Next-Generation Marine Energy Software Needs Assessment

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EXECUTIVE SUMMARY

The U.S. Department of Energy (DOE) Water Power Technologies Office's (WPTO) initial investment in marine energy software was driven by needs[1] identified over a decade ago [4]. WPTO-funded research was first launched because of a U.S. congressional mandate that called for the DOE to officially research marine energy technologies, which also established the DOE WPTO in 2008.[2] A congressional mandate requested the WPTO to evaluate a variety of marine energy devices,[3] establish baseline levelized cost of energy estimates, and provide an overall report to Congress. This congressional mandate led to the Reference Model Project (RMP), for which WPTO funded a national multi-laboratory team to develop these reference models, based on state-of-the-art designs of six marine energy converter archetypes that consisted of three current energy converters and three wave energy converters (WEC). Each device was designed to operate for a specific marine resource, thus allowing the devices to serve as reference models for future studies. The RMP congressional report cited the need for improved marine energy software to handle a variety of device designs, as well as a need to standardize performance outputs. Without validated software packages and established metrics, information presented to the WPTO by technology developers could be incorrect or inaccurate and result in misleading conclusions. The recommendation to coordinate WPTO investment in software for numerical modeling and analysis was given a high priority because it would directly fill needs at the time, and focused funding would amplify impact. By sponsoring software development, WPTO would provide industry developers, university researchers, and national laboratories software that could be used, customized, and advanced, thus supporting the overall advancement of marine energy.

In parallel with marine energy road-mapping efforts, lessons learned from the RMP led to WPTO's initial investment in software development. In 2012, Cardinal Engineering led the first software needs assessment based on software development gaps identified during the RMP. Cardinal Engineering collaborated with Sandia National Laboratories (SNL) and National Renewable Energy Laboratory (NREL) to conduct a needs assessment for modeling tools and generated a report describing the software landscape at the time, which identified areas of need [12]. The report noted that software was often developed without formal coordination or collaboration, from a variety of funding sources, and did not have standardized inputs and outputs. The Cardinal Engineering report identified nine significant industry needs based on the software landscape in 2012. These industry needs directly led to the first wave of software development.

Over the past decade the marine energy industry has continued to grow and evolve, with new concepts and technologies constantly being pursued. Additionally, the field of computing is vastly different today than it was 5 or 10 years ago. By utilizing advanced software and hardware architectures, like graphics processing units as well as parallelization and high-performance computing resources, software can produce higher quality or a higher volume of outputs. These software and hardware resources can enable the marine energy community to exploit computational advancements from other research fields, including machine learning, differentiable programming, and controls co-design. Better integration of existing software and development of potential new

[1] A "gap" refers to the lack of a particular modeling tool, and a "need" refers to the lack of a particular modeling tool that would accelerate the design process and lead toward more rapid commercialization.

[2] In 2008, the Wind and Water Power Program (WWPP) was established. In 2016, the WWPP was split into two offices: Water Power Technologies Office (WPTO) and Wind Energy Technologies Office. WPTO has funded DOE's marine energy research ever since. For the purpose of clarity, we will refer to the program as WPTO.

[3] At that time, referred to as marine and hydrokinetic energy devices

software is necessary to take advantage of trends in modern computing and respond to the current and future needs of the marine energy community.

After a decade of U.S. and international marine energy software development, WPTO decided to launch the Next-Generation Marine Energy Software effort to achieve the following goals:

1. Catalog the available numerical tools and provide this information to the marine energy community.
2. Develop an informed road map for future WPTO software investments.

The primary objective of the Next-Generation Marine Energy Software effort is to prioritize the development of the next-generation of WPTO-sponsored software that will support the current and future needs of the evolving marine energy industry.

To better understand the present marine energy software landscape and industry needs, WPTO tasked SNL and NREL to update the needs assessment by identifying existing software gaps, identifying software needs, and assisting WPTO in planning the next wave of marine energy software development. The proposed effort involved cataloguing and analyzing the available data on existing software related to marine energy. The marine energy software landscape has vastly changed from a decade ago. As of early 2023, there are nearly 230 different software packages utilized by the marine energy sector (see the Marine Energy Software knowledge hub on PRIMRE.org), compared to a decade ago when the Cardinal Engineering survey identified approximately 40 software packages. In 2012, the marine energy software landscape was captured in two tables, whereas the current marine energy software landscape required development of a software database to collect and categorize software. For more information about the marine energy software database developed for this landscaping study, see Appendix A: Marine Energy Software Database.

Establishing a software database was necessary due to the breadth of the present day software survey compared to the survey from 2012 [12]. The 2012 survey was completed by cataloguing the software used at SNL and NREL, and for the RMP. The present day software landscape expanded upon the 2012 survey to include publicly available information on marine energy software and establish categories of interest (refer to Appendix A for details). Care should be taken when comparing this present day landscape to the survey from 2012, since they differ in approach and scope. However, they can be used to understand how WPTO's investments have contributed to the present day marine energy software landscape.

An overview of the updated marine energy software landscape is in Figure 1, shown as a tree map. A tree map is a visual way to display hierarchical data, where each rectangle's area is proportional to the corresponding data value. The tree map highlights that the marine energy software landscape is heavily focused on the categories shown in Table 1[4]. For more information, refer to the Software Landscape section.

[4] refer to Appendix A: Marine Energy Software Database for definitions

Table 1. Categories With Highest Quantity of Relevant Software, Based on Tree Map (Figure 1)

Category	Highest Quantity
Discipline	Hydrodynamics and Site Characterization
Technology Readiness Level (TRL)	1–3
Technology	Wave Energy
Collection Method	Modeling
Life Cycle	Design
Country of Origin	International
License	Open Source
Method	Wave Spectral Analysis
Programming Language	Python, Fortran, and MATLAB
Interface	Graphical

These marine energy software trends largely reflect the overall state of marine energy. Marine energy is not yet a commercial technology (e.g., technology readiness level [TRL] 9), so it's reasonable that the software landscape is skewed toward lower TRLs (e.g., TRL 1–3). While some members of the marine energy sector have advanced to deployments, most technologies are skewed toward the earlier life cycle stages (e.g., design). These software trends also align with the focus on disciplines like hydrodynamics and site characterization, over disciplines like supply chain and manufacturability. The absence of or smaller rectangular size of data in the tree map (Figure 1) highlights gaps in currently available software; however, identifying software needs based on gaps alone is an incomplete view, as a gap does not necessarily imply a need. Nonetheless, the marine energy software landscape results provide valuable insight into where investments have been made, as well as areas where future investments could fill a gap.

Once the marine energy software landscape was updated, the SNL and NREL team solicited feedback on the identified gaps to assess if these gaps were indeed needs. Feedback was solicited through one in-person and one virtual workshop (refer to Section 3.2 for more information). Participant feedback was then used to identify marine energy software needs, using established qualitative data analysis methods (e.g., by performing an affinity analysis). The affinity diagram generated from the Next-Generation Marine Energy Software workshop data is shown in Figure 2. The affinity diagram groups feedback into multi-level themes, using a bottom-up approach. Third-level themes are generated directly from participant feedback (interpreted notes are in yellow); they are in blue and are the most specific. Second-level themes are groups of third-level themes; they are in pink. First-level themes are groups of second-level themes; they are in green and are the broadest. Refer to the Affinity Analysis section for more information, to Appendix C for first-, second-, and third-level themes, and to the high-resolution PDF for the workshop attendee quotes. These marine energy software needs will be used to guide future investments by WPTO.

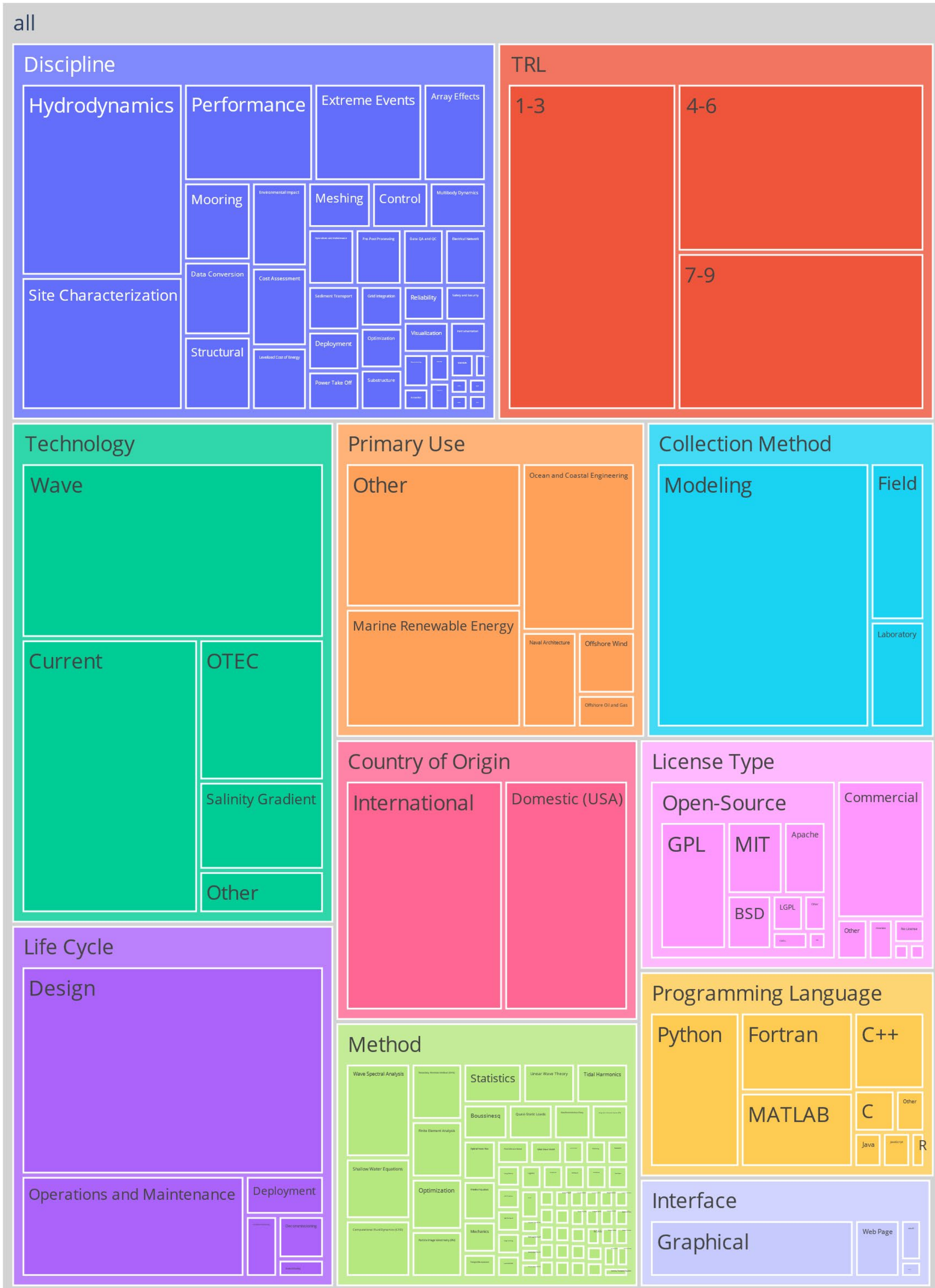

Figure 1. Tree map of the marine energy software database. Each rectangle has an area proportional to the quantity of relevant software, e.g., the discipline with the highest quantity of relevant software is Hydrodynamics, followed by Site Characterization and Performance

Figure 2. Digital affinity diagram developed by NREL and SNL from marine energy software workshop data (screenshot from Miro). A high resolution version of the above affinity diagram is provided at the end of the Executive Summary for readers interested in reviewing the details.

The affinity analysis provides an overview of the needs that emerged from the workshop participant feedback. First-level needs and their impact on the marine energy industry are listed in Table 2.

For example, new software could require several years (more than 3) of development before the software could become easily accessed, used, and maintained, and training available for the marine energy community. Conversely, adoption of state-of-the-art computational resources, or leveraging existing software for new applications, could have an immediate impact on the marine energy community. The long-term need for access to high-quality data is persistent and remains a need from the 2012 Cardinal Report. The need for high-quality data is relevant across all modeling and software development but was strongest for data-driven analyses (e.g., levelized cost of energy), where the quality of the analysis is highly dependent on currently unavailable, and often volatile, data (e.g., supply chain, materials, vessels, moorings, anchors, etc.). Furthermore, the success of algorithms developed to complete full system optimizations and apply machine learning approaches is based on the quality of the training data. Because of this sensitivity, any databases developed as training data for these approaches need to be verified for accuracy, breadth, standardization, and elimination of any biases.

The authors recommend that all WPTO-funded software projects have formal software development plans, written prior to initiating development, that are evaluated and revised on a regular (e.g., annual) basis. Software development plans should include the following elements: programming language and license (e.g., open source or proprietary), distribution and maintenance protocols (e.g., version control and team workflows), quality assurance best practices[5] (e.g., testing and continuous integration), documentation and user training (e.g., help boards and user support), and software sustainability, i.e., how to continue software maintenance without direct WPTO funding (e.g., indirect funding or sunsetting).

This recommendation is based on feedback from the community, and lessons learned from the past decade of WPTO investment in software. History has shown that unsupported software is essentially dead software, and all software should consider best practices. Marine energy is a rapidly evolving field, and strongly reliant on adaptable open-source software. Thus, software development plans must consider how to best achieve the intended impact on the marine energy community, and strongly weigh factors directly impacting the user community and long-term sustainability. Sustainable software should consider open-source software business models that enable continued development and support (dual-licensing, software as service, etc.; refer to Appendix D: Open-Source Software Business Models). Additionally, software should follow software quality best practices, such as compliance with ISO/IEC 9126.

Based on lessons learned from related fields, like wind energy, marine energy software needs will likely depend on TRL. As marine energy advances to higher TRLs, original equipment manufacturers will likely develop and maintain custom software relevant to their specific technology and market. However, there is significant benefit in having a validated and trusted open source MRE software package(s), that are maintained by WPTO, for the purposes of review, analysis, and results comparisons independent of other software. This open source MRE software can also be used for educational purposes and workforce training as the marine energy industry grows and matures while providing a low barrier of entry to new entrants and suppliers who may want to develop of components and subsystems.

[5] Examples of quality assurance best practices includes the systems development life cycle (SLDC) and applied methodologies such as Agile.

A high resolution PDF of the affinity diagram is available in Figure 3 for review. The authors request and welcome feedback from the broader marine energy community on the needs assessment. Please contact the authors of this report if you would like to provide additional feedback.

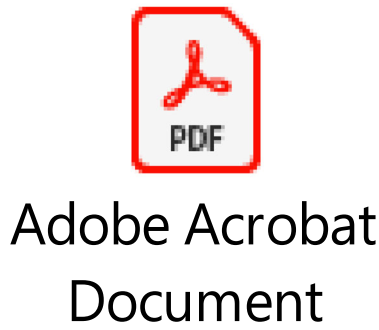

Figure 3. High resolution affinity diagram, double-click to access

Table 2: Prioritized Needs from the 2022 Next-Generation Marine Energy Software Assessment

First-Level Need[6]	Impact of Need on Marine Energy Industry	Opportunities
"We need to leverage state-of-the-art computational resources"	• Inability to utilize modern computing technologies results in slower development • Inability to leverage graphical processing units (GPUs) and high-performance computing (HPC) scalable resources such as Amazon Web Services results in slower development and inefficient workflows • Inability to exploit advancements in machine learning (ML) to analyze performance data to improve system design and operation results in limited innovation and optimization • Inability to perform simulations and optimizations with existing software results in slower development and inefficient workflows	• Develop new tools compatible with GPUs and HPC • Develop and validate machine learning (ML) applications for marine energy • Develop tools for integrated optimization workflows (e.g., Wind-plant Integrated System Design and Engineering Model [WISDEM] for offshore wind) and gradient-based optimization • Establish checklists or requirements for compatibility with advanced computing resources • Develop easily adaptable marine energy applications leveraging state of the art computing resources • Develop capabilities to support digital twins and hardware-in-the-loop for marine energy
"We need to overcome existing software limitations in order to advance marine energy technology"	• Inability to use existing marine energy software to meet marine energy needs results in lack of confidence in software outputs • Inability to use existing software across all marine energy technologies results in lack of confidence in software outputs and limited innovation • Inability to couple existing marine energy software results in inefficient workflows	• Incorporate additional device configurations and physics into existing software, especially for current energy technologies. • Establish applicability bounds of existing software (e.g., limitations of underlying theory) • Invest in existing software used by marine energy community (e.g., MoorDyn, OpenFAST, Capytaine) • Leverage existing tools to improve marine energy software interoperability (e.g., MHKiT, preCICE) and

[6] The affinity analysis processes used "I want" language, however this converted to "We need" for the needs assessment

		develop application programming interfaces (APIs) that are consistent and easy-to-use.
"We need to consider many factors and trade-offs when developing or using new marine energy software"	• Programming language, license, software speed, interoperability, and deployment on HPC systems impact interoperability and result in slower development and inefficient workflows • Differing opinions on commercial versus free and open-source software (consensus that the marine energy industry is willing to pay for tools if they are deemed valuable and save development time) results in differing approaches to software use and adoption[7]	• Invest in new software (e.g., framework, language) capable of supporting multiple technologies (e.g., hybrid systems, wave, current, wind, and solar energy) and products (e.g., power, water, carbon) • Prioritize development of multiphysics, multidomain tools (e.g., including power take-off and control co-design) • Support collaborations between MRE and offshore wind and solar on software development for hybrid systems.
"We need open-source software that is trusted, free, and easy to use"	• Open-source software is low cost, but if difficult to use, results in a lack of confidence and is a barrier to adoption (i.e., labor costs for software adoption)	• Encourage adoption of software quality best practices from ISO/IEC 25010 (e.g., documentation, examples, testing, continuous integration) • Improve verification and validation of existing marine energy software • Develop easily adaptable validated models using open-access datasets • Support User Interface/User Experience (UI/UX) development and marine energy applications for existing software to lower the learning curve, and reduce adoption time (i.e., reduce software adoption time burden) • Invest in long-term software development and support, e.g., new features, user support (issues), trainings (recorded webinars), and applications

[7] For example, the two leading software for wave and tidal/current modeling are WEC-Sim and OpenFAST, respectively. However, WEC-Sim is built in the MATLAB/Simulink environment where OpenFast is built in Fortran/C++.

		• Establish dedicated Research Software Engineers to support open-source software
"We need to advance marine energy technology, but data access is a barrier"	• Lack of relevant open-source validation data results in lack of confidence in software outputs • Lack of relevant data results in poorly defined inputs for data-driven analyses and lack of confidence in outputs	• Invest in open-access data sets and code comparison for model validation • Apply numerical models and machine learning to fill known data gaps (e.g., cost drivers, failure rates) • Update reference models, and include potentially groundbreaking technologies (e.g., distributed embedded energy converter technologies (termed DEEC-Tec), kites, ocean thermal energy conversion, salinity gradient) • Numerical reference models would not only demonstrate proper use of available simulation tools, but also provide example data and predicted performance results • Improve standardization of data outputs (e.g., units, descriptors) and improve usability of large data sets for analysis by algorithms (i.e., ML)

ACRONYMS AND DEFINITIONS

Abbreviation	Definition
AOP	annual operating plan
API	application programming interface
BEM	boundary element method
CEC	current energy converter
CFD	computational fluid dynamics
COE	cost of energy
CPU	central processing unit
DOE	U.S. Department of Energy
EWTEC	European Wave and Tidal Energy Conference
FOWT	floating offshore wind turbine
FY	fiscal year
GPL	general public license
GPU	graphical processing unit
HPC	high-performance computing
IoT	Internet of Things
IO&M	installation, operations, and maintenance
LCOE	levelized cost of energy
MEC	marine energy converters
METS	Marine Energy Technology Symposium
MHK	marine and hydrokinetic[8]
ML	machine learning
MRE	marine renewable energy[1]
NREL	National Renewable Energy Laboratory
OREC	Ocean Renewable Energy Conference
OSS	open-source software
OSTI	Office of Scientific and Technical Information
OTEC	ocean thermal energy conversion

[8] refers to marine energy

Abbreviation	Definition
PRIMRE	Portal and Repository for Information on Marine Renewable Energy
PTO	power take-off
RMP	Reference Model Project
ROS	robot operating system
R&D	research and development
SNL	Sandia National Laboratories
TRL	technology readiness level
U.S.	United States
WEC	wave energy converter
WPTO	Water Power Technologies Office

1. BACKGROUND AND MOTIVATION

The first marine energy research thrust began in the 1970s. Wave energy research was largely done in Europe, led by seminal researchers like Salter, Budal, and Falnes [1]-[4]. They explored innovative concepts in wave energy conversion (e.g., the Salter Duck), established theoretical energy capture limits (e.g., Budal's limit), and developed control strategies to maximize energy capture (e.g., latching control). Ocean wave energy conversion has a rich history, and readers are directed to [5] for greater historical perspective. The use of turbines to convert energy from thermal ocean currents, particularly the Florida Current, was proposed by U.S. researchers in 1974 [6].Overseas, the development of modern technology for conversion of tidally driven flows began in the United Kingdom in the early 1990s [7].

1.1. Water Power Technologies Office, 2008

Meanwhile, in the United States, research into renewable energy technologies at that same time was primarily focused on wind and solar energy. It was not until a congressional mandate that the U.S. Department of Energy (DOE) officially launched research into marine energy technologies and established the DOE Water Power Technologies Office (WPTO) in 2008.[9] A congressional mandate requested the WPTO to evaluate a variety of marine energy devices,[10] establish baseline levelized cost of energy (LCOE) estimates and provide an overall report to Congress.

1.2. Reference Model Project, 2010

In 2010, the WPTO launched the Reference Model Project (RMP), which funded a multi-laboratory team to develop reference models based on state-of-the-art designs of six marine energy converter (MEC) archetypes. Each device was designed to operate for a specific marine resource, thus allowing the devices to serve as reference models for future studies. The six reference models consisted of three current energy converters (CEC) and three wave energy converters (WEC) [8]:

- Reference Model 1: Tidal Current Turbine
- Reference Model 2: River Current Turbine
- Reference Model 3: Wave Point Absorber
- Reference Model 4: Ocean Current Turbine
- Reference Model 5: Oscillating Surge Flap
- Reference Model 6: Oscillating Water Column.

