wind-generated waves in coastal regions and inland waters (SWAN) coupled with large scale hydrodynamics (SNL-EFDC)	Open Source
Time/Frequency Domain	AQWA with DLL	Time domain nonlinear equations of motion	Commercial
	Simulink	Time domain nonlinear equations of motion	Commercial
	MATLAB	Frequency domain linear equations of motion	Commercial
	SNL-EFDC	Models surface-water flow, sediment transport, and water-quality	Open Source

Table 2 - Existing Tidal/Current Codes

Type	Code	Specific Behavior/Interaction	Open Source or Commercial
Marine Dynamics	ANSYS AQWA	Boundary Element Method (BEM) for device & mooring dynamic loads in frequency & time domains	Commercial
	aNySIM	Commercial code for sharing MARIN hydrodynamic software	Commercial
Mooring	MIMOSA	Calculates wave frequency and low frequency vessel motions and mooring tensions	Commercial
	WADAM	Hydrodynamics of wave/structure interactions	Commercial
	MOOROPT-2	Finds values of design variables that give minimum system cost while satisfying a specified set of constraints	Commercial
	AQWA with Coupled Cable Dynamics	Fully coupled device and mooring loads in frequency & time domains	Commercial
Turbine Performance	Harp_Opt	Blade design with optimization routine	Open Source
	WT_Perf	BEM blade hydrodynamic code	Open Source
	CACTUS	Horizontal Axis Turbine (HAT) & Vertical Axis Turbine (VAT) design code	Open Source
	FAST	Hydroelastic design	Open Source
	HydroDyne (not yet available)	Calculates lift, drag and pitching moments of blade or tower nodes. Also can consider blade and tip losses and the effects of dynamic stall.	Open Source
Computational Fluid Dynamics	STAR-CCM+	Commercial computational fluid dynamics code	Commercial
	OpenFOAM	Commercial computational fluid dynamics code	Open Source
	ANSYS-Fluent	Commercial computational fluid dynamics code	Commercial
	OverFlow	Navier-Stokes flow solver for structured grids	Open Source
	CFX	Commercial computational fluid dynamics code	Commercial
	Storm (CFD2000)	Models erosion, sediment, waterways, channel flow and water vehicle performance	Commercial
Arrays	SNL-EFDC	Models MHK devices in large scale hydrodynamic simulations	Open Source
Time/Frequency Domain	AQWA with DLL	Time domain nonlinear equations of motion	Commercial
	Simulink	Time domain nonlinear equations of motion	Commercial
	MATLAB	Frequency domain linear equations of motion	Commercial
Environmental	HSPF	Simulates watershed hydrology and water quality for both conventional and toxic organic pollutants	Commercial
	SNL-EFDC	Models surface-water flow, sediment transport, and water-quality	
	CUENCAS	Models single hill slopes to large (of the order of thousands of kilometers squared) watersheds	Open Source

2.2 FY09 Lab Call Funding Modeling Activities

The National Labs have been working on evaluating, developing and improving MHK design and performance codes. In 2009, DOE awarded Sandia National Laboratories (SNL) and the National Renewable Energy Laboratory (NREL) projects to support the MHK industry under the Advanced Water Power FOA (DE-FOA-0000070). A portion of the funds were directed to be used to support the development MHK modeling and codes, testing and materials/coating research. The objective of the award was applied science and technology development that would support industry as it develops more efficient, less costly and more robust MHK designs. Specifically, the labs were to address device performance with respect to computer design tools, simulation codes, and testing to predict machine performance, loads, and stability; development, validation, and application of tools and codes for marine power systems to understand their long-term performance, operation, and reliability; and prototype applications of new models and validation/verification studies. Oak Ridge National Laboratory (ORNL) and Pacific Northwest

National Laboratory (PNNL) were also awarded MHK tasking under this FOA. ORNL and PNNL are supporting various aspects of MHK design, testing, and simulation but this report will focus on tools under development and in use at NREL and SNL only.

2.2.1 SNL

Sandia is developing the code CACTUS (Code for Axial and Crossflow Turbine Simulation), which is scheduled to be publically available in September, 2012. CACTUS is a fast running design code that can be used for either horizontal axis turbines (HAT) or vertical axis turbine (VAT) designs. Sandia will document validation of CACTUS for prediction of MHK turbines operating near the water surface. CACTUS is scheduled to be released for public use to provide industry with a fast-running turbine performance evaluation tool.

Sandia has conducted the design of an HAT using a series of codes, including Xfoil, a publically available foil design code, an in-house MATLAB code for optimizing blade chord and twist, WT_Perf, an NREL HAT design code, Overflow, a NASA CFD code and ANSYS, a commercial FE Code for structural analysis. Blade acoustic analyses were performed using CHAMP, an ARL Penn State BEM code. These codes will be verified by comparison of the predicted performance with measurements conducted on a sealed blade section in the 12-inch water tunnel and a scaled turbine in the 48-inch water tunnel at ARL.

Sandia is also evaluating OpenFOAM, WAMIT, AQWA, and OrcaFlex for use in MHK device design and performance. In every case, validation exercises are being conducted to compare simulation results to experimental data. As part of this process, Sandia has discovered an error in the WAMIT code in FY12 and alerted the developer of the issue. The error has been rectified and the current version is now correct.

Finally, Sandia has developed the open source SNL–EFDC code to include tidal and current MHK devices in large scale hydrodynamic calculations for both environmental studies and array optimization. SNL will also further develop the SWAN code coupled with SNL-EFDC to implement for environmental studies and arrays for WEC devices. Validation tests are ongoing for these codes in both current and wave experimental facilities, and the initial version of SNL-EFDC for tidal or current turbines was released in summer of 2011 and the WEC version with SWAN is scheduled to be released at the end of 2012.