The RMP generated publicly available technical and economic data sets [9], which resulted in an official report that was presented to the U.S. Congress. The congressional report included the need for improved marine energy software to handle a variety of device designs, as well as the need to standardize performance[11] outputs. Without validated software packages and established metrics, information presented to the WPTO by technology developers could be incorrect or inaccurate and result in misleading conclusions.

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[9] In 2008, the Wind and Water Power Program (WWPP) was established. In 2016, the WWPP was split into two offices: Water Power Technologies Office (WPTO) and Wind Energy Technologies Office (WETO). WPTO has funded DOE's marine energy research ever since. For the purpose of clarity, we will refer to the program as WPTO.

[10] At that time, referred to as marine and hydrokinetic (MHK) energy devices.

[11] WPTO has provided support since 2009 for U.S. experts to participate in the International Electrotechnical Commission's Technical Committee 114 (IEC TC114) Marine Energy – Wave, tidal and other water current converters.

The RMP started under the assumption that sufficient software and modeling tools were already available, or could be developed quickly, to simulate the performance of the six listed marine energy devices. But as described by the congressional report, the reality was quite different, prompting WPTO to fund numerical analysis tools to support the program's research goals. As the development and maintenance of software tools cost program dollars that could be used across other parts of the WPTO portfolio, there was an opportunity for industry, academia, and national laboratories to leverage software investments to help maintain an active user community. These were the considerations that would eventually lead to the first round of WPTO-funded software investments intended to support the U.S. marine energy industry.

1.3. Road-Mapping, 2012

After the RMP, significant effort was placed in road-mapping future marine energy development. Road-mapping efforts were conducted to better understand the overall device design process and where each software fits. These efforts included Reed et al. [10] whose work established marine energy technology readiness levels (TRLs), and Ruehl and Bull [11], whose work proposed a design-to-commercialization road map for wave energy development, shown in Figure 4. The design-to-commercialization road map proposed in Ruehl and Bull's work highlighted the need for a combination of numerical modeling and experimental testing at different stages of TRL development. This established the need for marine energy software capable of modeling a wide range of TRL development stages.

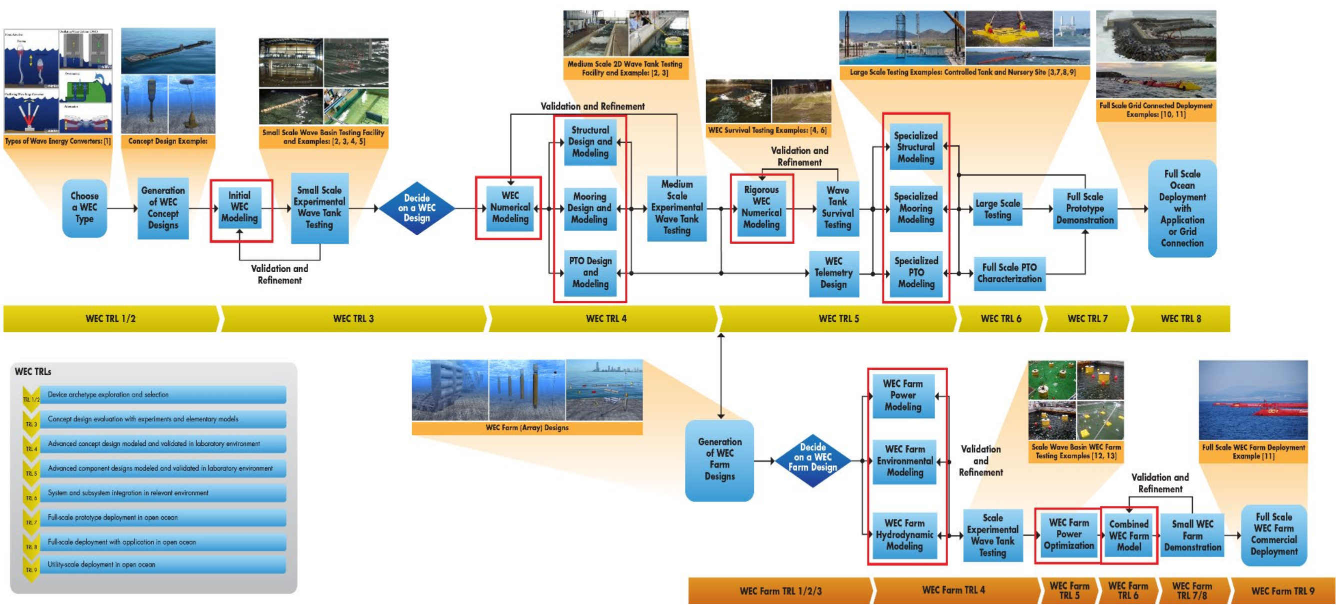

Figure 4. WEC Development Road Map: Design to Commercialization, October 2012. Stages highlighted in red include numerical modeling.

1.4. Marine Energy Software Needs Assessment, 2012

In parallel with marine energy road-mapping efforts, lessons learned from the RMP led to WPTO's investment in software development. In 2012, Cardinal Engineering led the first software needs assessment based on software development gaps identified during the RMP. A need refers to the lack of a particular modeling tool that would accelerate the design process and lead toward more rapid commercialization [12]. Cardinal Engineering collaborated with Sandia National Laboratories

(SNL) and National Renewable Energy Laboratory (NREL) to conduct a needs assessment for modeling tools and generated a report describing the software landscape at the time, identifying areas of need [12]. Excerpts from this report show lists of the commonly used software at the time,[12] with wave codes given in Table 4, and tidal/current codes given in Table 5. The report also noted that software was often developed without formal coordination or collaboration, from a variety of funding sources, and did not have standardized inputs and outputs. The Cardinal Engineering report identified nine significant industry needs, shown in Table 3. A subset of these needs is also included in Figure 4 to show how these needs map to the design process and TRL progression. Figure 4 highlights the numerical model development starting in the lower-left corner with single-device linear frequency domain models progressing to the upper-right corner with multi-device computational fluid dynamics models; however, the progression of effort is not linear, as the required level of expertise and access to computing power leads to a greater investment in hardware and time to implement properly. The required level of training and access to high-performance computing resources to complete higher-fidelity calculations can be a significant barrier to wider adoption by the marine energy community, even if open-source software is available. These considerations should be kept in mind when reviewing the catalog of existing marine energy software, as they can help one understand where larger investments in software development may be required to provide tools that can match the needs identified in the upper-right corner of Figure 4.

Additionally, the Cardinal report highlighted that most of the existing software were commercial packages leveraged from related fields (refer to Table 4 and Table 5). At the time, there were very few open-source packages developed for marine energy applications. The lack of open-source software[13] was also a notable result of Topper and Ingram [13], following a survey of software for modeling wave and tidal energy applications in use at the time, shown in Figure 5.

Based on these findings, investment in open-source software (OSS) development became a priority for WPTO, because it had the potential to:

- Reduce the cost barrier for access to software
- Address the unique challenges of modeling marine energy devices
- Modify source code to meet end-user needs.

This aspect of the marine energy software landscape has changed dramatically in the intervening decade, largely because of strategic funding decisions by funding agencies like WPTO. There is now an abundance of OSS available to the marine energy community, details of which are addressed in the Software Landscape section of this report.

[12] The 2012 report notes that, "While there are many more codes in existence than could be applied to MHK devices, *the tables* [sic] list the codes commonly used for the modeling of MHK technologies."
[13] At that time, referred to as community-developed software.

Table 3. Prioritized Needs, from "Progress Report on the Development of Design Tools for Wave and Current MHK Devices," Cardinal Engineering [12]

	Need	Impact of Need on Marine Hydrokinetic (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 cost of energy (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 create a 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 WECs 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 are essential to all model development efforts.	Applies to all modeling efforts (high priority)

Table 4. Existing Wave Codes, from "Progress Report on the Development of Design Tools for Wave and Current MHK Devices," Cardinal Engineering [12]

Type	Code	Specific Behavior/Interaction	Open Source or Commercial
Marine Dynamics	ANSYS AQWA	Boundary element method (BEM) for device and mooring dynamic loads in frequency and time domains	Commercial
	OrcaFlex	Mooring dynamics evaluation	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 nonlinear 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 and 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 5. Existing Tidal/Current Codes, From "Progress Report on the Development of Design Tools for Wave and Current MHK Devices," Cardinal Engineering [12]

Type	Code	Specific Behavior/Interaction	Open Source or Commercial
Marine Dynamics	ANSYS AQWA	Boundary element method (BEM) for device and mooring dynamic loads in frequency and 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 and 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 and vertical-axis turbine 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

Type	Code	Specific Behavior/Interaction	Open Source or 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

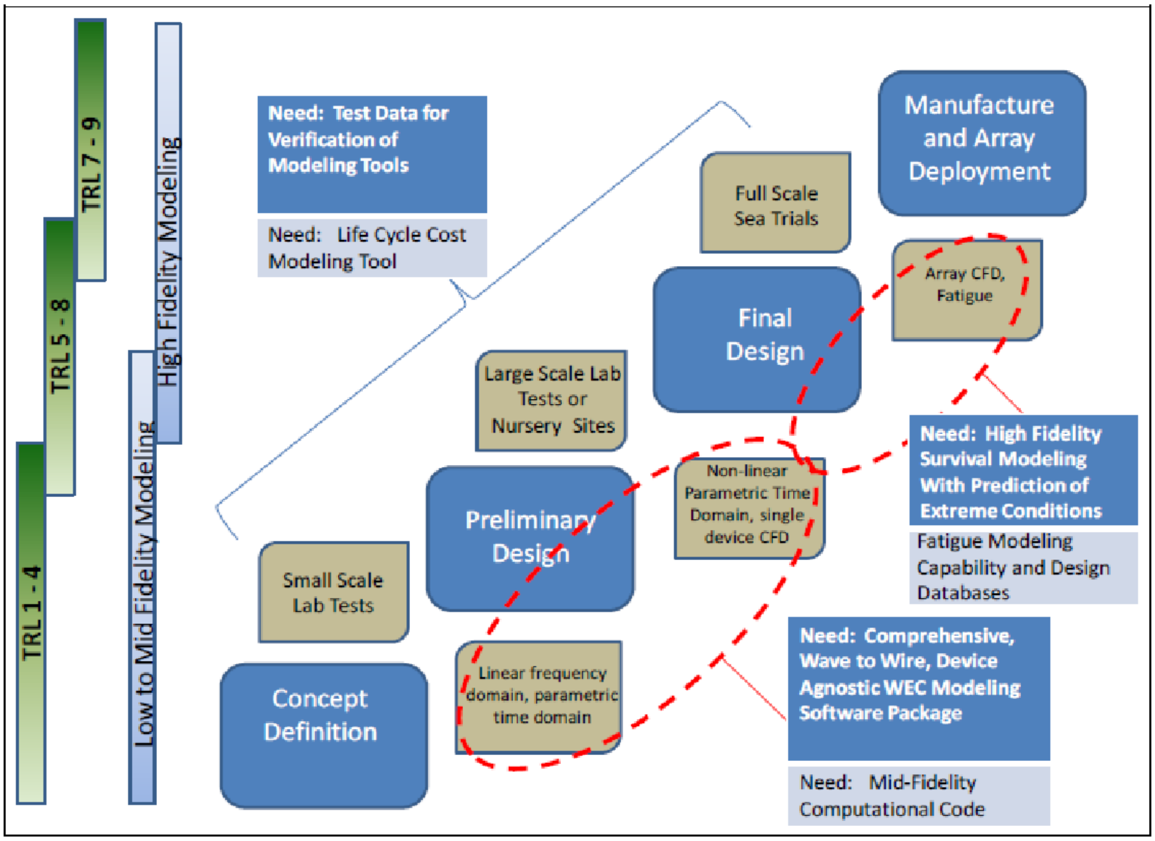

Figure 5. Design process and TRL progression, from "Progress Report on the Development of Design Tools for Wave and Current MHK Devices," Cardinal Engineering [12]

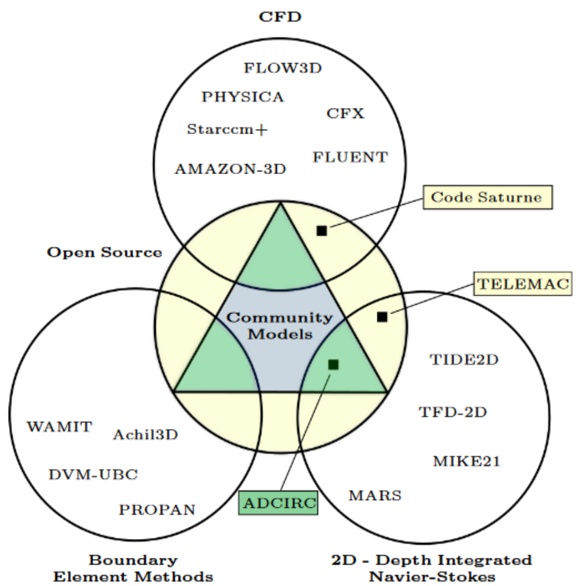

Figure 6. Venn diagram showing groupings of in use software packages. Highlighted are open-source packages and, within that grouping, community-developed models. Reprinted from Figure 1 in Topper and Ingram [13].

1.4.1. WEC-Sim, 2013

WPTO's role sponsoring the development of marine energy software is a response to the recommendations from the Cardinal Engineering needs assessment. In 2013, WPTO funded the WEC Modeling Project, co-led by SNL and NREL, which launched development of the WEC-Sim software. WEC-Sim is a numerical modeling software that models the dynamics of WEC systems that are composed of rigid and flexible bodies, power take-off systems, and mooring systems.

Since its initial release in 2014, NREL and SNL have jointly developed, released, and maintained new versions of the WEC-Sim software [14]. WEC-Sim has become a popular tool for WEC numerical modeling across academia and industry, for a variety of different wave energy device types [15] —and even for some non-wave energy applications [16] such as floating offshore wind turbines (FOWTs), and hybrid FOWT-WEC systems [17]. Furthermore, experimental validation studies have been conducted with a range of different device types, building confidence in WEC-Sim's versatility and ability to accurately model physical systems [18]. WEC-Sim's success was recognized with the second best score at WPTO Peer Review in 2019, a perfect score at the 2022 WPTO Peer Review [19], and through a R&D 100 Award[14] in the fall of 2021[20].

The long-term success and impact of software like WEC-Sim are direct results of WPTO's continued strategic investment in marine energy software development. Demonstrating this point, Figure 7 shows the activity on WEC-Sim's GitHub repository since its initial v1.0 release in 2014. Without continued support, these projects would not still be relevant nearly a decade after their initial investment. However, much of the software available ten years ago (listed in Figure 5, Table 4, and Table 5) and OSS projects funded by WPTO after the needs assessment are no longer used or

[14] The R&D100 Awards is the only science and technology awards competition that recognizes new commercial products, technologies, and materials for their technological significant that are available for sale or license. The R&D 100 Awards program identifies and celebrates the top 100 revolutionary technologies of the past year.

supported today. This fact highlights the importance of strategic investment and long-term support for future marine energy software development (refer to Appendix E for more information).

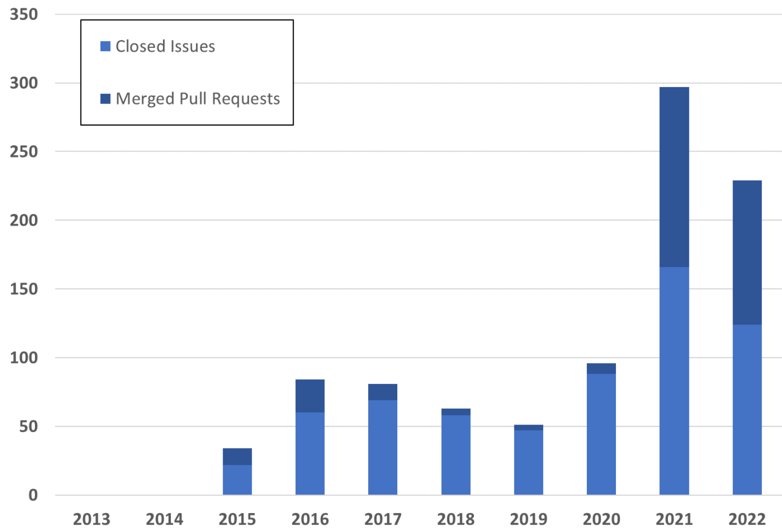

Figure 7. Activity on WEC-Sim's GitHub repository since its v1.0 release in 2014

1.4.2. OpenFAST, 2018

The open-source software OpenFAST [21] has been funded primarily by the DOE Wind Energy Technologies Office (WETO) since its first production release in 2018. OpenFAST is based on the long-standing wind turbine simulation code FAST, which NREL began developing more than 20 years ago, also through primarily WETO funding. It is a reduced-order engineering model for the simulation of land-based and fixed and floating offshore wind turbines. OpenFAST is a restructuring of FAST that aims to better support an open-source developer community and allow more flexibility in coupling to external software through increased modularity.

Within the last five years, the DOE WPTO and ARPA-E have invested significantly in current energy technologies (including tidal, ocean, and riverine), with funding aimed at developing new, economically competitive CEC designs and community-scale and grid-scale marine energy projects [22], [23]. These projects require numerical models that can analyze the performance of new CEC designs. Recent funding has supported work at NREL to adapt OpenFAST for axial-flow turbine CECs and develop a control co-design framework for CEC design and optimization that would include OpenFAST as its highest fidelity model. However, there is no centralized or long-term WPTO funding to support the development of numerical modeling tools such as OpenFAST for current energy converters. Furthermore, there is no support for developing modeling tools for other CEC topologies, such as cross-flow turbines, oscillating hydrofoils, kites, ducted turbines, or Archimedes' screw designs.

1.4.3. MoorDyn, 2017

MoorDyn is an open-source mooring system dynamics software designed to work in concert with other simulation tools. The software is based on a lumped-mass discretization of a mooring line's dynamics and adds point-mass and rigid-body objects to enable simulation of a wide variety of mooring and cabling arrangements. MoorDyn began in 2014 as an independent model development project by Dr. Matthew Hall during his graduate studies at the University of Maine. Initially developed in C++, it was coupled with NREL's FAST v7 floating wind turbine simulator and was validated against 1:50-scale floating wind turbine test data. This validation generated interest at NREL and prompted the creation of a separate Fortran implementation of MoorDyn that became a core module in FAST v8. Additional collaborations with researchers at Politecnico di Torino and NREL's water power team led to coupling of the C++ implementation with MATLAB/Simulink tools, including WEC-Sim [25]. Primary funding for MoorDyn's development from 2014 to 2019 came from the Natural Sciences and Engineering Research Council of Canada.

Beginning in 2019, Hall and MoorDyn's development moved to NREL, and a number of new capabilities were added with funding from WETO, WPTO, ARPA-E, and the National Offshore Wind Research and Development Consortium. The majority of funding was for wind energy applications, resulting in significant new modeling improvements, but without corresponding updates to the WEC-Sim-MoorDyn coupling to allow use of these new features with WEC-Sim. Beginning in 2022, the C++ version of MoorDyn underwent significant refactoring and current MoorDyn development efforts sponsored by WPTO are focused on properly integrating these external contributions to prepare for an updated coupling with WEC-Sim. MoorDyn is also implemented as a core module in OpenFAST following the FAST framework and thus can provide an open-source option for wave and tidal/current developers to utilize for mooring system design.

1.4.4. Funding Across Highlighted Software

The three software packages described previously, WEC-Sim, OpenFAST, and MoorDyn, represent the commonly used open-source software about wave energy, current energy, and mooring systems for a range of marine energy technologies (excluding ocean thermal energy conversion [OTEC] and salinity gradient). These software packages were all highlighted by the marine energy community during the outreach efforts described later in this report. However, the development and support (e.g., funding) across the three software packages vary substantially. Disparate funding priorities can be traced back to Table 3, where Needs 1 and 4 assigned a high priority to open-source WEC modeling, whereas Need 7 assigned a low priority to current energy and mooring model development due to the comparatively small current energy resources in the contiguous US and more limiting research budget at that time.

The high priority assigned to open-source WEC modeling has paid off in the large-scale adoption and wide recognition of the WEC-Sim software, which can be attributed, in part, to the investment from WPTO over the last decade. Conversely, the low priority assigned to open-source software for current energy and mooring means MoorDyn and OpenFAST have not achieved the same level of adoption by the marine energy community due to, in part, piecemeal funding by WPTO, which resulted in limited development and support over the past decade.

1.5. Next-Generation Marine Energy Software, 2022

Identifying needs and allocating research and development (R&D) funding for technology advancement is a challenging exercise. Funding agencies must balance existing stakeholder needs with strategic investments addressing future needs. Identifying future needs is inherently challenging, but failure to do so can result in short-term investments that do not support a long-term strategy to support the marine energy community toward commercialization. Since the establishment of the marine energy research program, WPTO has prioritized investment in software development. Even with limited and fluctuating funding levels, WPTO has continued to focus its foundational R&D on efforts that benefit the broader R&D community. Over the past decade, this rudimental R&D has focused on developing open-source marine energy software that can be adapted and modified to meet end-user needs.

The initial software needs assessment performed by Cardinal Engineering resulted in the first wave of WPTO-sponsored marine energy software development. These software development projects responded to both short- and long-term needs. Predicting the long-term success of a software project is challenging, while some of these software packages are no longer in use, others have active and growing user bases nearly a decade later. The success of these projects, as measured by their adoption and impact on the marine energy community, has resulted in a paradigm shift in the way marine energy software is used and developed. A decade ago, the marine energy community was heavily reliant on closed-source commercial software packages leveraged from related industries. As of 2023, there is an abundance of OSS developed for marine energy applications that can be customized to meet end-user needs because of dedicated funding by U.S. and international governmental renewable energy programs who have emphasized the development of OSS.

WPTO's initial investment in marine energy software was driven by needs identified nearly a decade ago. However, the needs that constituted funding then are not applicable today. Marine energy is a constantly growing and evolving field, with new concepts and technologies being pursued. Additionally, the field of computing is vastly different today than it was 5 or 10 years ago, and the marine energy software landscape understanding must evolve according to recent ventures. The identification, investment, and development of new software is needed to take advantage of trends in modern computing and respond to the current needs of the marine energy community.

After a decade of U.S. and international marine energy software development, WPTO decided to launch the Next-Generation Marine Energy Software effort to achieve the following goals:

1. Catalog the available numerical tools and provide this information to the marine energy community.
2. Develop an informed road map for future WPTO software investments.

The primary objective of the Next-Generation Marine Energy Software effort is to prioritize the development of the next-generation of WPTO-sponsored software that will support the current and future needs of the evolving marine energy industry. An overview of the Next-Generation Marine Energy Software Task approach is provided in Figure 8. The Data Gathering effort was focused on collecting information about the existing marine energy software landscape. The Needs Assessment reviewed the existing suite of marine energy software, identified gaps, and solicited feedback from the marine energy community to identify numerical modeling and simulation needs. A "gap" refers to the lack of a particular modeling tool, and a "need" refers to the lack of a particular modeling tool that would accelerate the design process and lead toward more rapid commercialization [4]. Thus, all gaps are not necessarily needs. By engaging the marine energy community, and through coordination with WPTO, the team of multiple U.S. national laboratories will develop a software development plan for the next generation of marine energy software tools. This software development plan will be based on current and future areas of strategic need identified by the marine energy community.

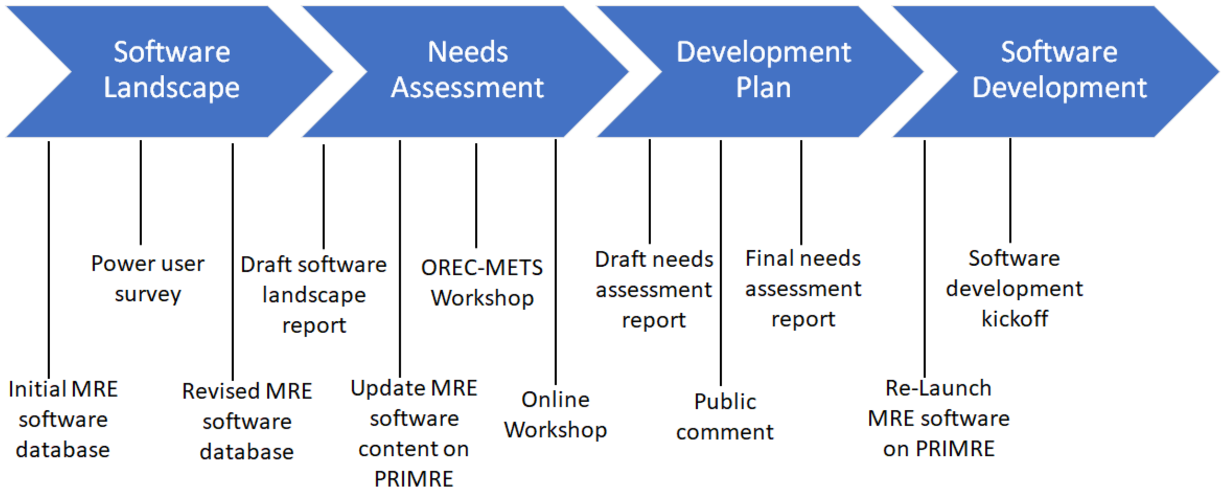

Figure 8. Next-Generation Marine Energy Software Timeline

2. SOFTWARE LANDSCAPE

The current marine energy software landscape (has vastly changed from a decade ago. A major difference is the quantity of software applicable to marine energy. There are now nearly 230 different software packages utilized by the marine energy sector, compared to a decade ago when the Cardinal Engineering survey identified approximately 40 software packages Figure 9. In 2012, the marine energy software landscape was captured in two tables, whereas the current software landscape required development of a database to collect and categorize software. For more information about the marine energy software database developed for this landscaping study, see Appendix A.

An overview of the current marine energy software landscape is shown in Figure 9, demonstrated as a tree map. A tree map is a visual way to display hierarchical data, where each rectangle's area is proportional to the corresponding data value. For this tree map, the size is proportional to the number of relevant software packages, e.g., the discipline with the highest number of software packages is hydrodynamics, followed by site characterization and performance.

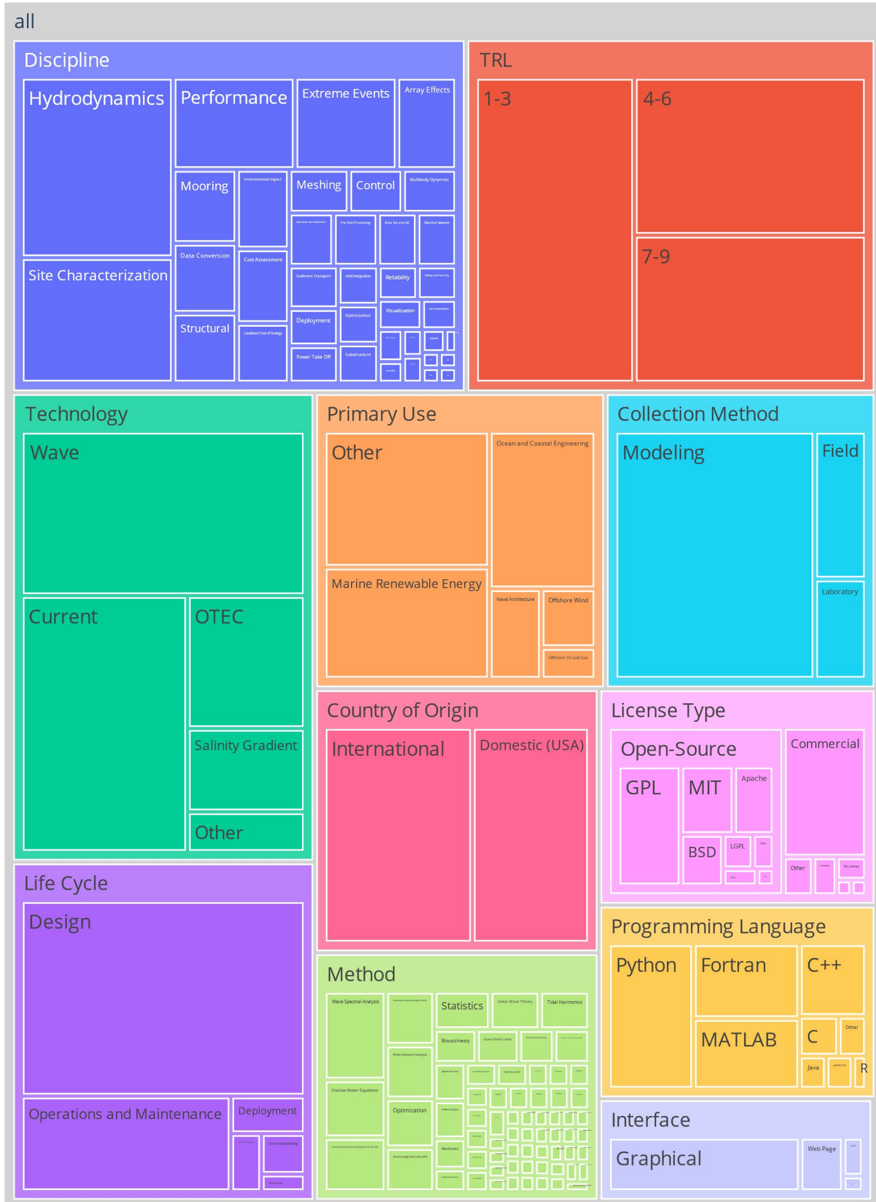

Figure 9. Tree map of the marine energy software database. Each rectangle has an area proportional to the quantity of relevant software, e.g., the discipline with the highest quantity of relevant software is Hydrodynamics, followed by Site Characterization and Performance

The tree map highlights that the marine energy software landscape is heavily focused on the categories shown in Table 6[15].

[15] Refer to Appendix A Marine Energy Software Database for definitions.

Table 6. Categories with highest quantity of relevant software, based on Tree Map (Figure 9)

Category	Highest Quantity
Discipline	Hydrodynamics and Site Characterization
Technology Readiness Level (TRL)	1-3
Technology	Wave Energy
Collection Method	Modeling
Life Cycle	Design
Country of Origin	International
License	Open Source
Method	Wave Spectral Analysis
Programming Language	Python, Fortan, and MATLAB
Interface	Graphical

These marine energy software trends largely reflect the overall state of marine energy. Marine energy is not yet a commercial technology (i.e., TRL 9), so it is reasonable that the software landscape is skewed toward lower TRLs (e.g., TRL 1–3). While some members of the marine energy sector have advanced to deployments, most technologies are skewed toward the earlier life cycle stages (e.g., design). These software trends also align with the focus on disciplines like hydrodynamics and site characterization over disciplines like supply chain and manufacturability. The absence of (or smaller rectangular size of) data in the tree map highlights gaps in currently available software. From the tree map alone, it is reasonable to conclude that the next-generation of marine energy software should focus on the following:

- **TRL:** Higher TRLs (e.g., TRL 4–6 and TRL 7–9)
- **Life Cycle**: Later life cycle phases (e.g., manufacturing, deployment, condition monitoring, and decommissioning)
- **Technology:** Current energy, salinity gradient, and OTEC
- **Collection Method**: Laboratory and field.

However, identifying software needs based on gaps alone is an incomplete view, as a gap does not necessarily imply a need. Nonetheless, the marine energy software landscape provides valuable insight. The software landscape is used to frame further discussion about the needs for the next generation of marine energy (refer to Section 3 Needs Assessment).

With a better understanding of the existing marine energy software landscape, the SNL and NREL project team solicited public feedback on the identified gaps to assess if these gaps were indeed needs. The public feedback solicitation was held through one in-person and one virtual workshop (for more detailed information on workshop content, please see Section 3.2). The participant feedback collected during the workshops was then used to identify marine energy software needs using an affinity analysis method. The affinity diagram generated from the Next-Generation Marine Energy Software workshop data is shown in Figure 2. First-level themes are in green, second-level themes are in pink, third-level themes are in blue, and interpreted notes are in yellow. Refer to Appendix C for first-, second- and third-level themes. These marine energy software needs will be used to guide future investments by WPTO. A high-resolution PDF of the affinity diagram can be made available upon request.

2.1. Discipline

Discipline is defined as "applicable functionalities of the software." Figure 10 shows the breakdown of software disciplines. Hydrodynamics, site characterization, performance, and extreme events dominate, primarily due to fundamental research into the feasibility of marine energy technologies. More industry-focused disciplines such as manufacturing, materials, and the supply chain are underrepresented, a reflection of the currently limited industrial base for marine energy technology. There are not yet original equipment manufacturers mass-producing marine energy devices. As most manufacturing is by custom request, dedicated manufacturing software is not available.

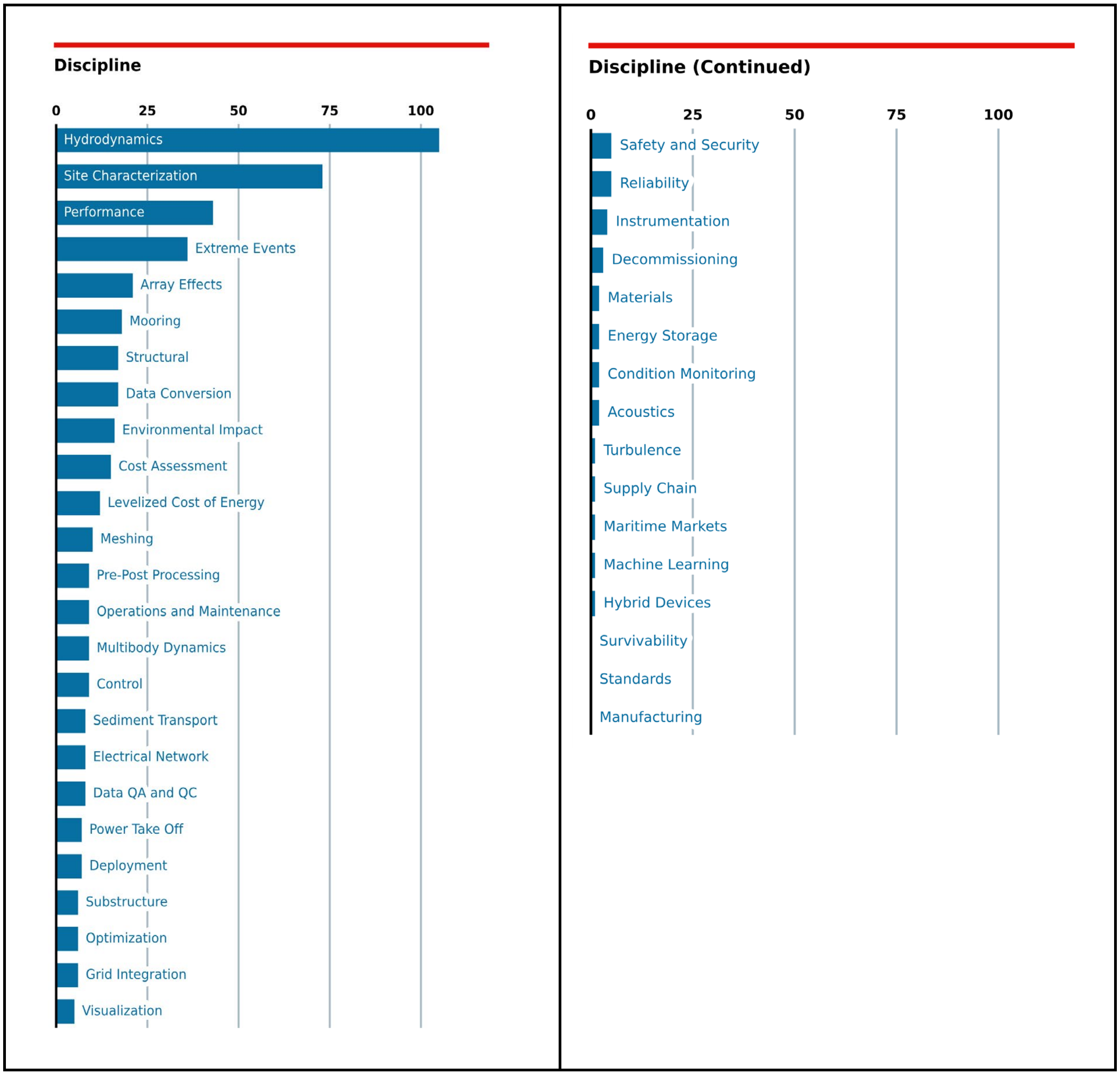

Figure 10. Marine energy software by discipline

2.2. Technology Readiness Level

TRL is defined as "applicable TRL ranges of the technology supported by the software." Figure 11 shows the breakdown of marine energy software by TRL. TRL 1–3 is highest, followed by 4–6 and then 7–9. In general, this is an accurate reflection of the marine energy industry, where considerable R&D is being conducted, with some prototype and full-scale deployments underway.

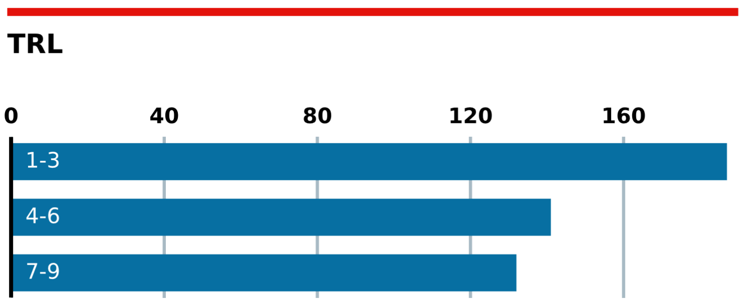

Figure 11. Quantity of Marine energy software by TRL

2.3. Technology

Technology is defined as "marine energy technologies applicable to the software." Figure 12 shows the breakdown of marine energy software by technology. Wave and current energy software are highest. A smaller number of software packages support OTEC and salinity gradient technologies. Figure 13 shows the relationship between technology and TRL where each of the technologies are well represented by the TRL ranges.

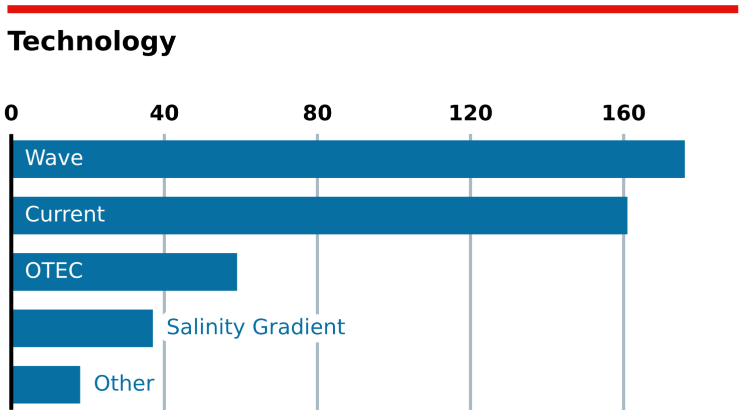

Figure 12. Quantity of Marine energy software by technology

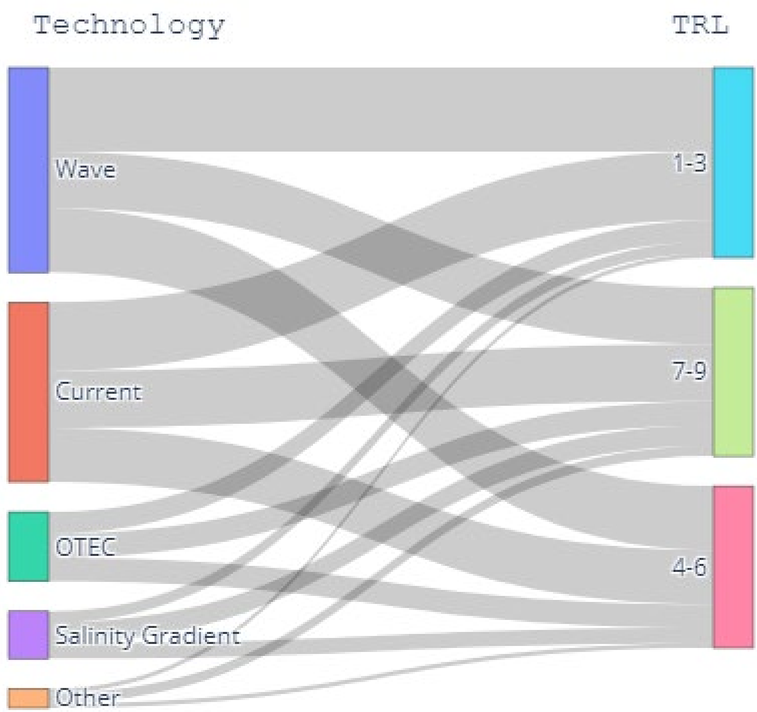

Figure 13. Sankey diagram showing relationship between technology and TRL

Figure 14 is a sunburst diagram that shows the relationship between technology and methods. The sunburst diagram highlights the top methods for each technology. For example, the top wave methods are wave spectral analysis and BEM, and the top current methods are shallow water equations and primitive equations. Whereas the top methods for both wave and current technologies are PIV and CFD. These results highlight the need for any software development to be applicable to multiple offshore renewable technologies to maximize impact and value. These methods are described further in the Methods section.

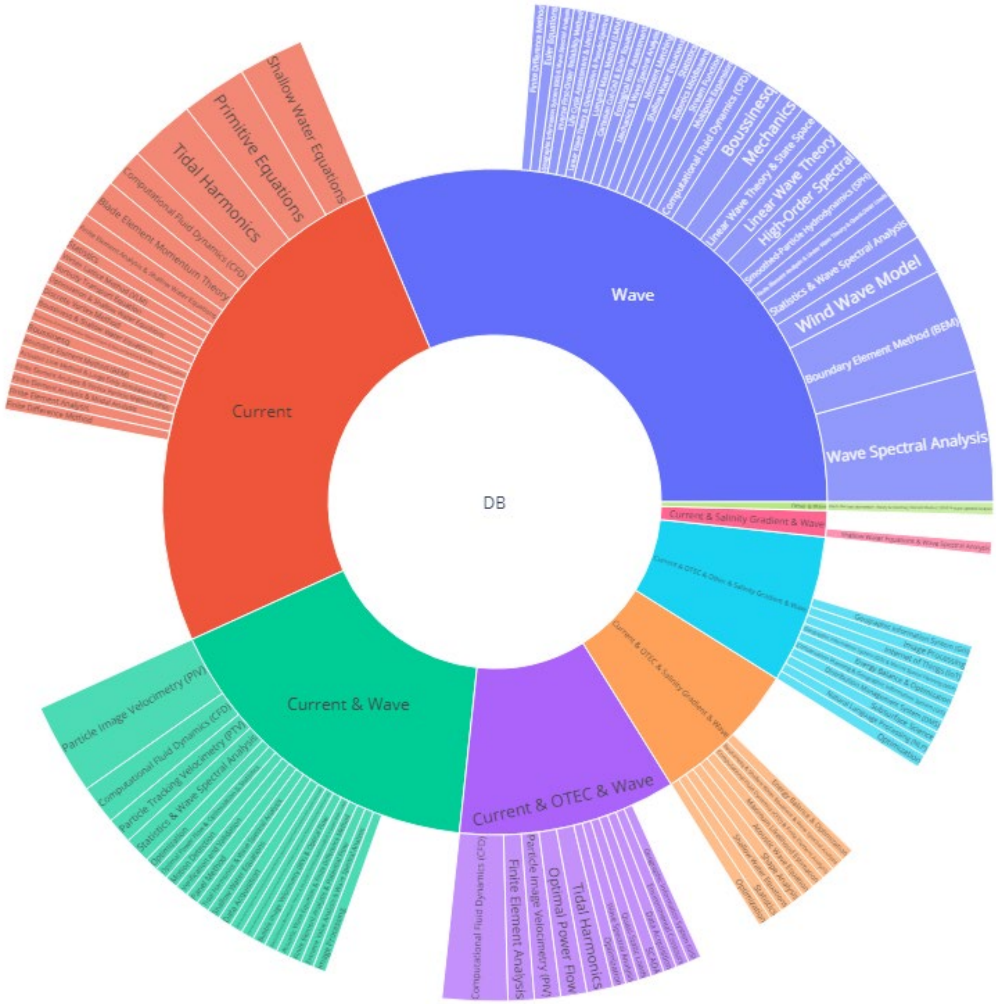

Figure 14. Sunburst diagram showing relationship between technology and method. Each technology is grouped by the cost common methods, e.g., the most common Wave method is Wave Spectral Analysis, and the most common Current method is Shallow Water Equations.