There is an existing plan in place to provide technology transfer to industry and regulators regarding the SNL-EFDC code. The plan includes individual developer training courses, workshops for larger audiences, and self-guided training to accommodate both users and reviewers of the software. Training has already commenced in 2011 for both industry and regulator stakeholders.

2.2.2 NREL

NREL is developing numerical codes and simulation methodologies to design and analyze wave and water-current energy systems. First, several existing numerical models were reviewed and evaluated. Specifically, potential flow codes (WAMIT and AQWA), Navier-Stokes codes (STAR-CCM+ and OpenFOAM), rotor analysis codes (Harp_Opt and FAST), and mooring and structural dynamics codes (OrcaFlex and LS-Dyna) were used to simulate the performance of various ocean energy devices. The results from these numerical codes were compared and validated against experimental results to identify the limitations of each numerical simulation technique. To address gaps in the current set of numerical modeling tools, NREL is developing a suite of open-source codes to assist in the design and analysis of ocean energy devices. The tools NREL researchers are developing are presented in Table 3. This table describes the codes and provides an update on the code development status.

Table 3 - NREL Software Tool Development

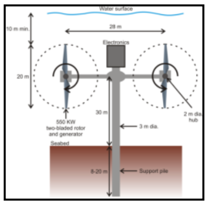
Resource	Product / Tool	Description
Wave	Wave-BEM	A frequency domain potential flow simulator for predicting hydrodynamic coefficients and wave excitation forces. A two-dimensional version of this code has been completed and work on a three-dimensional version is currently underway.
	MAP	A finite-element mooring line simulation tool is being developed that will interface with NREL's suite of WEC modeling tools. This code will perform both quasi-static and dynamic analysis of multi-segmented cables that are typically used to secure ocean energy devices to the seabed. A preliminary version of this code has been completed and this model was shown to compare well against a simulation performed using OrcaFlex.
	WaveSim	A pre-processer that generates random wave fields that can be used as input for WEC simulation tools.
	MPower-Sim	Multi-body dynamics and power-take-off model to facilitate the simulation of WEC devices that are comprised of connected rigid bodies.
Current	HARP-Opt	Horizontal Axis Rotor Performance Optimization (HARP-Opt) uses a multiple-objective genetic algorithm and blade-element momentum theory to optimize the design of horizontal-axis hydrokinetic turbine rotors. This code has been released on the NREL website. Updates and improvements will be released.
	HydroFAST	A simulation tool for hydro-servo-elastic analysis of horizontal-axis water current turbines. This code is based on NREL's FAST code that was developed to simulate horizontal axis wind turbines. Work is currently underway to include added mass effects.
	Hydro-TurbSim	A stochastic, full-field, turbulence simulator for tidal and ocean flows. Hydro-TurbSim is based on NREL's TurbSim code that was developed to facilitate the analysis of horizontal axis wind turbines. The output from Hydro-TurbSim is used as input for the Hydro-FAST simulation tool. A preliminary version of this code has been completed and is undergoing internal testing.

2.3 Reference Models

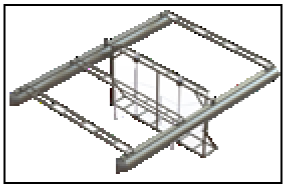
2.3.1 Codes used by the Reference Model Team

The Reference Model Team has used and is currently using a variety of software tools to design, model and assess indicative MHK device performance. The following provides an overview of the various tools used for each Reference Model:

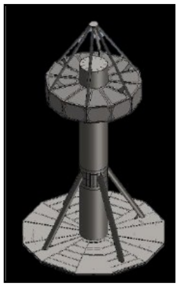
RM 1 (axial tidal turbine) – HarpOpt for blade shape and operating characteristics of rotor, StarCCM+ to model the flow field and FAST for hydro elastic design



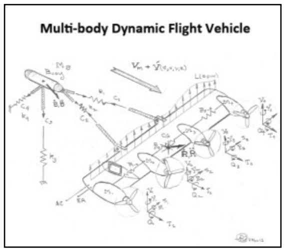
RM 2 (cross flow river turbine) – CACTUS for hydrodynamic performance and ANSYS for structural analysis



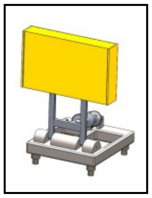
RM 3 (point absorber) – WAMIT and ANSYS-AQWA for hydrodynamic analysis and SolidWorks Simulation for structural analysis



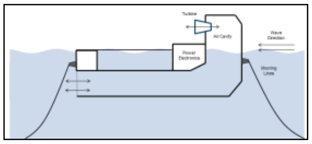
RM 4 (ocean current turbine) – HarpOpt for blade shape and operating characteristics of rotor, StarCCM+ to model the flow field, and FAST for hydro elastic design. OrcaFlex for mooring



RM 5 (surge wave energy converter) – WAMIT for linear response in the frequency domain and AQWA for nonlinear response in the time domain. Solidworks Simulation for structural analysis



RM 6 (oscillating water column) – WAMIT for linear response in the frequency domain and AQWA for nonlinear response in the time domain. Solidworks Simulation for structural analysis. OrcaFlex for mooring.



In general, the following combinations of codes can be used for wave and current reference models:

Table 4 - Reference Model Code Combinations

Wave Device						
Diffraction Dominant Wave Structure Interaction	**Detailed Navier-Stokes Analysis at Key Locations**	**Frequency Domain Equations of Motion**	**Time Domain nonlinear equations of Motion**	**Operational Mooring**	**Survival Mooring**	**Structural FEA Analysis**
WAMIT	CFD	MATLAB	MATLAB/Simulink	OrcaFlex (can do fatigue)	OrcaFlex	SolidWorks Simulation
AQWA	CFD	--	AQWA	AQWA Moor	OrcaFlex	SolidWorks Simulation

Current Device								
Device Type	**Inflow**	**Blade Design**	**Rotor Design**		**Survival**		**Mooring**	
			Prelim.	Final	Prelim.	Final	Linear	Nonlinear
HAT	Empirical	Harp_Opt CACTUS	WT_Perf	STAR-CCM+	HydroDyne	ANSYS	AQWA	AQWA with coupled cable analysis
VAT	Empirical	CACTUS	CACTUS	STAR-CCM+	HydroDyne	ANSYS	AQWA	AQWA with coupled cable analysis

2.3.2 Interaction Between the Reference Model Work and FY09 Lab Call Tasks

The Reference Models will assist industry by providing guidance on the appropriate codes for modeling particular devices. The Reference Model team will develop the models utilizing the full capabilities of the available tools and compare the results of the computer models to validation test results. Information from these comparisons will be used to update the codes, if necessary, and then communicated to industry via a report, outlining the strengths and weakness of each modeling approach. The MHK industry can use this information to make informed decisions on which tools and modeling approaches are best suited for their particular design and modeling needs.

The RM project has already highlighted gaps in existing codes. The weaknesses in certain tools that have emerged have helped DOE understand challenges that developers face. Some of the needs presented in this document have come directly from RM lessons learned. As those were identified, the Labs began applying FY09 Lab Call funds to address those issues.

For instance, Sandia will develop a new package that will be comparable to AQWA. The capabilities of WAMIT, OrcaFlex, and MATLAB/Simulink will be examined through the Reference Model effort to accomplish this activity. Validation tests will be conducted to determine the strengths and weakness of each code. The integration of the experimental results into the comparison of the numerical models will establish a foundation capable of guiding developers towards the most accurate numerical modeling package.

The codes are being partially evaluated as part of the reference model project, in particular, Reference Model 5, a surge device, and Reference Model 6, an oscillating water column. WAMIT is used to predict the linear response in the frequency domain, and AQWA is used to predict the nonlinear response in the time domain. The code will be evaluated against test data, which is expected in the beginning of FY 13.

Blade design codes are employed in the following Reference Models:

- RM 1 Horizontal Axis Tidal Turbine (HATT)
- RM 2 Vertical Axis Current Turbine (VACT)
- RM 4 Horizontal Axis Current Turbine (HACT)

The remaining task for these models is to verify those codes against experimental measurements. Physical model tests are planned for Reference Models 1, 2 and 4. Acquired data will include flow field measurements, along with rotor thrust, torque and RPM. The test results will be compared to predicted results from the Harp_Opt design and performance prediction code and from performance predictions using STAR CCM+ for code verification. In general, for any MHK device, the following measurements are required:

(1) Inflow conditions
(2) Response
(3) Vibration and its forcing function
(4) Stresses and deflections
(5) Fatigue

These measurements are conducted at appropriate model scales from very small (1:100) to full scale.

2.4 MHK Device Design Process and Context for Use of Modeling Tools

The existence and/or development of design and performance prediction codes for MHK technology are certainly important. Equally important is the proper use of those codes. To better comprehend the codes, a reader must be able to understand the overall device design process and where each code fits. The following section will walk through the design process, codes used and testing required for each step in the development of a wave and current device.

The National Labs are developing design processes for both MHK turbines and WEC devices. The processes include defining the discrete steps necessary for a successful design (usually in terms of technology readiness level - TRL), the interaction of the various performance areas (for instance, hydrodynamics and structures) and which codes to use for each step of the design process. An MHK device is a complicated system of systems. As such, it is ultimately desired to have a system of systems design approach in order to capture all of the system interactions in an efficient manner. Both Sandia and NREL are working toward that end. For instance, NREL is currently linking the design of the rotor with the design of the PTO. All interactions between the sub systems are being considered, such as steady and unsteady thrust and torque, revolutions per minute (RPM), etc. The system of system approach will make the process more efficient resulting in reduced design time or the completion of more design iterations for optimization in the same time frame. This system of systems design process development should continue and be expanded to include systems other than just the rotor and PTO.

The following figure depicts how modeling tools fit into the overall design process of a WEC with respect to TRL progression and increasing model fidelity. The six highest priority needs identified in this document are called out, showing which region of the design process they impact.