2.4. Primary Use

Primary use is defined as "the primary sector applicable to the software." Figure 15 shows the breakdown of marine energy software by primary use. Software developed for marine energy applications is highest,[16] followed by software developed for ocean and coastal engineering. The prevalence of ocean and coastal engineering software is likely due to many resource assessment tools.

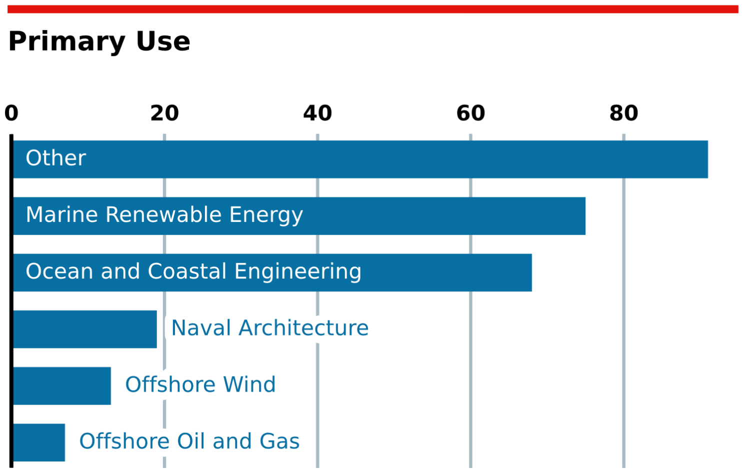

Figure 15. Marine energy software by primary use

2.5. Collection Method

Collection method is defined as the "point of use of the software, i.e., where the data used by the software originated." Figure 16 shows the breakdown of marine energy software by the collection method. This category is dominated by modeling (e.g., data from numerical models), which is both a reflection of the state of the marine energy industry and the use of software as a tool.

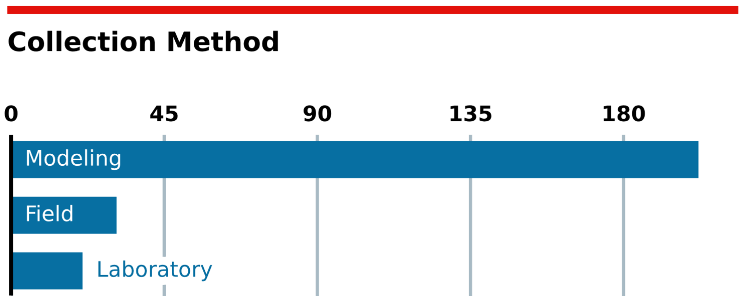

Figure 16. Marine energy software by collection method

[16] Excluding "other," since it is a catchall for software that does not fit into an existing category and software for which the original application is unknown.

2.6. Life Cycle

Life cycle is defined as "applicable marine energy life cycle phases for the software." Figure 17 shows the breakdown of marine energy software by life cycle. The design phase is highest, with operations and maintenance software also well represented. However, later life cycle phases have very few associated relevant software packages. Figure 18 shows the relationship between life cycle and primary use. From this figure, it can be seen that a large percentage of later life cycle phases (e.g., operations and maintenance) leverage software from fields other than marine energy.

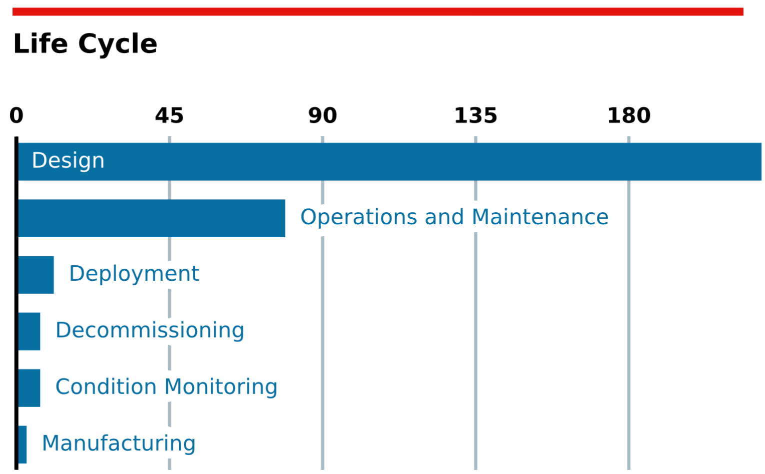

Figure 17. Marine energy software by life cycle

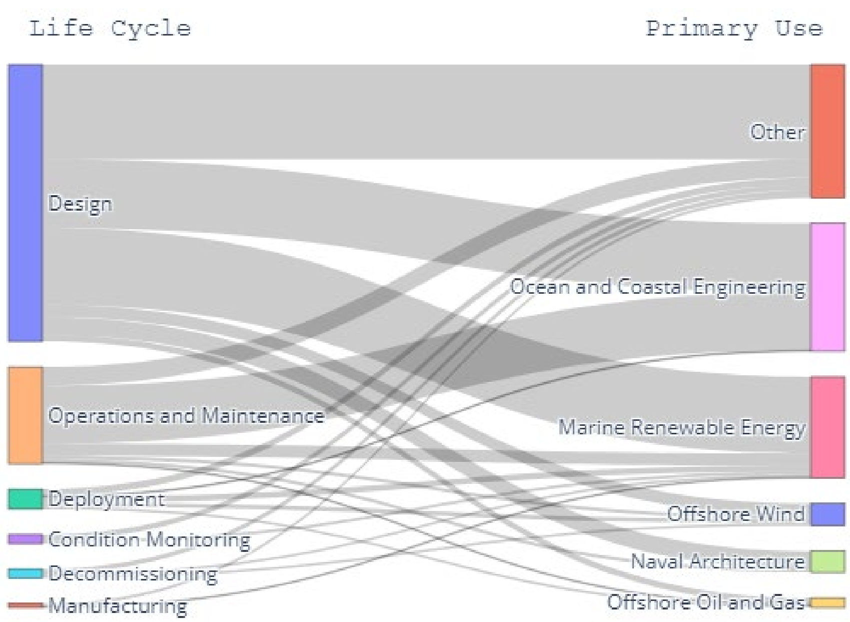

Figure 18. Sankey diagram showing relationship between life cycle and primary use

2.7. Country of Origin

Country of origin is defined as the "country from where the software originates." Figure 19 shows the breakdown of marine energy software by country of origin, either U.S. domestic or international. The U.S. has developed, or been associated with the development of, approximately 40% of the identified packages. Figure 20 shows the relationship between country of origin and technology, in which it can be seen that most of the domestic marine energy software is applicable to wave or current energy.

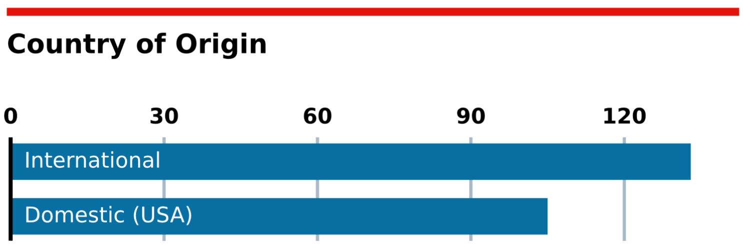

Figure 19. Quantity of Marine energy software by country of origin

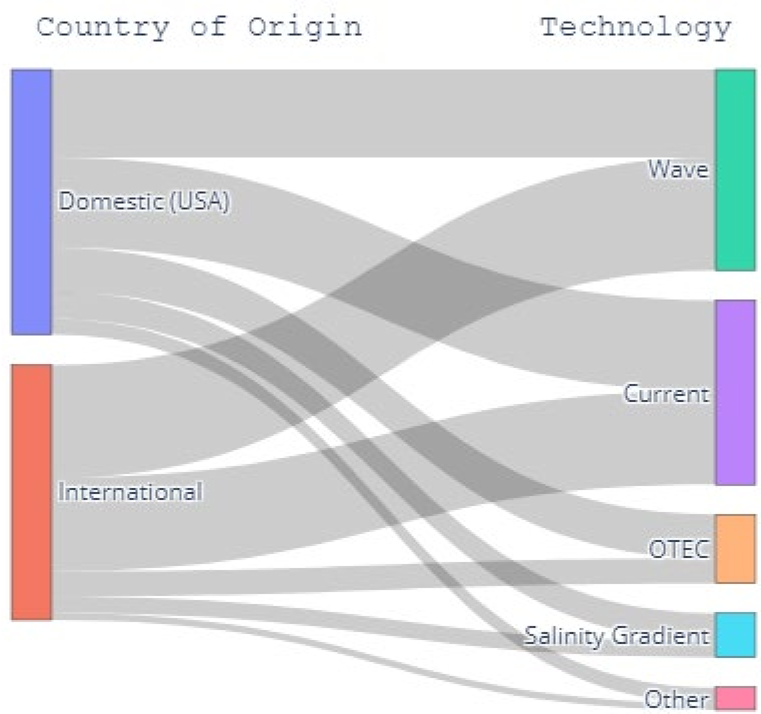

Figure 20. Sankey diagram showing relationship between country of origin and technology

2.8. License

License is defined as "the license governing use and development of the software." Figure 21 shows the breakdown of marine energy software by license. OSS is the highest, with almost three times as many open-source licenses as commercial licenses. This represents a paradigm shift in the marine energy software landscape compared to a decade ago. Previous studies highlighted the lack of OSS, whereas now there is a proliferation of OSS[17] [12], [13].

Also notable is the handful of nonstandard licenses used by some of the packages (indicated by the "Other" category in Figure 21), which include licenses that restrict use to certain geographical boundaries or that add unusual conditions, such as sharing all modifications with the license provider.

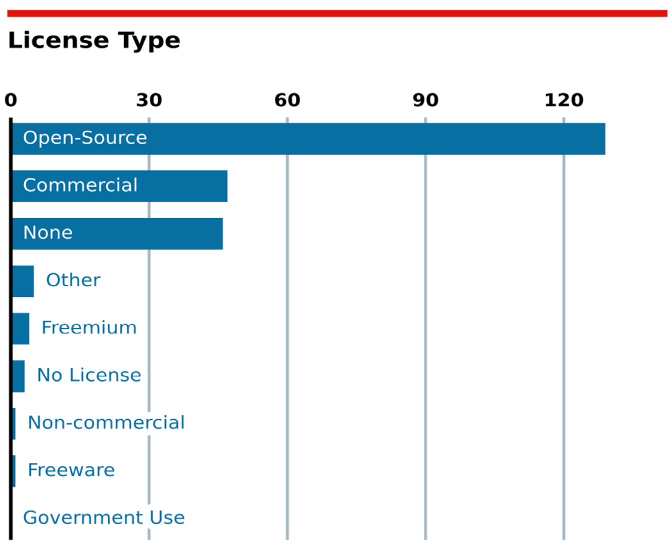

Figure 21. Quantity of Marine energy software by license

Figure 22 shows the breakdown of marine energy software by license, including sub-categories. Most marine energy software is OSS, and the most popular open-source license is General Public License (GPL), followed by MIT, Apache, then BSD. Licensing of OSS is an important factor to consider because some open-source licenses are more permissive than others [27]. Licenses broadly fall into one of three categories: copyleft, permissive, and public domain. Copyleft licenses require derived work to be published under the same license; permissive licenses have less restrictive clauses, such as attributing the authors of the previous work; and public domain licenses have no restrictions at all. Commercial developers often avoid including copyleft software in their products, as revenue cannot be generated from sales of the derivative work. Table 7 shows the license category for several popular open-source licenses.

[17] However, many software packages categorized as open source are distributed with closed source binary files. These binaries are often strong dependencies of the software, meaning the software should not be categorized as open source, strictly speaking.

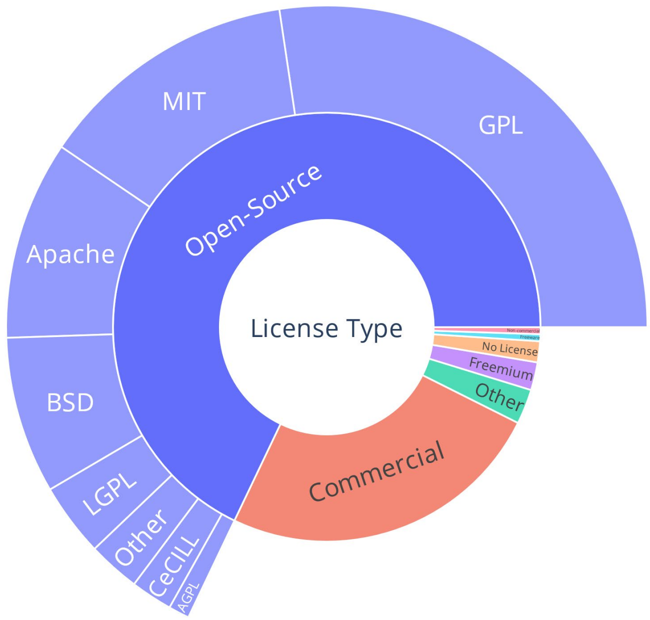

Figure 22. Marine energy software by license, with children categories

Table 7. Popular Open-Source Software Licenses, Grouped by Category

Category	Licenses
Copyleft	GPL, LGPL, AGPL, CeCILL
Permissive	MIT, Apache, BSD
Public Domain	The Unlicense

2.9. Method

Method is defined as "the underlying theory or method of the software." Figure 23 shows the breakdown of marine energy software by method. Classic methods of hydrodynamics and resource characterization, such as wave spectral analysis, shallow-water equations, computational fluid dynamics (CFD), and boundary element methods (BEM), are well represented. Also well represented is software for analyzing lab experiments using particle image velocimetry or similar image-based techniques. Optimization and statistics software is also well represented. However, there are also several methods with very little software, such as ecological risk assessment, marine and spatial planning, and life cycle assessment.

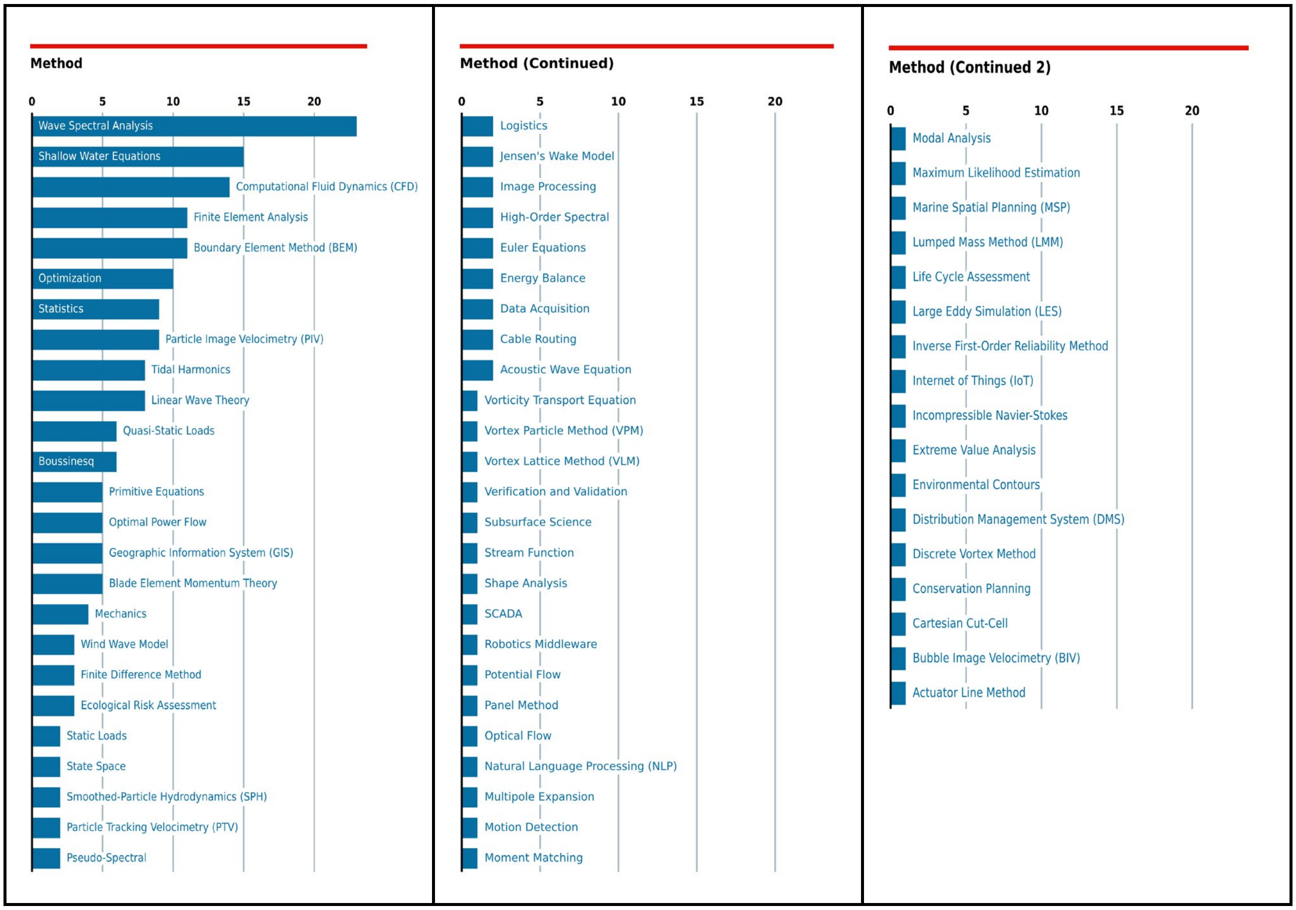

Figure 23. Quantity of Marine energy software by method

Figure 24 is a Venn diagram showing the relationship between open-source software and wave energy methods. This figure mixes a data driven and schematic approach to scale the sets. The Venn diagram shows that are more open source software are available in more traditional research fields, like BEM and wave spectral analysis, whereas fields like CFD have more commercial software reflecting the maturity of the target industries. Historically offshore engineering CFD efforts have been focused on container ship design, offshore oil platforms, and other service vessels which have alternative revenue streams and increased risk to human life. In these fields, the cost for a commercial CFD package is a smaller proportion of overall project costs and often worth the investment to produce trusted results that regulators, classification bodies, and permitting agencies are more familiar with.

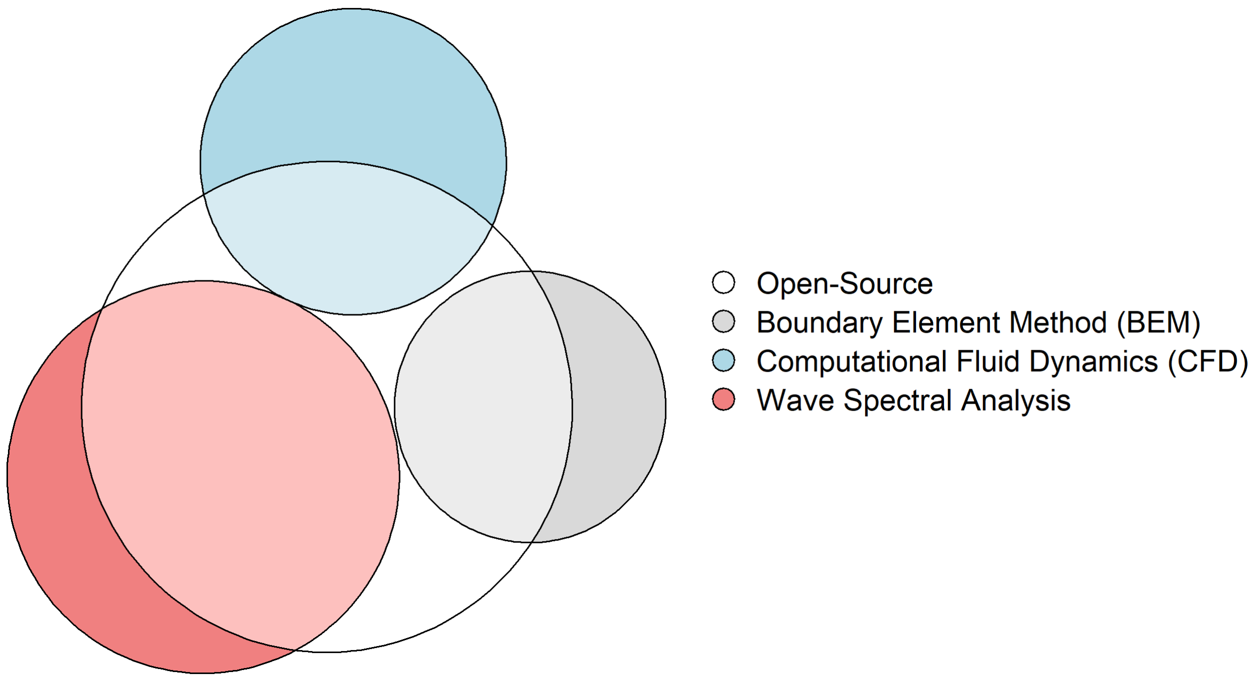

Figure 24. Venn diagram showing relationship between open source software and wave energy methods

2.10. Programming Language

Programming language is defined as "programming languages used to create (or operate) the software." Figure 25 shows the breakdown of marine energy software by programming language.[18] Python is used the most, a reflection of its success in the science and engineering space. Fortran is used second most, a reflection of its performance advantages over Python, and of legacy packages. MATLAB is the third highest, a reflection of its established user base, even though it is a commercial product. More web-focused languages such as Java and JavaScript are less well represented, a reflection of the dominance of desktop-based tools for engineering.

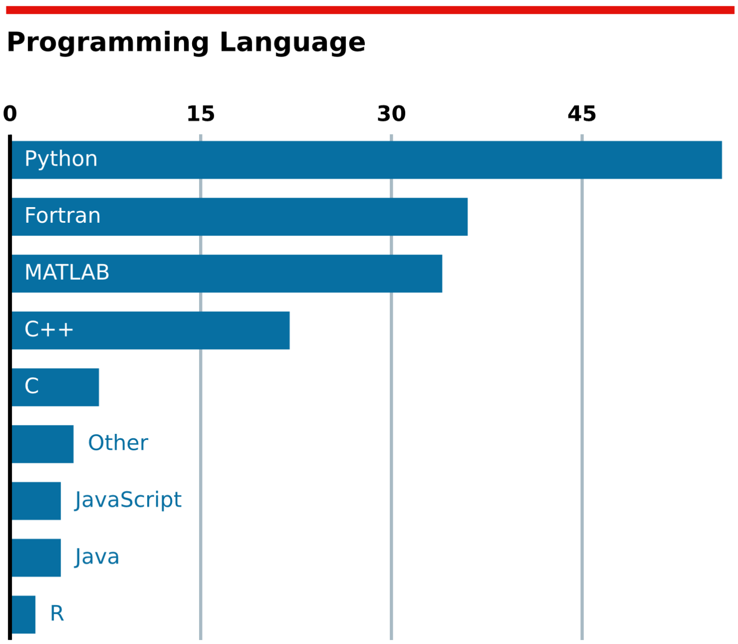

Figure 25. Quantity of Marine energy software by programming language

[18] Where information was available. Commercial software does not often specify programming language.