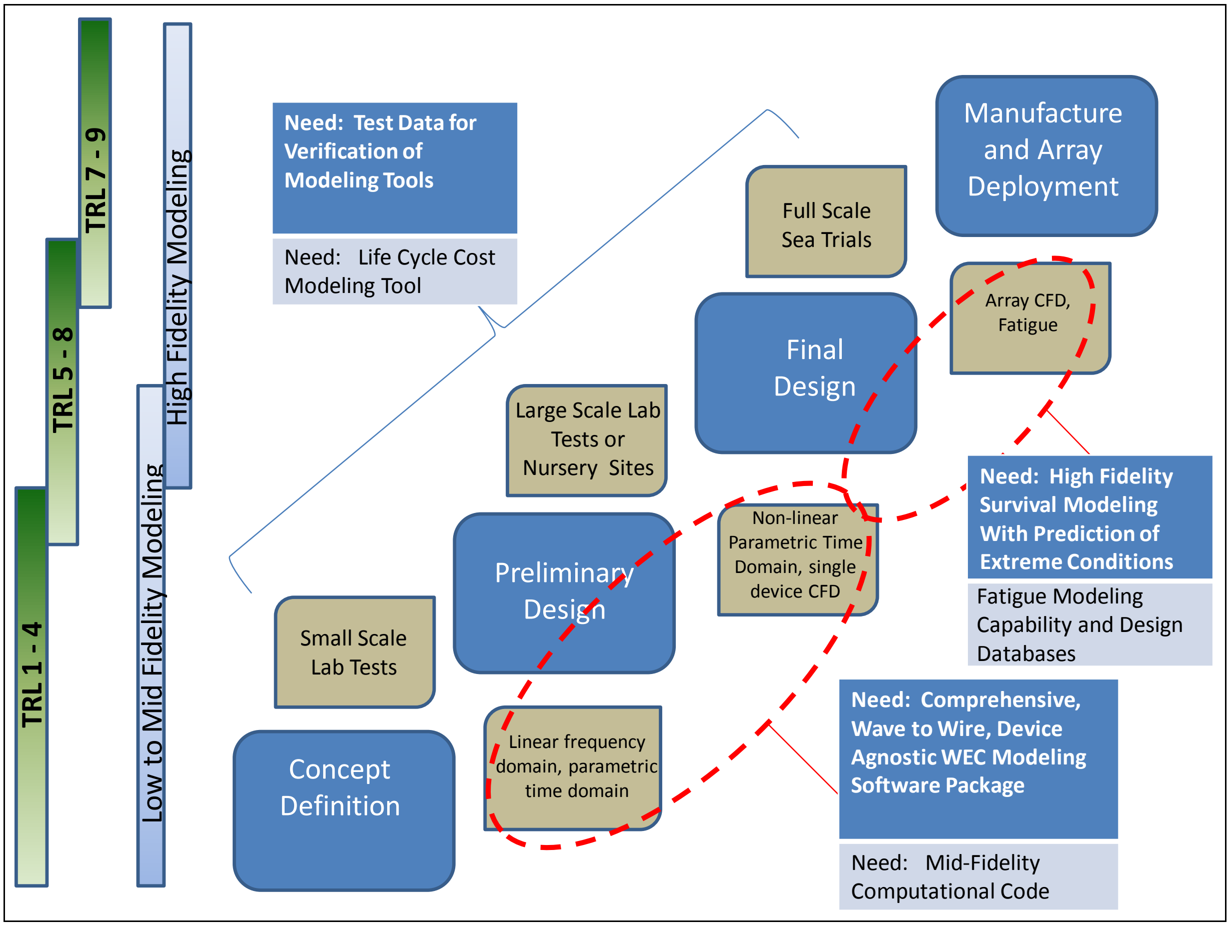


Figure 1 - Design Process & TRL Progression

2.4.1 Wave Energy Convertor Design Process Development

An excellent example of the development of the design process is given by Ruehl (1), where a suggested WEC development process is outlined and relates each stage of development to a corresponding Water Power TRL. In addition to considering code applications, testing is considered as it provides verification of the design performance and feedback to improve the codes and the design. Figure 2 below and the following summarize the design process suggested by Ruehl (1).

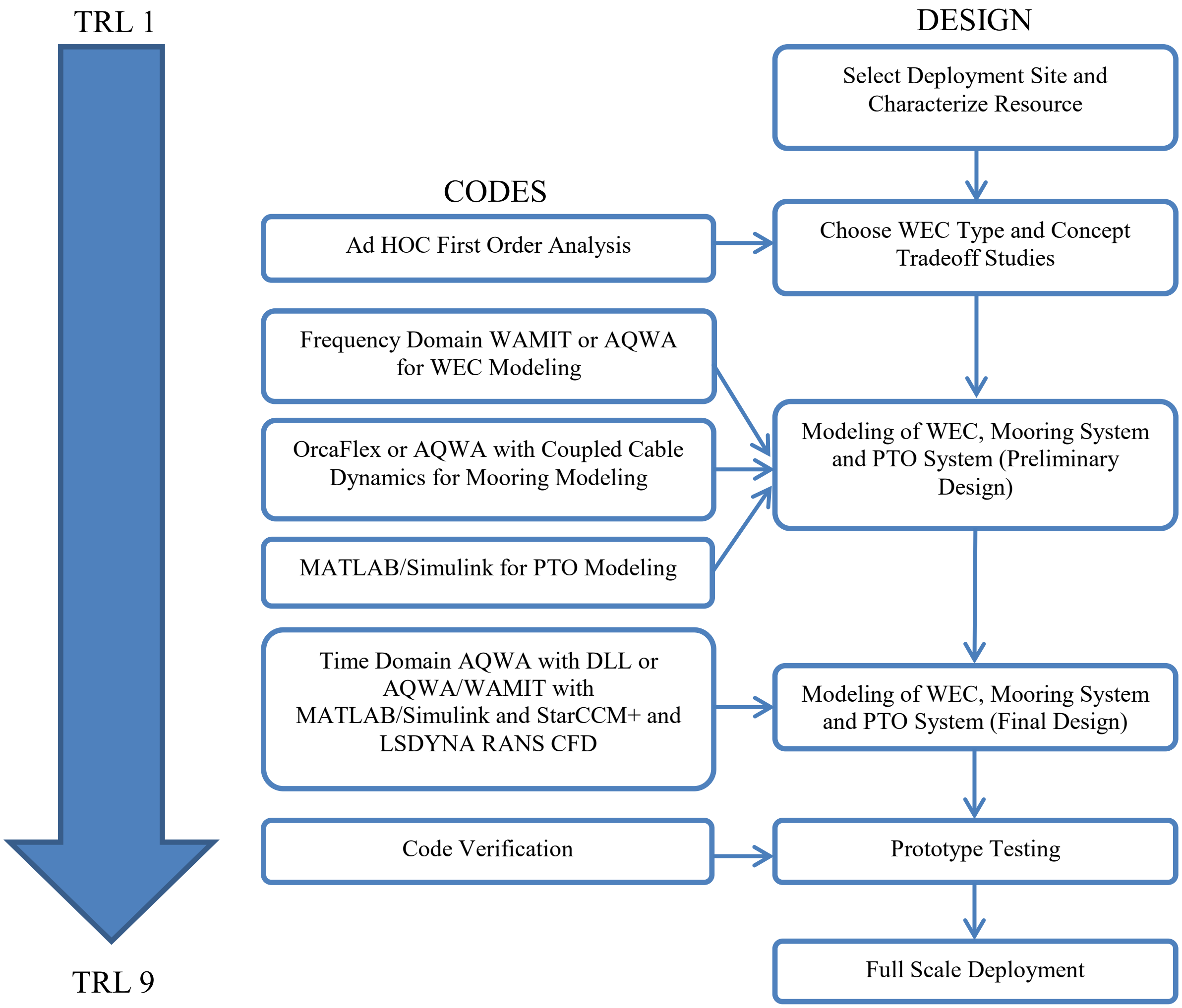


Figure 2 - WEC Design Process

TRL 1-3: The first stage of development is to determine what type of WEC to pursue. For that determination, it is necessary to establish design performance metrics, limitations and constraints, maintenance and survivability. It is also important to establish the Power Takeoff (PTO) that will be used. Once a WEC type is established, several WEC concepts are developed having various design features. For each concept design, the basic physics must be established along with the resulting mathematical relationships. Simplified analyses only are required at this stage of the design.

Small-scale testing (1:25 – 1:100) with no modeled PTO are conducted to obtain relative, qualitative assessment of the concepts. Possible mooring approaches can also be assessed as part of these tests. Tests should be conducted in a wave tank with regular waves. The test results are then compared to expected performance from the design performance predictions for each concept. Once the test results have been assessed and comparisons with predicted performance made, one concept design should be chosen for further design considerations.

TRL 4: TRL 4 design entails three parallel efforts: numerical modeling of the WEC, mooring system and its modeling and PTO system and its modeling. Again, this is a system of systems design, since each subsystem is interdependent of the others and, as such, each subsystem design must be done in parallel.

For initial WEC modeling, linear frequency domain models, such as WAMIT or AQWA, should be used. To account for nonlinearities due to the mooring and PTO systems and control strategies, time domain models should be used, such as AQWA with its time domain solver. An alternate approach for considering nonlinearities is to use the frequency domain response of AQWA or WAMIT with a time domain wraparound in MATLAB/Simulink using the Cummins' impulse response function (2). In addition, if deemed necessary to consider nonlinearities due to viscous effects in the fluid structure interaction, initial considerations for CFD modeling should be undertaken, using, for instance, STAR CCM+.

For mooring system design, OrcaFlex is the industry standard. However, the Coupled Cable Dynamics program has been recently integrated with AQWA by ANSYS, which would be useful to those using the AQWA time domain code, since OrcaFlex requires developing a new 3D model. Since the mooring system is a WEC cost driver, its cost should also be considered at this point in the design. In addition to capital costs, mooring system operation and maintenance costs, feasibility, ease of installation and its translation to different deployment sites should be considered as part of the design.

The first step of the PTO design is to choose between the various methods of power conversion, including direct drive, hydraulic, mechanical and several turbine types. PTO cost, system constraints and limitations are an important part of this choice. Given the choice of power conversion method, the PTO system is typically modeled in MATLAB/Simulink, which is also used to model control strategies.

An important part of TRL 4 stage design is verification testing. Tests should be done at mid-scale (1:10 – 1:25) in a wave tank or a 2D wave flume. Instrumentation should include a motion tracking system and accelerometers. The test model should include the envisioned mooring system and, if possible depending on scale, the PTO. Tests should be conducted in a scaled wave environmental representative of that existing at the proposed full-scale deployment site. Test results should be used to verify the predicted performance of the WEC and to improve the design codes, if necessary, for further design iterations. The WEC resonance periods, Response Amplitude Operators (RAO) for each wave period and response to waves of different steepness should be measured.

TRL 5/6: The next stage of design should employ high fidelity codes, including time domain nonlinear BEM codes, such as AQWA with DLL or AQWA/WAMIT with MATLAB/Simulink, and RANSCFD codes, such as STAR CCM+ and LSDYNA. A systems approach should be taken, so the PTO and control system can be modeled and the design process should be integrated among the subsystems.

Testing for survivability is important at this stage of the design given the harsh environment in which the WECs ultimately operate. Tests should be conducted in a wave tank, at the largest WEC size possible given the tank size. The test model should include a representative model of the mooring system but no model of the PTO, apart from a modeled representation of the mass and center of gravity. Additionally, tests should be conducted with extreme wave conditions representative of the deployment site. The test results will be used to assess survivability and structural integrity and will feed into any required redesign.

In addition to survivability, tests at large scale (1:3 – 1:1) should be conducted to assess performance in normal seas. Tests should be conducted for regular and irregular waves in an appropriately sized wave tank. The test model should include the PTO, mooring and control systems. The results should be used to verify predicted performance and to improve the performance predictions codes, where necessary.

TRL 7/8: Prototype (1:1 scale) testing should be conducted in the open ocean at a location having a wave environment that is representative of the deployment site. Tests should include models of the PTO, mooring, control, data acquisition systems and a method to track incident waves. Prototype testing will verify that the WEC and all subsystems are ready for full-scale deployment and, if instrumented properly, should also be used for further code verification and refinement.

TRL 9: The final stage is full-scale deployment with grid connection. These tests are for certification and demonstration.