2.11. Interface

Interface is defined as "the means by which the user interacts with the software." Figure 26 shows the breakdown of marine energy software by user interface. The most common user interface is graphical. However, this is an incomplete representation of the database, because only one-third of the software has a user interface. The Sankey diagram in Figure 27 shows a more complete picture of the database. It shows that the most common interface for commercial software is graphical, whereas most OSS do not have a user interface at all.[19] There are also some web interfaces (and associated application programming interfaces (APIs) available. These are split between public domain services (e.g., National Oceanic and Atmospheric Administration and United States Geological Survey), and commercial data (e.g., subscription-based U.K. Hydrographic Office Admiralty Tidal API).

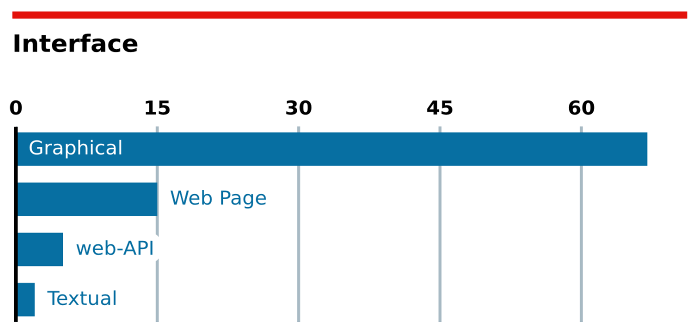

Figure 26. Quantity of Marine energy software by interface

Figure 27 also shows the relationship between TRL, license, and user interface. It shows that the range of TRLs are well supported by different software licenses, although open-source software does trend toward lower TRLs (e.g., TRL 1–3). It also shows that freemium licenses have a strong relationship with web-API interfaces, a common business model for web technologies.

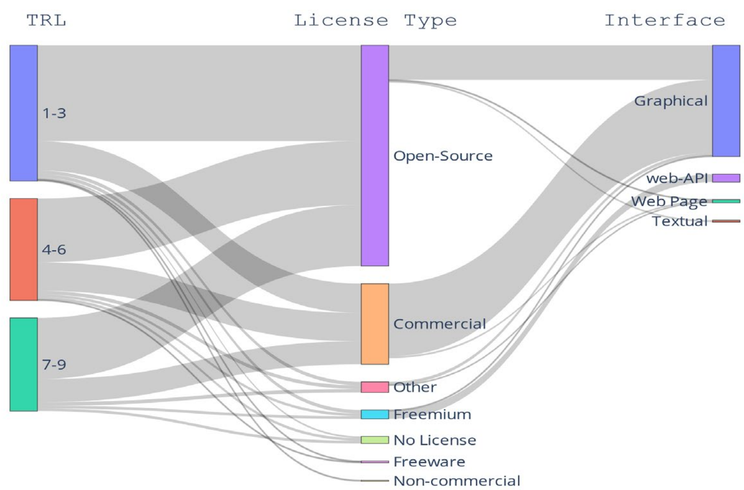

Figure 27. Sankey diagram showing relationship between TRL, license, and interface

[19] OSS typically have programmatic interfaces.

3. NEEDS ASSESSMENT

After a decade of U.S. and international marine energy software development, WPTO decided to launch the Next-Generation Marine Energy Software effort to achieve the following goals:

1. Catalog the available numerical tools and provide this information to the marine energy community.
2. Develop an informed road map for future WPTO software investments.

The primary objective of the Next-Generation Marine Energy Software effort is to prioritize the development of the next-generation of WPTO-sponsored software that will support the current and future needs of the evolving marine energy industry. This was achieved by soliciting input from the marine energy community. The needs assessment was completed by using the marine energy software landscape to identify gaps and develop discussion topics, and then by hosting a series of workshops to solicit input from the marine energy community.

3.1. Discussion Topics

Discussion topics were selected by WPTO and the national labs based on analysis of the marine energy software landscape and feedback from the marine energy community. Table 8 lists the topics used to frame discussion during the need assessment workshops. Refer to Appendix B for more information.

Table 8. Marine Energy Workshop Topics

Topics	Description
Cost Drivers	Identify software associated with the largest cost drivers
Interoperability	Data generated from software for different disciplines should be easily accessible from other software
Software Quality	Identify software gaps for marine energy specific applications and improve existing software accuracy and usability
Productivity	By utilizing advanced software and hardware architectures, like parallel CPU/GPU and supercomputers, software can produce higher quality or higher volume of outputs

3.2. Workshops

To solicit input from the marine energy community on the current marine energy software landscape and the tools needed in the next 10 years to accelerate marine energy development, a series of Next-Generation Marine Energy Software Workshops were held. The first workshop was held in conjunction with the Ocean Renewable Energy Conference–Marine Energy Technology Symposium (OREC-METS), and the second workshop was held online to diversify marine energy stakeholder attendance. Feedback from both workshops was then used to perform an affinity analysis on workshop data to identify common needs. Workshop details are presented in the following sections.

Both workshops began with an overview presentation to provide context about the project, followed by a description of the topics and workshop structure. The full agenda is shown in Table 9.

Participants were randomly assigned to four breakout groups that were roughly equal in size. Each topic was assigned a facilitator and notetaker who rotated from group to group and led 15-minute discussions with each of the four breakout groups. This allowed each group to discuss all four topics, and for the facilitator and notetaker to discuss the same topic with each of the breakout groups.

After each group had discussed all four themes, each facilitator presented a summary of the breakout discussions. The breakout group discussion points, comments, and suggestions collected by the notetakers, were tabulated in a spreadsheet and later used to develop an affinity diagram of findings from both workshops. The qualitative data analysis approach using an affinity diagram is further described in Section 3.3 Affinity Analysis.

Table 9. Agenda for Next-Generation Marine Energy Software Workshops

Agenda		Duration (minutes)	Description
Overview		15	Background, motivation for workshop, and introduce gaps/themes.
Breakout Groups	Rotation 1	15	Each of the breakout groups rotated through each of the four identified themes. Each theme had one facilitator and one notetaker. The facilitator and notetaker rotated among groups.
	Rotation 2	15	
	Rotation 3	15	
	Rotation 4	15	
Break		5	Break for attendees, facilitator, and notetaker to synthesize findings
Wrap-Up & Discussion	Cost Drivers	10	Each theme facilitator presented on the key takeaways from the notes taken during the four rotations.
	Interoperability	10	
	Software Quality	10	
	Productivity	10	
Total		120	

3.2.1. OREC-METS Workshop

The first Next-Generation Marine Energy Software Workshop was held in person on Thursday, September 15, 2022, 10:30–12:30 p.m. PT. The 2-hour workshop was held in conjunction with OREC-METS 2022, which was organized by the Pacific Ocean Energy Trust.

The workshop was attended by 16 people from across the U.S.-based marine energy community. However, the attendees did not fully capture our target audience, as shown in Figure 28. This was a known risk of holding the workshop in person. OREC-METS workshop attendees skewed heavily toward academia and national laboratories, with expertise in wave energy. There were few industry attendees.

The notetakers during each breakout group were responsible for recording the discussions and commentary in response to the questions posed by the facilitator. These recorded notes were broken into unique statements and given a participant identification number before being tabulated in a spreadsheet combining all notetaker recordings. The information recorded in the spreadsheet provided a qualitative data set that was used in conjunction with notes from the second workshop to complete an affinity analysis.

Although the workshop did not entirely capture the target audience, valuable data were still collected. Additionally, the organizers were able to learn from this workshop to inform the structure of future workshops.

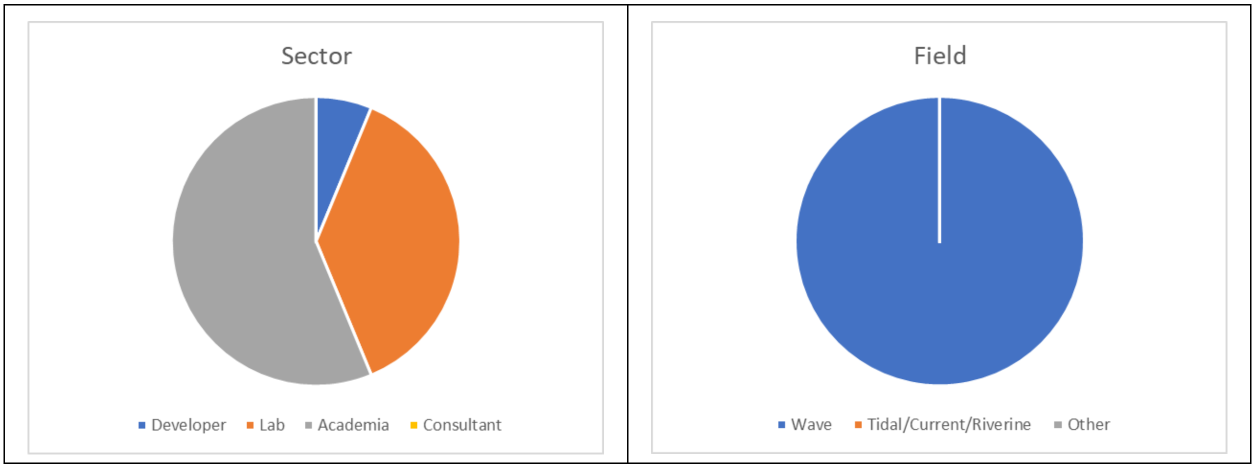

Figure 28. OREC-METS workshop attendees by sector and field

3.2.2. Online Workshop

While the OREC-METS in-person workshop collected valuable feedback from the marine energy community, it did not fully reach the target audience. As a result, using feedback from this workshop alone would not reflect the needs of technology developers or the tidal/current/riverine field. To solicit broader feedback from key stakeholders, an invitation-only webinar was hosted on November 28, 2022, from 9:00 to 11:30 a.m. MT. For this workshop, a top-down approach was taken that identified the desired composition of attendees to fully capture marine energy fields and sectors.

As shown in Figure 29, the composition of the attendees targeted better representation from developers and the tidal, current, and riverine energy space.

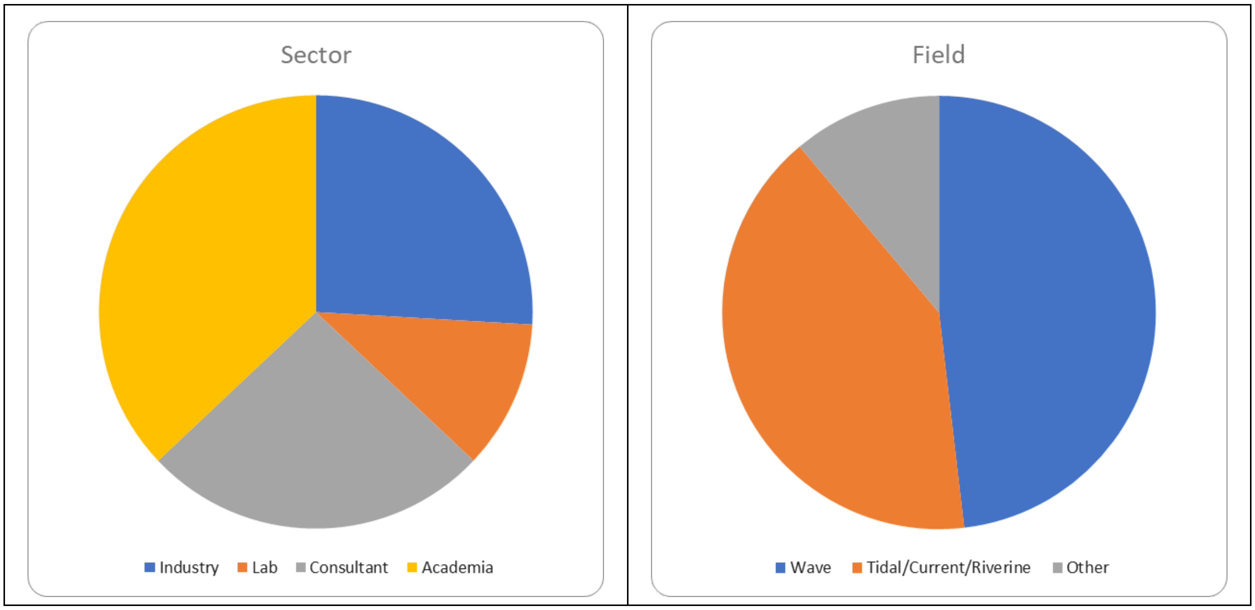

Figure 29. Online workshop attendees by sector and field

The online workshop used the same agenda as OREC-METS workshop, except each breakout group was given an additional 5 minutes for discussion and an additional 10 minutes were provided during the break. Like the OREC-METS workshop, the approximately 30 attendees were divided into four groups of roughly the same size. The structure of the workshop remained the same.

The same four topics were discussed by each of the four breakout groups, and discussion was facilitated using the same set of questions. The notetakers were responsible for recording the breakout group discussions. These recordings were converted to written transcripts of the discussions. The transcripts were then used as the qualitative data set to complete an affinity analysis.

3.3. Affinity Analysis

In total, the in-person and online workshops solicited feedback from nearly 50 marine energy stakeholders. The comments, questions, and feedback collected during the two workshops resulted in nearly 650 unique statements. The data were collected using semi-structured interviews, facilitated by questions asked during the breakout groups about the four topics. While these four topics were used to facilitate discussion, ultimately these topics were discarded to analyze the data. Instead, a bottom-up approach was used to analyze the data, using a qualitative data analysis method called an affinity analysis [28].

Affinity analysis an established qualitative data analysis method used to generate an affinity diagram—a tool used to organize ideas and data. It is typically used to brainstorm, categorize, and organize ideas by their natural relationships. Affinity diagrams are often used in project management, product development, and problem-solving because they are well suited for:

- Analyzing verbal data, such as survey results
- Collecting and organizing large verbal data sets
- Developing relationships or themes among ideas.

To create an affinity diagram, data are gathered and recorded into a collection of interpreted notes (yellow notes, commonly on sticky notes). A team then organizes the interpreted notes into related groups (blue themes). This is an iterative process, where the team moves notes and groups around until clusters develop (pink and green themes). This iterative process facilitates a bottom-up approach to analyzing qualitative data. The team is encouraged to follow general guidelines based on the size of their data set when developing the affinity diagram. For example, a blue theme should include yellow notes from more than one person, and it should not contain more than one yellow note from the same person. An example of an affinity diagram is shown in Figure 30.

Figure 30. Example of an affinity diagram ("UX Clinic - Affinity Diagram Session" by Encora Mexico is licensed under CC BY-NC-SA 2.0)

Affinity diagrams are commonly used to assess business and user experience needs due to their ability to organize large amounts of information, identify patterns and relationships, and facilitate group collaboration. They are useful for identifying needs and brainstorming potential solutions. However, affinity diagrams require participation and engagement from the team to be effective since the collected data often requires subject matter expertise to be properly interpreted. Additionally, affinity diagrams are not useful for quantifying data or information and are not a good fit for projects that require a more structured or formal approach (e.g., methods used to analyze the software data in this report's landscaping study).

Since the working group was unable to meet in person, the digital platform Miro was used to develop the affinity diagram. Miro is a digital whiteboard and real-time collaboration platform that allows users to create and share interactive diagrams and facilitates remote teamwork. Miro was used to develop the affinity diagram because of its ability to use note squares and text boxes and because it could be easily exported and backed up.

Initially, the data were manually preprocessed in a spreadsheet into interpreted notes (yellow notes) from the raw data obtained from workshop participants. The spreadsheet data were then imported into Miro, where they were converted into individual square notes. The team then organized the notes following the affinity diagramming guidelines.

3.4. Workshop Findings

The affinity diagram generated from the Next-Generation Marine Energy Software workshop data is shown in Figure 31. First-level themes are in green, second-level themes are in pink, third-level themes are in blue, and interpreted notes are in yellow. The first-level themes identified from the workshop data are:

- "We need to leverage state-of-the-art computational resources."
- "We need to overcome existing software limitations in order to advance marine energy technology."
- "We need to advance marine energy technology, but data access is a barrier."
- "We need to consider many factors and trade-offs when developing or using new marine energy software (for example, language, architecture, license)."
- "We need open-source software that is trusted, free, and easy to use."

Each of these first-level (green) themes is discussed in detail in the following sections. Refer to Appendix C for the first-, second-, and third-level themes, and to the high-resolution PDF for the workshop attendee quotes.

Figure 31. Digital affinity diagram developed by NREL and SNL from marine energy software workshop data (screenshot from Miro). This figure is illustrative of the affinity diagramming process. Refer to the following sections for more information, and to Appendix C for the full affinity. A high resolution PDF of this figure, along with the individual comments is also provided.

3.4.1. "We need to leverage state-of-the-art computational resources."

The need for marine energy software to take advantage of state-of-the-art hardware and software resources emerged during the workshops as one of the most pressing areas for improvement. Participants discussed how simulations and optimizations could be significantly accelerated by more effective usage of modern computing resources, such as graphics processing units (GPUs), high-performance computing (HPC), cloud computing and machine learning (ML). Figure 32 provides a breakdown of the first-, second-, and third-level themes identified for "I want to leverage state-of-the-art computational resources." Refer to Appendix C for the full affinity diagram.

The need for more advanced and powerful computing resources was a common concern among participants, as was the need for better support and training in how to use these resources effectively. One of the key second-level themes identified within the overarching theme was the need for better support and training to learn how to use advanced tools such as GPUs and ML. The participants mentioned the desire to use cloud computing for simulations. One of the benefits mentioned was having multiple programs installed on a cloud machine. Cloud computing could also be useful to solve interoperability issues between different software packages. Also, having multiple marine energy software packages on a cloud machine could save time for users who need to simulate different aspects relevant for their specific application. Participants also mentioned the importance of having reliable software tools for optimization studies, their needs regarding the possible use of digital twins to perform co-design analysis, and their desire to use hardware-in-the-loop simulations for hardware design.

These findings demonstrate the importance of considering the use of advanced hardware and software resources when designing and implementing marine energy software and highlight the need for software developers and designers to prioritize the use of these resources in their work.

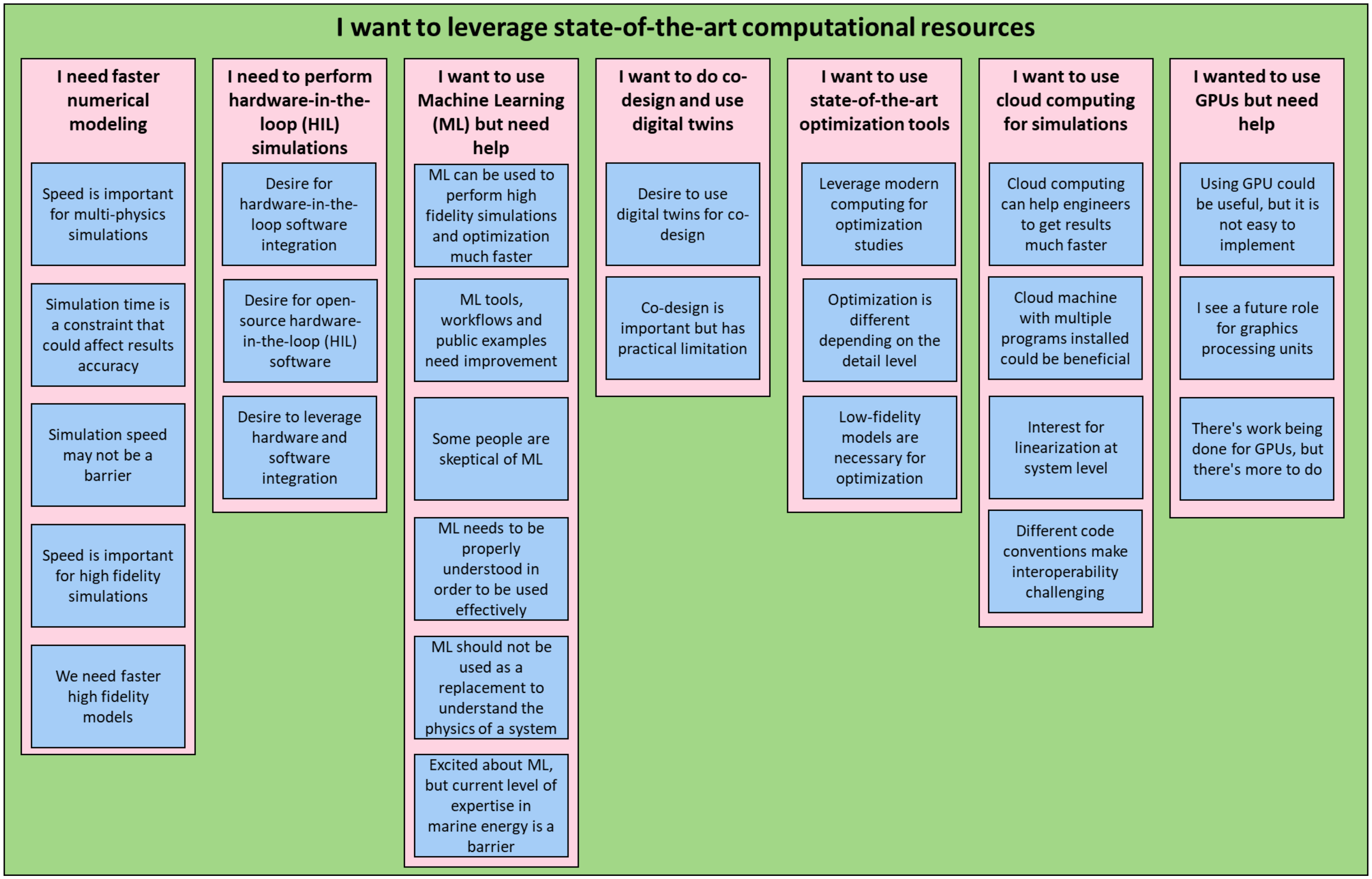

Figure 32. "We need to leverage state-of-the-art computational resources" first-, second-, and third-level themes

3.4.2. "We need to overcome existing software limitations in order to advance marine energy technology."

The need to overcome existing marine energy software limitations also emerged during the workshops. A key concern among participants was that the current offering of marine energy software does not meet all their needs and requires improvement to advance marine energy technology. Figure 33 provides a breakdown of the first-, second-, and third-level themes identified for "We need to overcome existing software limitations in order to advance marine energy technology." Refer to Appendix C for the full affinity diagram.

A need highlighted by participants included the development of new software to model CECs (including tidal, ocean, and riverine). Participants also expressed desire to better model power take-off and control systems, and for the ability to design mooring systems. They also expressed the desire to perform high-fidelity simulations and optimization, and the need for differentiable and interoperable BEM software.

Among existing tools, participants highlighted the need to improve WEC-Sim and BEM software—with speed and interoperability being key concerns. While some work to enable OpenFAST to model CECs is underway, support is spread across multiple short-term projects, with no centralized, long-term funding. A consolidated strategy is needed to support continued software development for CECs and ensure tools are properly verified and validated. Similarly, some participants discussed the need to modify OpenFAST for CECs. Participants also discussed the need for software that can easily connect with other systems and tools through APIs—several examples were provided from the wind energy sector about how interoperable software can be used to create a multi-fidelity simulation framework.

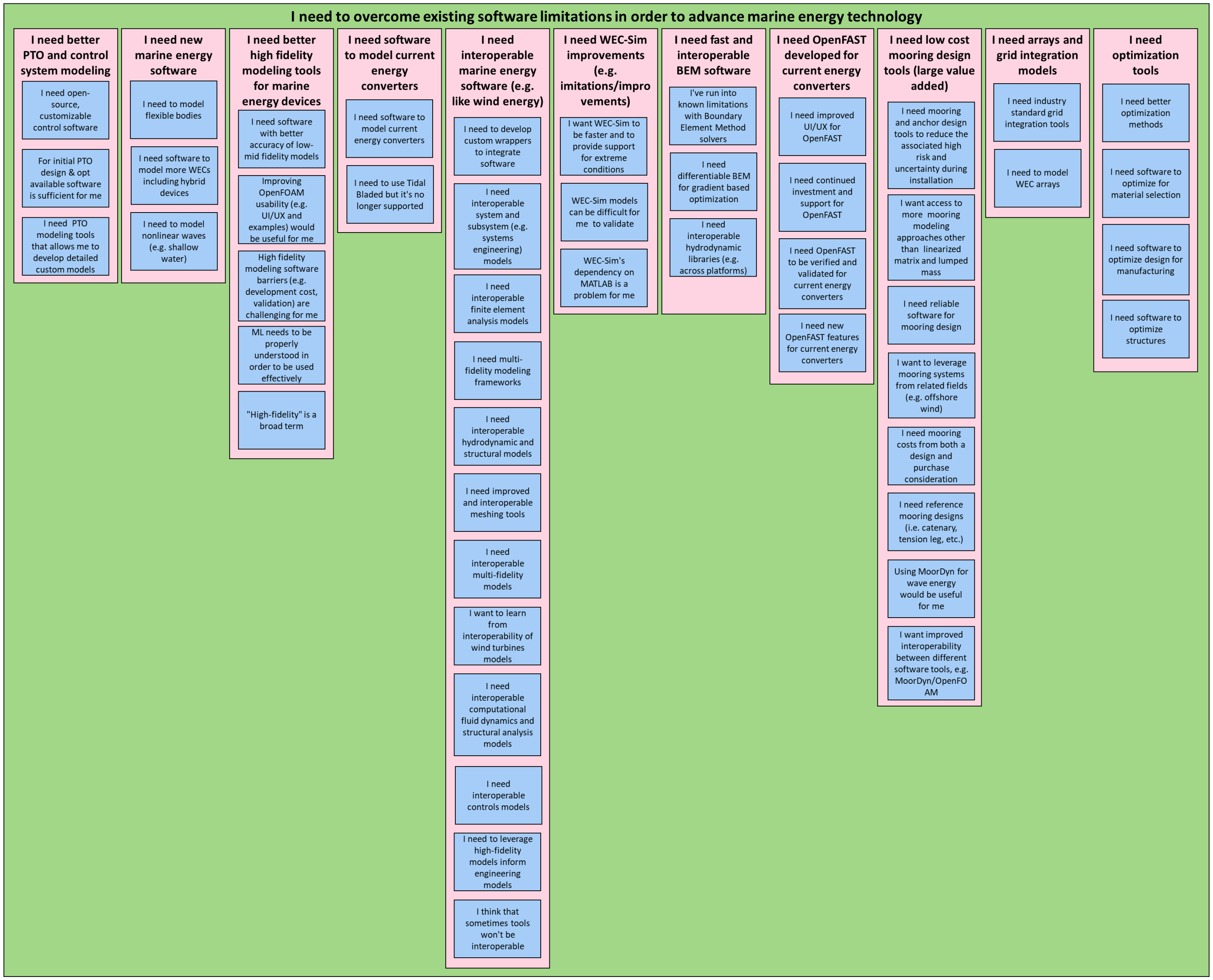

Figure 33. "We need to overcome existing software limitations in order to advance marine energy technology" first-, second-, and third-level themes

3.4.3. "We need to advance marine energy technology, but data access is a barrier."

Access to data emerged as a critical theme among workshop participants. While it may not strictly qualify as a "software need," the lack of adequate data access was identified as a significant obstacle to effectively using software. Participants discussed how a lack of data can be a barrier to developing models and applying software and expressed how access to relevant data is often a greater barrier than the software itself. Figure 34 provides a breakdown of the first-, second-, and third-level themes identified for "We need to advance marine energy technology, but data access is a barrier." Refer to Appendix C for the full affinity diagram.

For example, having accurate data on the cost of components and modes of failure is essential for modeling reliability and optimizing marine energy systems. Participants also mentioned the need to standardize software data inputs and outputs to improve interoperability. Another important data access barrier is the need for software validation data to improve numerical models. Participants noted that lack of data in areas like installations, operations, and maintenance is impeding the advancement of marine energy technology. Participants expressed the desire to establish component data repositories and to establish data standards to build trust in and improve interoperability between software.

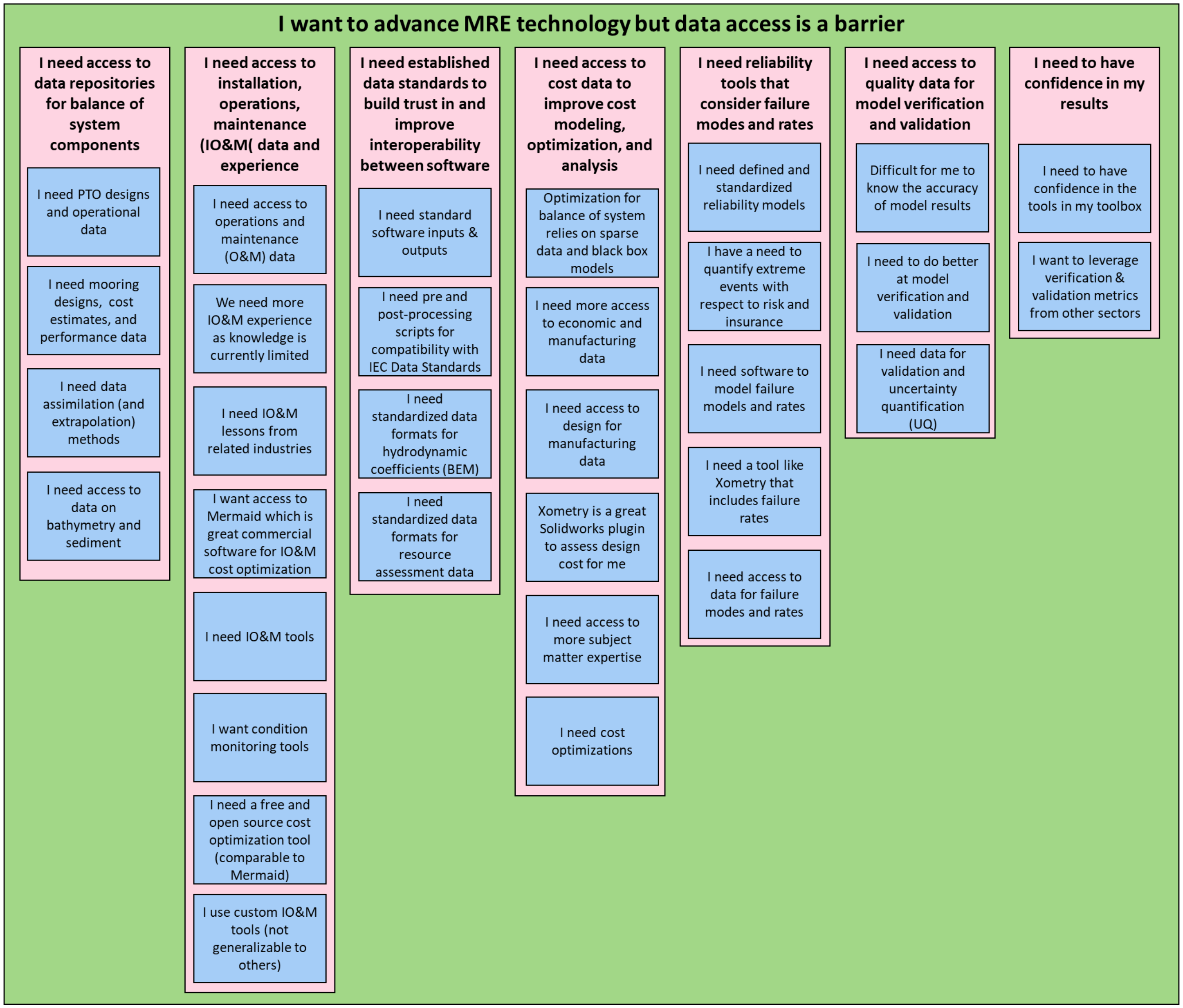

Figure 34. "We need to advance marine energy technology, but data access is a barrier" first-, second-, and third-level themes

3.4.4. "We need to consider many factors and trade-offs when developing or using new marine energy software (e.g., language, architecture, license)."

During the workshop, there were many discussions about various software development decisions—such as which programming language(s) to use, how to approach API development, and licensing options. These choices can have a significant impact on factors such as speed, interoperability and HPC compatibility. Figure 35 provides a breakdown of the first-, second-, and third-level themes identified for "We need to consider many factors and trade-offs when developing or using new marine energy software (e.g., language, architecture, license)." Refer to Appendix C for the full affinity diagram.

On the topic of software *usage*, many participants mentioned a need for reliable software and that the cost of some commercial software options is worth it because of their reliability. In addition, commercial software packages usually have a GUI that facilitates adoption by new and less experienced users. Hence, participants expressed the desire to improve support and interfaces for open-source software. They mentioned that open-source software is often lacking in this regard, and that ensuring quality in open-source software requires long-term funding for ongoing verification, validation, maintenance, and support.

On software *development*, participants spoke about the benefits of using low-level languages, such as C++, for computationally intensive simulation software. Additionally, the development of APIs (particularly using Python) was seen to improve interoperability. Many participants expressed optimism about the growth and potential of Python, and several explained that they are currently transitioning from MATLAB to Python, citing concerns over MATLAB's inaccessible source code, barriers to collaboration, interoperability with other software, and HPC compatibility. However, other participants expressed that MATLAB is an effective tool for them, since MATLAB is trusted and includes high-quality technical support.

Overall, workshop participants acknowledged that there are many software decisions that can impact the success of a project, and that there is no one-size-fits-all solution. They also acknowledged the importance of evaluating the trade-offs among the cost, licenses, support, interoperability, speed, accuracy, and other technical capabilities when creating a software development strategy and/or choosing software for a project.

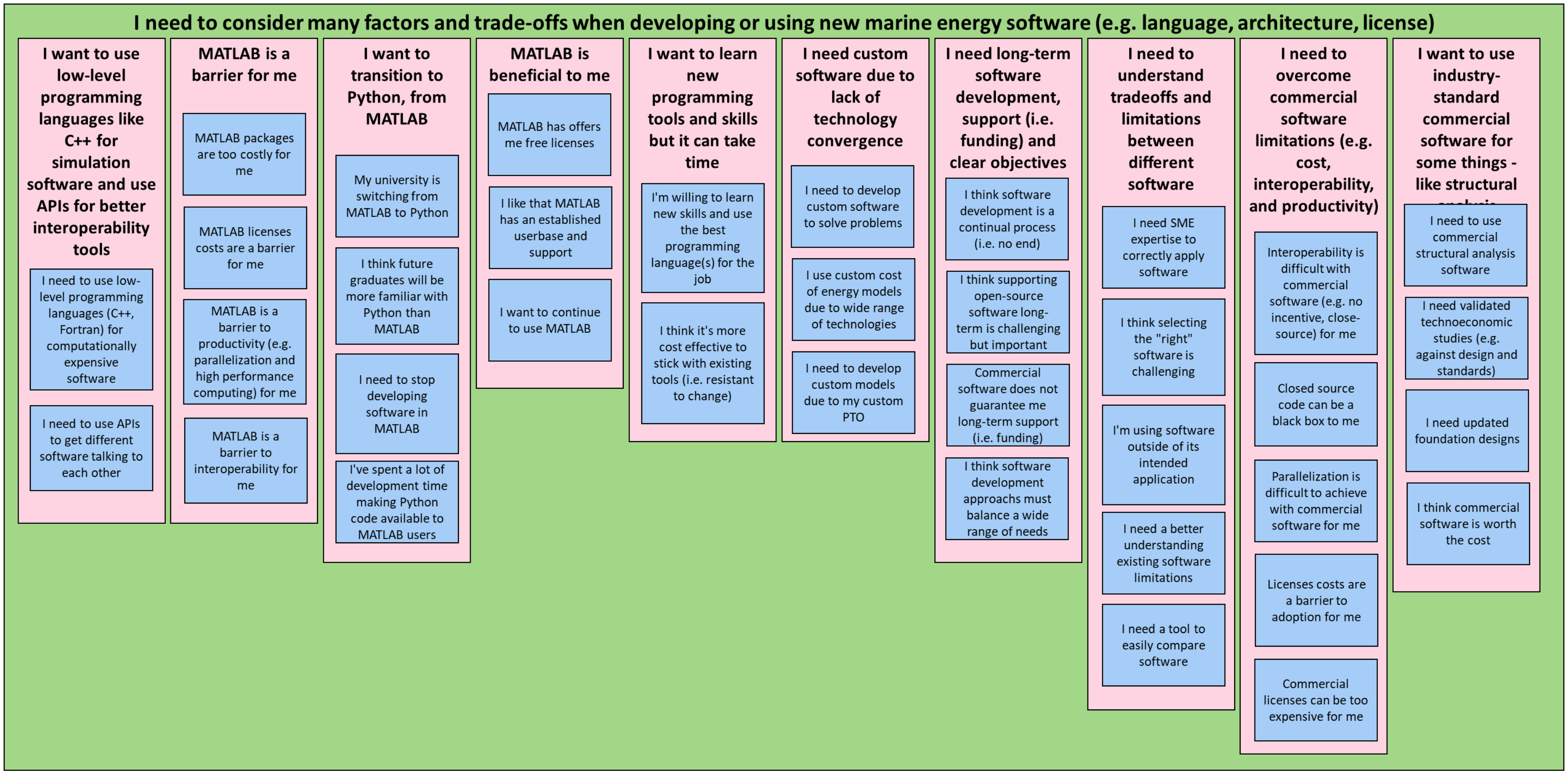

Figure 35. "We need to consider many factors and trade-offs when developing or using new marine energy software (e.g., language, architecture, license)" first-, second-, and third-level themes

3.4.5. *"We need open-source software that is trusted, free, and easy to use."*

The theme of "trusted, free, and easy-to-use open-source software" emerged as an important topic among participants in the workshop on software gaps and needs. Participants recognized the need for open-source software that is easy to use, low cost, and with results users can have confidence in. Participants identified that long-term software support can help provide this. Figure 36 provides a breakdown of the first-, second-, and third-level themes identified for "We need open-source software that is trusted, free, and easy to use." Refer to Appendix C for the full affinity diagram.

Participants discussed the importance of open-source software that is reliable and trustworthy with a proven track record of accuracy. Participants emphasized the need for open-source software that is free of charge to the user, recognizing that while software development is not free, an open-source environment transfers the funding burden to government agencies, private investment, or crowd funding, which allows for more widespread use and adoption. An important aspect identified for open-source software was that it should be multi-platform (i.e., be able to run on Windows/Mac/Linux). Furthermore, the need for open-source software that is easy to install and use, with as minimal training as possible, and a clear and logical layout of features was also highlighted as an important requirement. However, despite wanting to have as low a learning curve as possible, the feedback received was that clear documentation, recorded training materials, and access to an issues board (which is frequently monitored) are necessary to ensure proper use of the code. As highlighted in discussions after Figure 5, the more complex a software package becomes, the more expert knowledge is generally required to make the best use of the software and not misuse it or generate incorrect results. Therefore, having a combination of live in-person trainings, live webinar trainings, and recorded webinars hosted on the software webpage provides ample opportunities to introduce new users to the software and demystify initial impressions of interested new users.

The combination of trust, cost, and ease of use were highlighted as critical factors in the adoption of an open-source software.

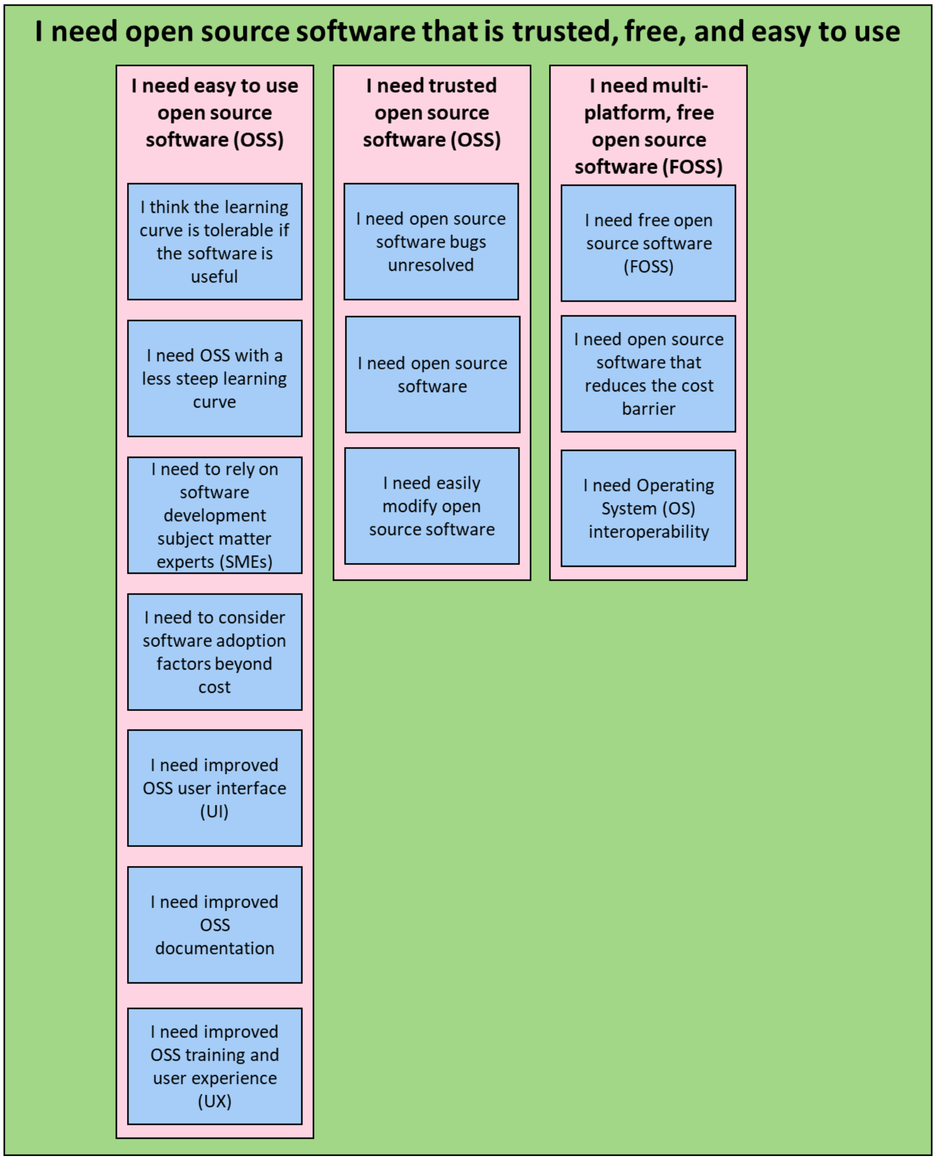

Figure 36. "We need open-source software that is trusted, free, and easy to use" first-, second-, and third-level themes

4. CONCLUSION

Updating the 2012 marine energy software needs assessment revealed that the marine energy software landscape has vastly changed in the last decade. The approximately 40 software packages identified in the last assessment could be listed in two tables, whereas the nearly 230 software packages identified in this work required the formation of the Marine Energy Software Database (Appendix A).

Figure 9 presented an overview of the updated marine energy software landscape in the form of a tree map. The tree map highlights that the marine energy software landscape is heavily focused on the categories shown in Table 6, which reflect the overall state of marine energy. Some of these trends include:

- Low TRL (1–3) because marine energy has not yet reached commercialization
- Technologies in the design life cycle stage (though some have advanced to deployment)
- Discipline focus on topics like hydrodynamics and site characterization more than topics like supply chain or manufacturability.

The absence of, or smaller area of, data in the tree map highlights gaps in currently available software; however, as discussed in this report, gaps do not necessarily imply need and must not be viewed in isolation. Nonetheless, the marine energy software landscape results provide valuable insight into where investments have been made, as well as areas where future investments could fill gaps.

After updating the marine energy software landscape, the SNL and NREL team held two workshops to solicit feedback on the identified gaps and to assess if these gaps were indeed needs. Participant feedback was used to identify marine energy software needs using an affinity analysis method. First-level needs and their impact on the marine energy industry are listed in Table 10.