2.4.2 WEC Device Measurements

For surface operating WEC designs, an important measurement is the response of the WEC to waves. For some concepts, the response is directly tied generation of electricity, e. g., point absorbers, and for other concepts, e.g., the response is critical to survival. Laboratory measurements under controlled conditions and when deployed under actual forcing function conditions should be conducted. Coincident measurements of the wave characteristics should be captured. Test results will be used to verify response codes for design. The Reference Model Project has identified tuning as a potential discriminator in WEC performance. Point absorber WEC's should tune their response to incoming waves in order to optimize their output. In order to optimize the tuning system properly, knowledge of the incoming waves is required. A wave measurement system should be developed for real time assessment of the incoming waves entering a WEC array.

2.4.3 Current Device Design Process

Lawson et al. (3) provides a process for the preliminary design of a HATT. This effort is designated as a preliminary design, since it was developed as part of the Reference Model task whose primary purpose is to facilitate Cost of Energy (COE) estimates and not to generate a final design. The following summarizes the preliminary design process described by Lawson et al. (3), for Reference Model 1. The same process was used for the preliminary design of Reference Models 2 and 4, a vertical axis and horizontal axis current turbine, respectively. The design process is shown below in Figure 3.

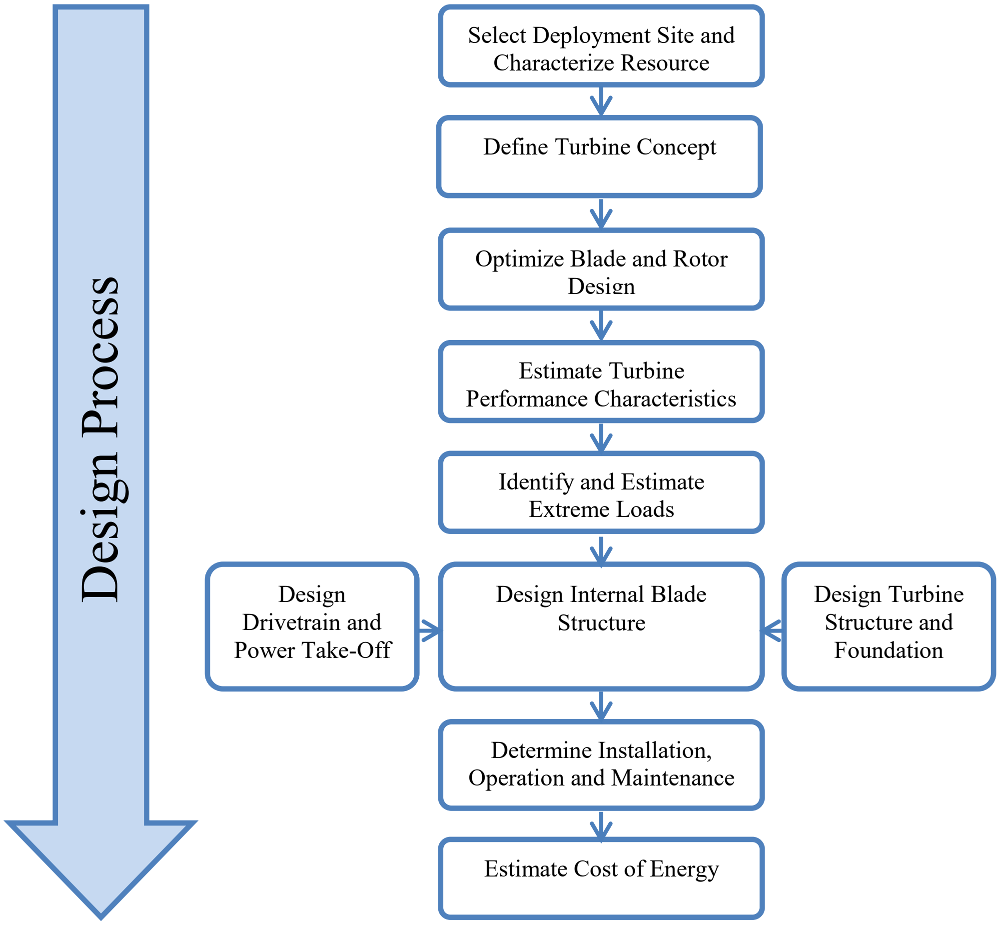


Figure 3 - Design Process for the RM- 1, 2 and 4 (Lawson, et al (3))

The first step of the process is to select the deployment site and characterize its resource. The selection of the deployment site is based on its resource potential, good access to infrastructure for maintenance and repair and access to the electric grid.

The next step is to choose and define the turbine concept that is primarily based on a low COE. Other criteria include sufficient depth such that the tip of the axial turbine rotor does not interfere with marine traffic, high power to minimize COE, and positioning and sizing the rotor to extract the maximum amount of energy given the resource characteristics. For Reference Model 1, a twin rotor configuration was mounted on a tower affixed to the channel bottom. A variable speed, variable pitch control system was selected in order to control rotor thrust and torque and to minimize loads when the rotor is not operating. Reference model 2 is a vertical axis, cross flow river turbine with a twin rotor configuration mounted on a floating frame. Reference Model 4 has four axial flow turbines mounted on a wing that "flies" in an ocean current. It is moored to the ocean bottom and uses a combination of wing lift and buoyancy to control its position in the current.

The next step is to design and optimize the rotor. Harp_Opt was used to design and optimize the blade shape and rotor operating conditions for RM 1 and 4. WT_Perf predicted operation without stall for all normal operating conditions. In addition, high-fidelity CFD predictions of performance were made using STAR CCM+ to verify the BEM predictions. For RM 2, CACTUS was used to design the rotors and to predict their performance. No test data are currently available to compare to predictions.