For example, new software could require several years of development before the software could become easily accessed, used, and maintained, with training available for the marine energy community (medium timeline). By contrast, adopting state-of-the-art computational resources or leveraging existing software for new applications could be accomplished in a shorter timeline and have an immediate impact on the marine energy community, refer to Table 10. The need for access to high-quality data is persistent and remains on the list from the 2012 Cardinal Report (long timeline). The need for high-quality data is relevant across all modeling and software development but was strongest for data-driven analyses (e.g., levelized cost of energy), where the quality of the analysis is highly dependent on currently unavailable and often volatile data (e.g., supply chain, materials, vessels, moorings, anchors). High-quality data are also necessary for full system optimizations.

Opportunities

Based on the data collection and analysis in this effort, the authors recommend that all WPTO-funded software projects start with formal software development plans, written prior to initiating development, that are evaluated and revised on a regular (e.g., annual) basis. Software development plans should include the following elements:

- Programming language and license (e.g., open source or proprietary)
- Distribution and maintenance protocols (e.g., version control and team workflows)

- Quality assurance best practices (e.g., testing and continuous integration)
- Documentation and user training (e.g., help boards and user support)
- Software sustainability, or how to continue software maintenance without direct WPTO funding (e.g., indirect funding or sunsetting).

These recommendations are based on feedback from the community and lessons learned from the past decade of WPTO investment in software. History has shown that unsupported software is essentially dead software, and all software should consider best practices, including quality best practices such as compliance with ISO/IEC 9126. Because of the relative immaturity of the marine energy industry, technology development is strongly reliant on open-source software. Thus, software development plans must consider how to best achieve the intended impact on the marine energy community and strongly weigh factors directly impacting the user community and long-term sustainability. Sustainable software should consider OSS business models that enable continued development and support (e.g., dual-licensing, software as service; refer to Appendix D).

Once the industry is more mature with adequate revenue streams, it is anticipated that developers would invest in and maintain their own custom codes relevant to their technology and market needs.

The detailed data and feedback provided by the user community has been interpreted, condensed, and expressed in the first level needs. Their impacts and associated mitigation and improvement opportunities are listed in Table 10. This table provides a solid basis for further strategic planning on the overall marine energy sectoral and methodological levels. Future strategic planning should reflect on newly raised concerns such as:

- How can the application of diverse software tools within the software toolbox best be shaped, implemented and supported to reduce technology development cost, time, and risk to deliver effective, efficient and successful technology development outcomes to achieve market entry?
- How can the existing and evolving software maintain and shape its structure and interoperability while providing access and training for the user community to support a variety of applications (i.e., markets)?

To effectively support the marine energy industry towards a successful market entry and have an increased impact, further strategic considerations – alongside the detailed community-based (user) needs analysis will be used to develop a detailed, robust development strategy and roadmap.

Table 10: Prioritized Needs from the 2022 Next-Generation Marine Energy Software Assessment

First-Level Need[20]	Impact of Need on Marine Energy Industry	Opportunities
"We need to leverage state-of-the-art computational resources"	• Inability to utilize modern computing technologies results in slower development • Inability to leverage graphical processing units (GPUs) and high-performance computing (HPC) scalable resources such as Amazon Web Services results in slower development and inefficient workflows • Inability to exploit advancements in machine learning (ML) to analyze performance data to improve system design and operation results in limited innovation and optimization • Inability to perform simulations and optimizations with existing software results in slower development and inefficient workflows	• Develop new tools compatible with GPUs and HPC • Develop and validate machine learning (ML) applications for marine energy • Develop tools for integrated optimization workflows (e.g., Wind-plant Integrated System Design and Engineering Model [WISDEM] for offshore wind) and gradient-based optimization • Establish checklists or requirements for compatibility with advanced computing resources • Develop easily adaptable marine energy applications leveraging state of the art computing resources • Develop capabilities to support digital twins and hardware-in-the-loop for marine energy
"We need to overcome existing software limitations in order to advance marine energy technology"	• Inability to use existing marine energy software to meet marine energy needs results in lack of confidence in software outputs • Inability to use existing software across all marine energy technologies results in lack of confidence in software outputs and limited innovation	• Incorporate additional device configurations and physics into existing software, especially for current energy technologies. • Establish applicability bounds of existing software (e.g., limitations of underlying theory) • Invest in existing software used by marine energy community (e.g., MoorDyn, OpenFAST, Capytaine)

[20] The affinity analysis processes used "I want" language, however this converted to "We need" for the needs assessment

	• Inability to couple existing marine energy software results in inefficient workflows	• Leverage existing tools to improve marine energy software interoperability (e.g., MHKiT, preCICE) and develop application programming interfaces (APIs) that are consistent and easy-to-use.
"We need to consider many factors and trade-offs when developing or using new marine energy software"	• Programming language, license, software speed, interoperability, and deployment on HPC systems impact interoperability and result in slower development and inefficient workflows • Differing opinions on commercial versus free and open-source software (consensus that the marine energy industry is willing to pay for tools if they are deemed valuable and save development time) results in differing approaches to software use and adoption[21]	• Invest in new software (e.g., framework, language) capable of supporting multiple technologies (e.g., hybrid systems, wave, current, wind, and solar energy) and products (e.g., power, water, carbon) • Prioritize development of multiphysics, multidomain tools (e.g., including power take-off and control co-design) • Support collaborations between MRE and offshore wind and solar on software development for hybrid systems.
"We need open-source software that is trusted, free, and easy to use"	• Open-source software is low cost, but if difficult to use, results in a lack of confidence and is a barrier to adoption (i.e., labor costs for software adoption)	• Encourage adoption of software quality best practices from ISO/IEC 25010 (e.g., documentation, examples, testing, continuous integration) • Improve verification and validation of existing marine energy software • Develop easily adaptable validated models using open-access datasets • Support User Interface/User Experience (UI/UX) development and marine energy applications for existing software to lower the learning curve, and reduce adoption time (i.e., reduce software adoption time burden)

[21] For example, the two leading software for wave and tidal/current modeling are WEC-Sim and OpenFAST, respectively. However, WEC-Sim is built in the MATLAB/Simulink environment where OpenFast is built in Fortran/C++.

		• Invest in long-term software development and support, e.g., new features, user support (issues), trainings (recorded webinars), and applications • Establish dedicated Research Software Engineers to support open-source software
"We need to advance marine energy technology, but data access is a barrier"	• Lack of relevant open-source validation data results in lack of confidence in software outputs • Lack of relevant data results in poorly defined inputs for data-driven analyses and lack of confidence in outputs	• Invest in open-access data sets and code comparison for model validation • Apply numerical models and machine learning to fill known data gaps (e.g., cost drivers, failure rates) • Update reference models, and include potentially groundbreaking technologies (e.g., distributed embedded energy converter technologies (termed DEEC-Tec), kites, ocean thermal energy conversion, salinity gradient) • Numerical reference models would not only demonstrate proper use of available simulation tools, but also provide example data and predicted performance results • Improve standardization of data outputs (e.g., units, descriptors) and improve usability of large data sets for analysis by algorithms (i.e., ML)

5. FEEDBACK REQUEST

A high resolution PDF of the affinity diagram is available in Figure 37. The authors welcome feedback from the broader marine energy community on the needs assessment. Please contact the authors of this report if you would like to provide additional feedback.

Figure 37. High resolution affinity diagram, double-click to access

5.1. Author's Contact Information

Please feel free to reach out to the author with any feedback or suggestions on this work.

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APPENDIX A. MARINE ENERGY SOFTWARE DATABASE

This appendix describes the marine energy software database used to assess the marine energy software landscape described in Figure 9.

Five key principles were followed for developing and managing the database:

- **Consistency:** To extract meaningful analysis from the data, once collected, the records stored within the database must be consistent. To allow automation, it is important that records are similarly structured; for accurate counting of related fields within records, it is important to enforce consistent syntax. To enforce consistency on the records, each record within the database conforms to a fixed "schema," which acts as a template for the records.
- **Definitions:** Another important aspect of ensuring consistent meaning in the collected data is making the field definitions clear and unambiguous. This is important for correctly classifying the data when entering records into the database and for users of the database to understand the analysis of the data. To clearly define the schema fields, an unambiguous description is given to each.
- **WPTO Priorities:** An important consideration in the design of the schema was alignment with WPTO priorities. This was accomplished by leveraging prior WPTO efforts to define marine energy technologies taxonomies, such as Tethys Engineering. Tethys Engineering defines a taxonomy to categorize documents about technical and engineering aspects of marine renewable energy. As such, that categorization was adopted within this project's database schema for describing the relevant marine energy software.
- **Database Structure:** One notable aspect of the *Tethys Engineering* categorization was that it contained hierarchical relationships; thus, it was decided that the schema should allow for similar relationships. The schema developed within this work uses a taxonomic structure allowing fields to have "children" that are associated with a "parent." Nevertheless, it was important to avoid excessive use of child fields to avoid overcomplication in the schema.
- **Version Control:** Given the collaborative nature of this project, change management on the collected data is an important consideration. Additionally, good change management processes can prevent loss of data and enable errors to be identified and corrected. To enable change management of the schema and the database records, a text-based system was implemented and placed under version control using Git.

A.1. Data Gathering

The purpose of the data gathering effort was to collect information about the current marine energy software landscape. This was accomplished by reviewing related software databases, gathering data on existing marine energy software, soliciting feedback from power users, and updating the marine energy software database.

The national laboratories reviewed existing software databases, including the Office of Scientific and Technical Information (OSTI) DOE Code, NASA Software Catalog, and Code.gov [29]-[31]. This review served two purposes: It provided a comprehensive list of existing software, some of which was relevant to marine energy. It also provided examples of existing software databases. This information informed the structure of the marine energy software database used for the software landscape, and it will inform future development of the Marine Renewable Energy (MRE) Software Knowledge Hub on PRIMRE.

The labs then solicited feedback from members of the marine energy community actively using and developing software, referred to as "power users," and from the marine energy community at large. The labs provided power users a preliminary software database and asked for feedback on its schema and content. To solicit broader feedback, the labs presented the marine energy software effort at the European Wave and Tidal energy Conference (EWTEC) 2021, and during a virtual workshop at OREC 2021 [32]. Feedback from these community engagement efforts varied in form and scope, but could be grouped into four categories:

- **Schema**: suggestions for updates to the database schema
- **Content**: suggestions for updates to the database content
- **Knowledge Hub**: suggestions for updates to the MRE Software Knowledge Hub on PRIMRE
- **Other**: suggestions related to gap analysis methods and software usability.

Feedback was tracked in an action tracking sheet, tagged with the relevant category, mapped to an action, and assigned a point of contact responsible for its closeout.

The marine energy software database schema and content was then updated and used to assess the current software landscape. The software database is a living document that is regularly updated with new content. However, the nearly 230 software packages identified as relevant to marine energy have been added to the Code Catalog on the PRIMRE MRE Software Knowledge Hub.

A.2. Database

This section provides an overview of the database. The tables show the title of the database schema node and its description. Each nested level is added as a separate table. Links between the "parent" nodes are given in the "children" column. The schema is also presented in Table 11.

Table 11. Root Node

Name	Description	Children
Title	The name of the software package.	**Table 12**

Table 12. Children of "Title"

Name	Description	Children
Developer	The name of the software developer, e.g., company, research body, individual.	
Web Address	The URL of the software package.	
Country of Origin	Countries from which the software originates. Particularly useful if the software is only licensed for use within a designated territory.	Table 13
License Type	The types, if any, of license governing use and development of the software.	Table 14
Primary Use	The primary sector applicable to the software package.	Table 16
Technology	Marine energy technologies applicable to the software package.	Table 17
TRL	Applicable technology readiness level ranges of the technology supported by the software package.	Table 18
Collection Method	Point of use of the software package, i.e., the physical source of data transformed by the software.	Table 19
Life Cycle	Applicable marine renewable energy technology life cycle phases for the software package.	Table 20
Discipline	Applicable disciplines or functionalities of the software package.	Table 21
Programming Language	Programming languages used to create (or operate) the software package.	Table 22
Method	Underlying theory or method of the software package.	Table 23
Dependencies	Major dependencies and add-on packages of the software package, e.g., for pre- and postprocessing.	
Interface	The means by which the user interacts with the software.	Table 24
PRIMRE Knowledge Hub	Inclusion of this software package on the PRIMRE Knowledge Hub.	Table 25
Note	Additional notes for the software package.	

Table 13. Children of "Country of Origin"

Name	Description	Children
Domestic (USA)	United States of America origin of software development.	
International	Origin of software development outside of the United States of America.	

Table 14. Children of "License Type"

Name	Description	Children
Open Source	A type of license that allows the software's source code and/or binaries to be used, modified and/or shared under defined terms and conditions.	Table 15
Commercial	A paid-for license which reserves rights to use, modify, or share the software.	
No License	No license has been applied to the software. No formal permission has been granted to use, modify, or share the software.	
Freemium	A license that grants use of basic features free of charge, but additional features are subject to a commercial license.	
Freeware	A license that grants use of the software free of charge, although the source code is typically not made available.	
Non-commercial	A license that grants use of the software free of charge for non-commercial purposes, but a commercial license is otherwise required.	
Government Use	A license that grants the local territory's government and its contractors use of the software.	
Other	Any other license type not listed.	

Table 15. Children of "Open Source"

Name	Description	Children
GPL	The GNU General Public License is a copyleft license, where any derivative work, or interfacing software must be distributed under the same or equivalent license terms.	
LGPL	The GNU Lesser General Public License is similar to the GPL license, except that the copyleft clause does not apply to interfacing software.	
AGPL	The Affero General Public License closes a loophole in the GPL license, where, by using but not distributing the software, the copyleft provisions are not triggered.	
CeCILL	The CEA CNRS INRIA Logiciel Libre is a copyleft license adapted to both international and French legal matters, where modifications to the software be distributed under the same license terms.	
MIT	The MIT License is a permissive free software license which requires attribution in derived source code.	
BSD	BSD licenses are a family of permissive free software licenses which require attribution in derived source code and binaries.	
Apache	The Apache License is a permissive free software license which requires notifications to be added stating changes made to any files.	
The Unlicense	The Unlicense is a public domain equivalent license with a focus on an anti-copyright message.	
Other	Any other open-source license not listed.	

Table 16. Children of "Primary Use"

Name	Description	Children
Marine Renewable Energy	Wave, Current, OTEC, and Salinity Gradient.	
Naval Architecture	The design process, building, maintenance, and operation of marine vessels and structures.	
Ocean and Coastal Engineering	Engineering concerned with construction at or near the coast, as well as the development of the coast itself.	
Offshore Oil and Gas	Activity undertaken at or under the sea in association with oil or natural gas extraction.	
Offshore Wind	Activities associated with wind energy extraction sited in bodies of water.	
Other	Any other use not listed.	

Table 17. Children of "Technology"

Name	Description	Children
Wave	Capturing energy from water waves.	
Current	Capturing energy from tidal channels, ocean currents, or rivers.	
OTEC	Capturing energy using temperature gradients across water depths.	
Salinity Gradient	Capturing energy using salinity gradients where freshwater meets seawater.	
Other	Any other technology not listed.	

Table 18. Children of "TRL"

Name	Description	Children
1–3	Fundamental technology research.	
4–6	Technology demonstration at lab and prototype scale.	
7–9	Market launch and commercialization.	

Table 19. Children of "Collection Method"

Name	Description	Children
Modeling	The software is applied in a simulation environment.	
Laboratory	The software is applied in a laboratory setting.	
Field	The software is applied in a real-world scenario.	

Table 20. Children of "Life Cycle"

Name	Description	Children
Design	The software is applied to developing a technology before it is built.	
Manufacturing	The software is applied in the physical manufacturing of the technology (or its ancillaries).	

Name	Description	Children
Deployment	The software is applied during the installation of the technology.	
Condition Monitoring	The software is applied while monitoring the health of the technology while in operation.	
Operations and Maintenance	The software is applied during the operational lifetime of the technology (excluding condition monitoring).	
Decommissioning	The software is applied during the removal of the technology at the end of its life span.	

Table 21. Children of "Discipline"

Name	Description	Children
Acoustics	Analysis or measurement of the noise made by a technology.	
Array Effects	Impacts of multiple units of a technology deployed together.	
Condition Monitoring	Monitoring the health of a technology while in operation.	
Control	Optimal design of the technology's control system, e.g., to maximize electricity generation, minimize stall, etc.	
Cost Assessment	Analysis of a technology's cost, economic feasibility, or other cost-related factors (e.g., techno-economic assessments, cost optimization).	
Data Conversion	Transformation of data from one format to another.	
Data QA and QC	Data quality assurance and quality control.	
Deployment	Installation of the technology.	
Decommissioning	Removal of the technology at the end of its life span.	
Electrical Network	The interconnection of electrical components used to transmit energy to shore.	
Energy Storage	Capture of energy produced for later use.	
Environmental Impact	Relating to change of the natural environment, adverse or beneficial.	
Extreme Events	Related to the prediction of environmental events that are safety critical to a technology, e.g., rogue waves.	
Grid Integration	How technologies integrate with the preexisting electrical grid, including storage.	
Hybrid Devices	Devices collecting energy from multiple sources (e.g., wind and wave).	
Hydrodynamics	Understanding the interactions between fluids and structures.	
Instrumentation	Instruments for monitoring a technology or its effects.	
Levelized Cost of Energy	Analysis of energy cost over the lifetime of a technology.	
Machine Learning	Method of data analysis that automates analytical model building.	

Name	Description	Children
Manufacturing	Related to the manufacturing process or costs.	
Maritime Markets	Markets and potential applications for marine renewable energy other than commercial electricity generation.	
Materials	Analysis of the substances from which a technology is made.	
Meshing	Discretization of a domain for computational analysis or modeling.	
Mooring	Relating to the components that keep a technology on station.	
Multibody Dynamics	System that consists of solid bodies, or links, that are connected to each other by joints that restrict their relative motion.	
Operations and Maintenance	Relating to the operational phase of a technology, particularly logistics, energy production and lifetime costs due to maintenance.	
Optimization	Relating to automatic minimization of some cost function (of an arbitrary number of inputs).	
Performance	Analysis of technology performance in various conditions or operating modes.	
Power Take-Off	Relating to the system used to convert absorbed energy into a usable form.	
Pre/Postprocessing	Pre- or postprocessing of data to be used or generated by software.	
Reliability	Prediction of the reliability of a technology over its operational lifetime.	
Safety and Security	Relating to the safety and protection of personnel and assets.	
Sediment Transport	Relating to movement of solid particles (sediment) in a body of water, typically due to the presence of a technology.	
Site Characterization	Surveying a potential site for bathymetry, energy potential, etc.	
Standards	International or country standards related to marine renewable energy.	
Structural	Relating to the structural design of a technology or component (e.g., blade design, loading).	
Substructure	Relating to the base/foundation for a technology (e.g., pile, floating substructure).	
Supply Chain	Relating to the network of suppliers required to produce a technology.	
Survivability	Relating to a technology's performance under extreme operational conditions.	
Turbulence	The study of fluid motion characterized by chaotic changes in pressure and flow velocity.	
Visualization	Data visualization.	

Table 22. Children of "Programming Language"

Name	Description	Children
C	A general-purpose, procedural, statically typed, compiled programming language with a static type system.	
C++	A superset of the C programming language with support for object-oriented programming among other features.	
Fortran	A general-purpose, statically typed, compiled programming language that is designed for numeric computation and scientific computing.	
Java	A general-purpose, object-oriented, statically typed, compiled programming language that runs on Java virtual machines (JVMs). Typically used for web applications.	
JavaScript	A general-purpose, dynamically typed, interpreted programming language that runs inside of a web browser.	
MATLAB	Proprietary general-purpose, dynamically typed, interpreted programming language and numeric computing environment.	
Python	A general-purpose, dynamically typed, interpreted programming language.	
R	A dynamically typed, interpreted programming language and software environment for statistical computing.	
Other	Any other programming language not listed.	

Table 23. Children of "Method"

Name	Description	Children
Acoustic Wave Equation	The acoustic wave equation governs the propagation of acoustic waves through a material medium.	
Actuator Line Method	A method which applies a body force, based on tabular data, along lines corresponding to individual rotor blades.	
Blade Element Momentum Theory	Analytical method for determining the power and forces generated by a rotor, taking into account its angular momentum.	
Boundary Element Method (BEM)	Computational method of solving linear partial differential equations (such as Laplace's equation), e.g., for potential flow.	
Boussinesq	An approximation for water waves that is valid for weakly nonlinear and fairly long waves.	
Bubble Image Velocimetry (BIV)	Processing of images of tracer bubbles (in a Eulerian frame of reference) to determine the velocity field of a fluid in an experiment.	
Cable Routing	Algorithms for determining the optimal positioning of cables within a farm of devices.	
Cartesian Cut-Cell	Computational method that uses a Cartesian grid over most of the domain with cells cut into smaller irregular cells when intersected by a boundary.	
Computational Fluid Dynamics (CFD)	General computational methods for solving the Navier- Stokes equations.	
Conservation Planning	The process of locating, configuring, implementing, and maintaining areas that are managed to promote the persistence of biodiversity and other natural values.	

Name	Description	Children
Data Acquisition	Sampling signals and converting the resulting samples into digital numeric values.	
Discrete Vortex Method	A numerical technique for the solution of the two-dimensional Navier-Stokes equations in vorticity-transport form.	
Distribution Management System (DMS)	Applications designed to monitor and control the entire distribution network efficiently and reliably.	
Ecological Risk Assessment	The process for evaluating how likely it is that the environment might be impacted as a result of exposure to one or more environmental stressors.	
Energy Balance	Verification and analysis of emergence, transformation, and use of energy sources within an economic zone.	
Environmental Contours	A method to define multivariate extremes based on a joint probabilistic model of variables.	
Euler Equations	The Navier-Stokes equations with zero viscosity and zero thermal conductivity.	
Extreme Value Analysis	A branch of statistics dealing with the extreme deviations from the median of probability distributions.	
Finite Difference Method	Finite difference methods simulate physical phenomena by discretizing a domain into small elements, using a regular grid.	
Finite Element Analysis	Finite Element Analysis simulates physical phenomena by discretizing a domain into small elements, using an unstructured mesh.	
Geographic Information System (GIS)	Relating to databases for geographic data and tools to manipulate that data.	
High-Order Spectral	The solution of differential equations as a sum of high-order “basis functions” with coefficients chosen to satisfy the differential equation as well as possible.	
Image Processing	Processing digital images through an algorithm.	
Incompressible Navier-Stokes	The incompressible form of the Navier-Stokes equations.	
Internet of Things (IoT)	Physical objects (or groups of such objects) with sensors, processing ability, software, and other technologies that connect and exchange data with other devices and systems over the Internet or other communications networks.	
Inverse First-Order Reliability Method	A semi-probabilistic reliability analysis method devised to evaluate the reliability of a system.	
Jensen’s Wake Model	An analytical method for determining the velocity within the wake of a turbine.	
Large-Eddy Simulation (LES)	Direct simulation of the Navier-Stokes equations replacing small scale phenomena with analytical solutions.	