Rotor survivability is driven by the extreme loads expected to be experienced throughout its life. Extreme load conditions were identified and defined for each of the Reference Models considered. BEM and CFD predictions were performed for the extreme conditions to provide loads for survivability assessments.

The next step is the structural design and performance predictions of the blade. The experience gained in designing wind turbines was brought to bear for the water turbine designs. First, the blade layout is defined. For RM 1 and 4, a code based on wind turbine preliminary structural design, Bir (4), was modified for marine turbine applications and used to conduct the structural design. Ultimate strength and buckling resistance criteria for the selected composite materials were used to compute the required laminate thickness at all selected span wise locations. The code was also used to calculate blade properties, given the thickness distribution, including bending and torsional stiffness, mass, moments of inertia, etc. Given the loads, the assumed materials and their use in the blade construction, the code was exercised to determine the thickness of each material necessary to withstand the extreme loads and also minimize weight. For RM 2, ANSYS was used to conduct the structural design of the blades. The final step is the preliminary design of the structures to which the rotors are mounted.

The design process considered the dimensions and wall thicknesses of the structures sufficient to satisfy the design criteria, including: maximum bending stress, maximum deflection, mismatch of natural frequencies and rotor rotational frequency, load due to rotor maximum thrust and loads due to construction and deployment. If the natural frequencies match the rotor rotation rate, very large vibration amplitudes result, exacerbating failure due to fatigue.

ANSYS was used for RM 2 and FAST was used for RM 1 and 4 for the structural design to determine dimensions and wall thicknesses. Given the dimensions, wall thicknesses, and the resulting masses, the first natural frequencies of the structures were calculated. If the first natural frequency matched or was close to the rotor rotation rate, design iteration was performed with new dimensions and/or wall thicknesses.

The reader is reminded that the design method just described was for a preliminary design for estimating COE. A final design would involve higher fidelity codes, (STAR CCM+ for the fluid dynamics and Finite Element Method (FEM) codes such as ANSYS or NASTRAN), and more stringent criteria.

Turbulent gusts cause unsteady pressures on the blades of a rotor that lead to blade vibration, which can result in fatigue failure of those blades. This is unacceptable due to the expense incurred for replacing the blades and the downtime while the blades are being replaced. The turbulent inflow should be measured to better understand the physics thereof, to provide guidance for developing a code for predicting turbulence and to serve as a database for code verification. Code development is also required and, due to the physics involved, Large Eddy Simulation (LES) CFD or some other advanced method is needed. The application of the resulting code for verification will be site specific, so the measurements must be made at the same site. For good verification, several sites should be considered.

Given the mean and turbulent inflow, the unsteady lift or pressures generated by the blade is calculated. Several codes (see Table 2) are available for these calculations. The blade unsteady response results in blade vibrations. Analytical and Finite Element Analysis (FEA) methods are available for these vibration predictions. The blades will be fabricated of composite materials with an internal structure much like that of a wind turbine blade and airplane wing. The vibration codes have been verified for those particular applications and their composite material layups but not for MHK turbine blade designs. Vibration measurements should be made on very large model scale or full scale blades in both the laboratory, under controlled conditions, and at the site, under actual conditions. For the onsite tests, coincident measurements should be made of the turbulent inflow and the unsteady pressures. No vibration measurements should be made on small to mid-scale blades due to the difficulty in adequately scaling the composite material and its layup. That is, one can scale the blade overall dimensions accurately but not the composite layup since the composite material thickness cannot be scaled. The test results would be used for code verification and to better understand the physics of the process.

To better understand the physics of fatigue failure, coupon testing and full scale testing to failure should be conducted. These tests will help identify the failure mechanisms of the particular composite materials and layups used in MHK turbine blades. The blade modeling for FEA will then be able to capture the failure modes with adequate modeling fidelity. Fatigue failure is a reasonably well understood phenomenon that has several methods for modeling already established. Those methods need to be assessed for MHK blades using the previously discussed test data and the best method selected for application.

2.4.4 Current Device Measurements

Measurements are in general, lacking. A variety of measurements are needed to validate codes for MHK current devices. Let us first consider the input to the various design codes. The codes that are used to design the blades and predict the rotor performance require the flow field steady and turbulent parameters as input. At present, measurements are the only viable way to accurately define these parameters. In addition, these parameters are site specific. Therefore, measurements of mean velocities, turbulent intensities and turbulent length scales should be made at each site of interest, in order to provide input for reliable blade designs and performance predictions. In addition, the measurement results will lead to a better understanding of the physics of these flow fields, which might lead to future prediction capabilities.

In addition to flow field measurements, a variety of other measurements are equally important. For turbines, blade and tower vibrations, as they impact fatigue, are required to verify codes and to monitor the health of the device. Due to scaling issues for composite materials, fatigue measurements are required at large model scale or full scale. Measurements should be conducted in the laboratory, under controlled conditions, and when deployed, under actual forcing function conditions. Composite material coupon testing of fatigue failure should be done to help identify the failure mechanisms. Fatigue tests on a full scale blade are currently underway at NREL for a commercially designed and fabricated blade. Similar tests should be performed on other blade designs, since their material, geometry and internal structure will likely be different than the one currently being tested. In addition, testing is underway by SNL and Montana State University to ascertain the effects of the marine environment on the composite materials of choice. For instance, submersion in water can saturate the composite material which can lead to changes in its material properties and those changes are being measured for typical water turbine composite materials.

3. Gaps and Barriers

As mentioned previously, this report is by no means an exhaustive study of the modeling needs of the MHK industry nor is it a full characterization of the modeling capabilities of the National Laboratories. However, even in its “first pass” approach, it is clearly evident that nine gaps and or barriers are present in the MHK tool development arena:

3.1 Comprehensive, Wave to Wire Device Agnostic WEC Modeling Software Package

The package should be modularized and integrate pre-processor, preliminary design, and post processor capabilities. A framework should be developed to use existing commercial and open source codes. Interface codes and modular design would allow the user to plug in appropriate modules to model any type of WEC. By using primarily existing codes, development of this tool is expected to take 2-3 years. As additional open source codes are developed in parallel and commercial codes are adapted to more accurately predict WEC performance, they can be integrated into the framework. A longer term goal would be to create open source versions of all commercial codes in order to reduce cost to the user. Given the flexibility described previously, this development effort is not trivial and will require software architecture expertise and / or utilization of software development best practices such as Agile Software Development.

3.2 Mid-Fidelity Computational Code

Cost-effective and faster numerical methods that can capture non-linear and turbulent effects should be developed. Potential codes are fast and inexpensive to run but miss some of the important physics, while CFD codes capture more of the important physics but are expensive and time consuming to run. Therefore, there is a need to develop a code for solving those equations whose assumptions, cost and run-times are between the potential and CFD codes.

3.3 Life Cycle Cost Modeling Tool

The Reference Model project has developed device specific cost models; however a generic framework needs to be defined and a modeling tool created that allows a user to predict the cost of any MHK system. The tool should be designed in a manner such that it may be integrated into the overall design process. Ideally a smooth and efficient transfer of data will be supported, allowing for COE to be included as a key design driver. Long term, this could become a module in the Wave to Wire modeling package (see 3.1).

3.4 Open Source Versions of Hydrodynamic Modeling Tools

Existing commercial codes such as WAMIT and AQWA are capable of accurately modeling offshore platforms; however they rely on certain assumptions that do not accurately represent WEC’s. Open source versions of these codes should be developed and adapted to the unique needs of WEC devices with the capability to model mooring, PTO, control and environment in the time domain.

3.5 High Fidelity Survival Modeling – Prediction of Extreme Conditions

Survivability is critical to the design of WECs and is driven by extreme wave events. At present, there is no capability to predict the extreme waves required for the design process. CFD holds the greatest promise for developing a viable code due to the water/air interface and its ability to model this complicated interaction.

3.6 Fatigue Modeling Capability and Design Databases

System and component level fatigue modeling capabilities as well as improved fatigue design databases are needed to better evaluate the durability and survivability of MHK devices. Offshore oil and gas developers cite fatigue as one of the major challenges of their industry. Fatigue testing is essential to build up the knowledge base and for code verification.

3.7 Simulation of Multiple WEC's on a Single Structure

Capabilities are limited for modeling multiple WEC's that are attached to a single rigid structure. Software exists for simulating multiple rigid bodies such as ships or oil and gas platforms, but not single bodes with multiple rigid parts that are constrained to move together.

3.8 Simulation of Turbines on a Moored or Floating Structure

There are limited capabilities for simulating the dynamics (i.e. motion and performance) of moored or floating turbines. These types of devices experience different operating conditions than wind turbines and wind codes need to be adapted to simulate energy converter operation on a moving structure.

3.9 Test Data for Verification of Modeling Tools

Measurements are needed across the board both for verification of existing tools as well as creation of new ones. This applies to both wave and current simulation packages at any stage in the design process. Any modeling development effort should include a testing program to generate the necessary information to evaluate the accuracy of the performance predictions. Partnerships between National Labs and DOE funded industry demonstration projects at any TRL could provide model verification data. Consideration should be given to acquiring data through Annex V for this purpose.

4. Acknowledgements

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4. Bir, G. S., "Computerized Method for Preliminary Structural Design of Composite Wind Turbine Blades," Journal of Solar Energy Engineering, 123(4), 2001.

Appendix A – National Lab Staff / Software Tool Expertise Matrices

Model Topic Area	Codes	SNL Water Power Personnel
Structural Dynamics and Statics	PRESTO*, ANSYS, SolidWorks Sim	R. Jepsen, D. Griffith
Computational Fluid Dynamics	Stormflow†, CFX, Star CCM+, OpenFoam††	R. Jepsen, E. Johnson, S. James
Environmental Hydrodynamics	SNL-EFDC††, HSPF††, CUENCAS††	J. Roberts, J. Barco, E. Johnson, S. James
Fluid-Structure Interaction	AWQA, WAMIT	D. Bull, K. Ruehl
Mooring	ORCAFlex	D. Bull
Turbine Performance Codes	CACTUS	M. Barone, E. Johnson

*Developed at Sandia, license required
†Commercial
††Open Source

Model Topic Area	Codes	NREL Water Power Personnel
Structural Dynamics and Statics	ANSYS†, SolidWorks Sim†	F. Driscoll, M. Masciola
Computational Fluid Dynamics	Star CCM+†, FLUENT†, SPhysics†, OpenFoam††	M. Lawson, Y. Yu, Y. Li
Environmental Hydrodynamics	Hydro-TurbSim‡, WaveSim‡	L. Kilcher
Potential Flow Wave Hydrodynamics	AWQA†, WAMIT†, Wave-BEM‡	Y. Yu, M. Lawson, Y. Li
Mooring	OrcaFlex†, MAP‡	M. Masciola, F. Driscoll, Y. Li, Y. Yu, M. Lawson
Turbine Performance Codes	Harp_Opt‡, Hydro-FAST‡	M. Lawson, Y. Li
Multi-body and power-take-off simulator	MPower-Sim‡	M. Masciola, F. Driscoll, Y. Li, Y. Yu, M. Lawson

‡Developed at NREL(open source)
†† Open Source
†Commercial