Name	Description	Children
Life Cycle Assessment	A methodology for assessing environmental impacts associated with all the stages of the life cycle of a commercial product, process, or service.	
Linear Wave Theory	An approximation for water waves based on linearization of the boundary conditions of Laplace's equation.	
Logistics	Relating to the process of acquisition, storage, and transportation of components.	
Lumped Mass Method (LMM)	An approximation to a long continuous mass using discrete point masses.	
Marine Spatial Planning (MSP)	A process that brings together multiple users of the ocean, including energy, industry, government, conservation, and recreation, to make informed and coordinated decisions about how to use marine resources sustainably.	
Maximum Likelihood Estimation	A method of estimating the parameters of an assumed probability distribution, given some observed data.	
Mechanics	The area of mathematics and physics concerned with the relationships between force, matter, and motion among physical objects.	
Modal Analysis	The study of the dynamic properties of systems in the frequency domain.	
Moment Matching	An approximation based on interpolating a certain number of points on the complex plane, termed moments.	
Motion Detection	The process of detecting a change in the position of an object relative to its surroundings.	
Multipole Expansion	An angle based mathematical series which is used to approximate functions, such as for boundary element methods.	
Natural Language Processing (NLP)	Processing and analyzing large amounts of natural language data by computers.	
Optical Flow	Relating to the pattern of apparent motion of objects, surfaces, and edges in a visual scene caused by the relative motion between an observer and a scene.	
Optimal Power Flow	Algorithms for optimizing the costs of an electrical network.	
Optimization	Algorithms for automatic minimization of some cost function.	
Panel Method	Numerical schemes for solving potential flow problems using a series of singularities.	
Particle Image Velocimetry (PIV)	Processing of images of tracer seed particles (in a Eulerian frame of reference) to determine the velocity field of a fluid in an experiment.	
Potential Flow	Fluid flow where the velocity field is described as the gradient of a scalar function, known as the velocity potential, typically used for incompressible flow.	

Name	Description	Children
Primitive Equations	A set of nonlinear partial differential equations that are used to approximate global atmospheric flow and are used in most atmospheric models.	
Pseudo-Spectral	A spectral method applied in a discrete space.	
Particle Tracking Velocimetry (PTV)	Tracking the motion of tracer seed particles (in a Lagrangian frame of reference) to determine the velocity field of a fluid in an experiment.	
Quasi-Static Loads	Related to solid mechanics algorithms where inertial effects are considered to be negligible.	
Robotics Middleware	Middleware to be used in complex robot control software systems.	
SCADA	Supervisory control and data acquisition (SCADA) is a control system for high-level supervision of machines and processes.	
Shallow Water Equations	Depth-integrated form of the Navier-Stokes equations, where the horizontal length scale is much greater than the vertical length scale.	
Shape Analysis	The automatic analysis of geometric shapes.	
Smoothed-Particle Hydrodynamics (SPH)	The discretization of a continuous medium is into a set of particles that interact with each other and move at the fluid’s velocity.	
State Space	A model of a physical system as a set of input, output and state variables related by first-order differential equations or difference equations.	
Static Loads	Solid mechanics analysis where loads do not change with time.	
Statistics	Relating to the application of probability theory to data.	
Stream Function	A function where flow velocity components can be determined from its derivatives.	
Subsurface Science	Relating to subterranean processes, such as subsurface flows.	
Tidal Harmonics	The representation of tides as the superposition of basic waves using Fourier analysis.	
Verification and Validation	Relating to the processes for quantifying and building confidence (or credibility) in numerical models.	
Vortex Lattice Method (VLM)	A method which models a lifting surface as an infinitely thin sheet of discrete vortices.	
Vortex Particle Method (VPM)	A mesh-free approach to computational fluid dynamics, where fluid is discretized into discrete particles.	
Vorticity Transport Equation	An equation that describes the evolution of the vorticity of a particle of an incompressible fluid as it moves.	
Wave Spectral Analysis	Discretization and analysis of ocean wave energy as frequencies of wavelengths.	
Wind Wave Model	Models which predict sea states and the evolution of the energy of wind waves subject to forcing from wind and/or tides.	

Table 24. Children of "Interface"

Name	Description	Children
Graphical	A native user interface that has interactive graphical elements.	
Textual	A native user interface driven by purely text-based elements.	
web-API	A general interface that can be accessed over the web using HTTP, typically used by other software.	
Web Page	A graphical user interface that is accessed through a web browser.	

Table 25. Children of "PRIMRE Knowledge Hub"

Name	Description	Children
Code Catalog	The software is included in the PRIMRE Code Catalog.	
Code Hub	The software is included in the PRIMRE Code Hub.	

APPENDIX B. BREAKOUT GROUP DISCUSSION TOPICS

B.1. Cost Drivers

Definition: Identify software associated with the largest cost drivers.

In a recent wave energy LCOE elicitation, industry experts believed that the greatest cost contributors to the LCOE are the following cost categories:

- Structural assembly
- Operations
- Power take-off
- Mooring, foundation, and substructure
- Electrical infrastructure.

Figure 38 shows the top six cost contributors to LCOE as identified by the experts involved in the wave energy LCOE elicitation [33].

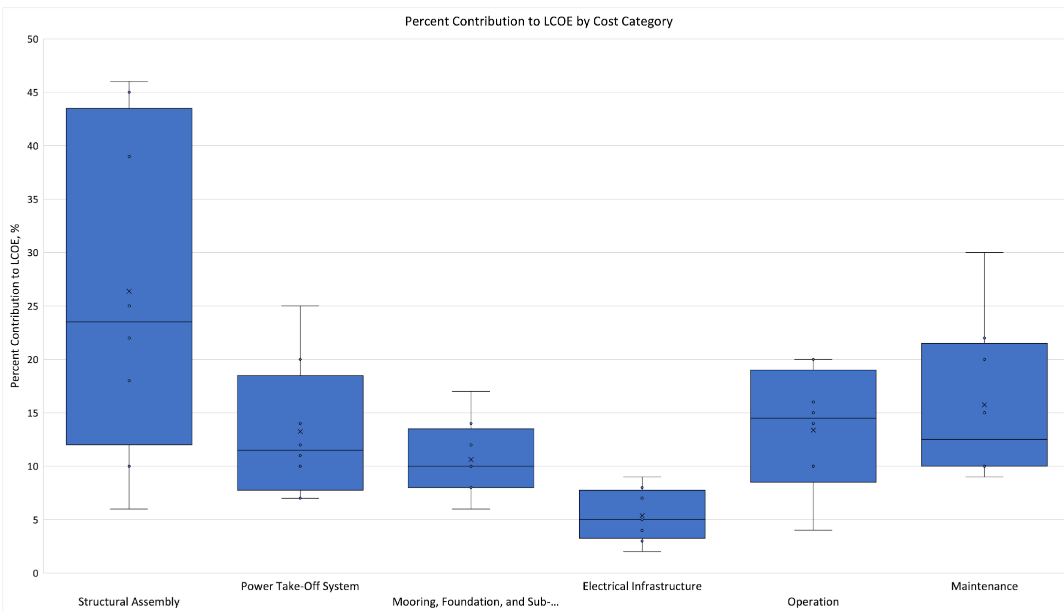

Figure 38. Percent Contribution to LCOE by Cost Category

A tidal energy expert LCOE elicitation is currently underway. While the results of the elicitation are not yet available for tidal energy analysis using reference model data has shown a similar trend Figure 39. For tidal energy, the top contributors to LCOE are likely the same but with a slightly different order.

B.1.1. *Structural Assembly*

Given the importance of the structural assembly to marine energy costs, the availability of applicable software was examined. Figure 39 shows the breakdown of Primary Use for software tagged with the Structural discipline.

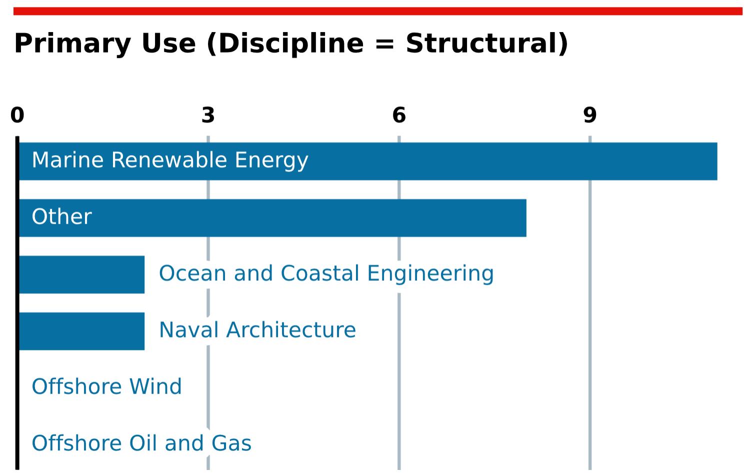

Figure 39. Primary use for software having the structural discipline field value

The 11 software packages specific to marine energy are mapped to their applicable Technology in Figure 40.

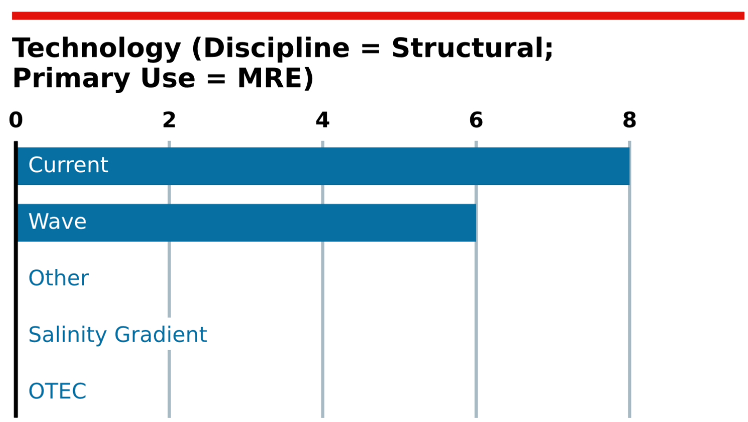

Figure 40. Technologies for software having the structural discipline field value and primary use as marine energy

B.1.2. Operations and Maintenance

Given the importance of operations and maintenance to marine energy costs, the availability of applicable software was examined. Figure 41 shows the breakdown of Primary Use for software tagged with the Operations & Maintenance discipline.

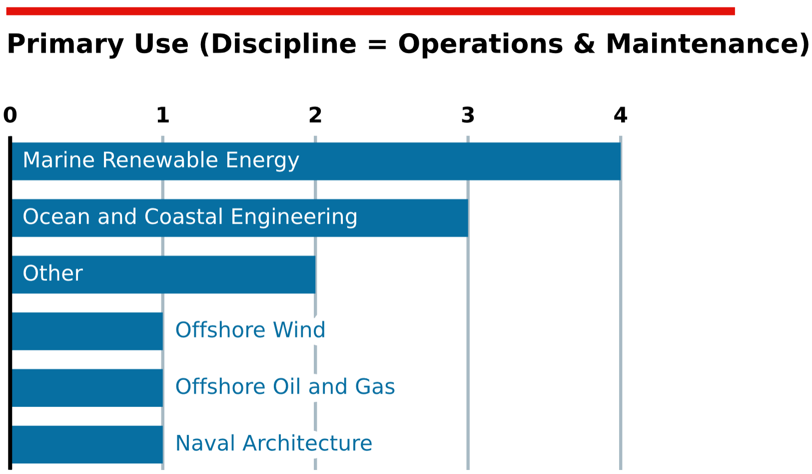

Figure 41. Primary use for software having the operations and maintenance discipline field value

The four software packages specific to marine energy are mapped to their applicable Technology in in Figure 42.

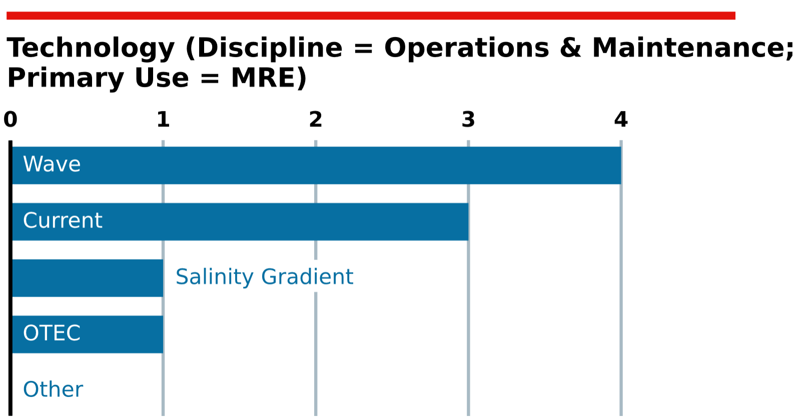

Figure 42. Technologies for software having the operations and maintenance discipline field value and primary use as marine energy

B.1.3. Power Take-Off

Given the importance of power take-off to marine energy costs, the availability of applicable software was examined. Figure 43 shows the breakdown of Primary Use for software tagged with the Power Take-Off discipline.

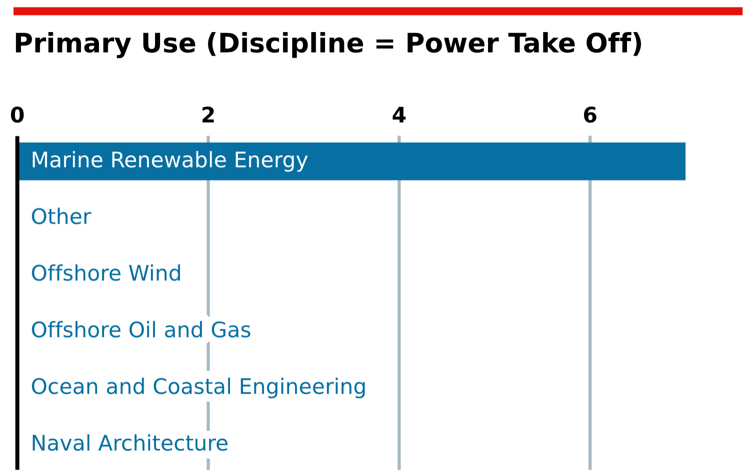

Figure 43. Primary use for software having the power take-off discipline field value

The seven software packages specific to marine energy are mapped to their applicable Technology in Figure 44.

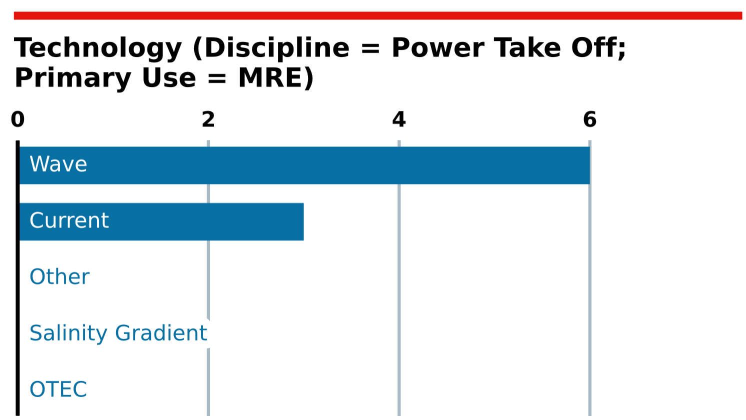

Figure 44. Technologies for software having the power take off discipline field value and primary use as marine energy

B.1.4. Mooring, Foundation, and Substructure

Given the importance of mooring, foundation, and substructure to marine energy costs, the availability of applicable software was examined. Figure 45 shows the breakdown of Primary Use for software tagged with either the Mooring or Substructure discipline.

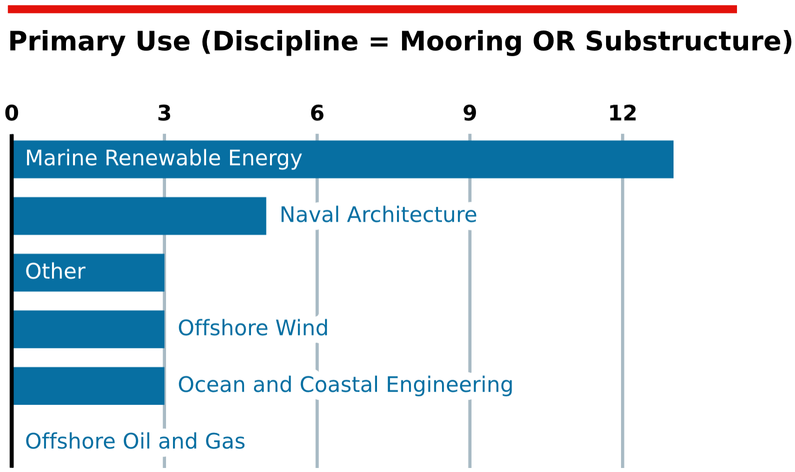

Figure 45. Primary use for software having the mooring or substructure discipline field values

The 13 software packages specific to marine energy are mapped to their applicable Technology in Figure 46.

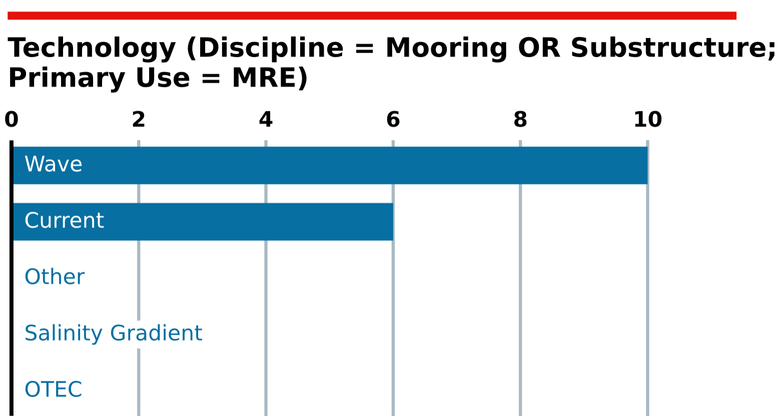

Figure 46. Technologies for software having the mooring or substructure discipline field values and primary use as marine energy

B.1.5. Electrical Infrastructure

Given the importance of electrical infrastructure to marine energy costs, the availability of applicable software was examined. Figure 47 shows the breakdown of Primary Use for software tagged with the Electrical Network discipline.

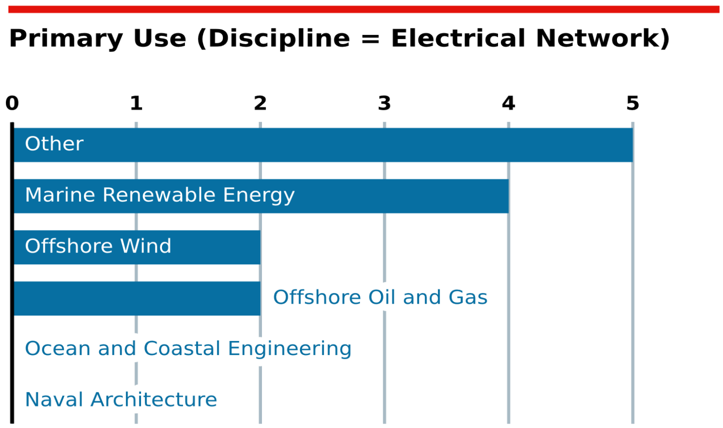

Figure 47. Primary use for software having the electrical network discipline field value

The four software packages specific to marine energy are mapped to their applicable Technology in Figure 48.

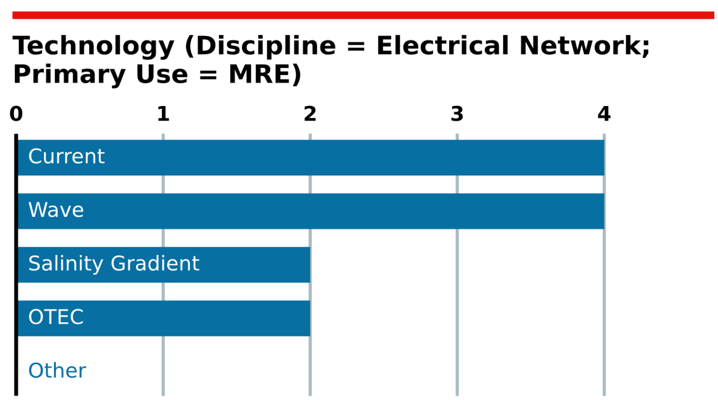

Figure 48. Technologies for software having the electrical network discipline field value and primary use as marine energy

5.1.1. Questions

- What software does your organization use to assess or optimize the following cost categories?
  - Structural assembly
  - Power take-off
  - Mooring, foundation, and substructure
  - Electrical infrastructure
  - Operations, maintenance
- Which cost categories would most benefit from additional software support and why?
- Are there other cost categories that lack software (e.g., installation, development, etc.)?

B.2. Interoperability

Definition: Data generated from software for different disciplines should be easily accessible from other software.

Upon reflection a decade later, the focus on developing stand-alone programs, with interoperability a lesser priority, has resulted in a current scenario where software development is often siloed, and coupling software is challenging. Future software development may have an improved focus on interoperability to allow improved communication between open-source APIs, databases, and commercial codes to streamline workflows and improve productivity. However, the verification and validation of any software is dependent on available wave tank and open-water data, which to date are limited.

Figure 49 is a sunburst diagram showing the relationship between TRL and discipline. It highlights hydrodynamics as top discipline for both TRL 1-3 and TRL 1-3/4-6. However, the top disciplines across all TRLs (i.e., TRL 1-3/4-6/7-9) are site characterization and extreme events, whereas hydrodynamics has few software applicable across all TRLs. This highlights the lack of hydrodynamic interoperability across TRLs.

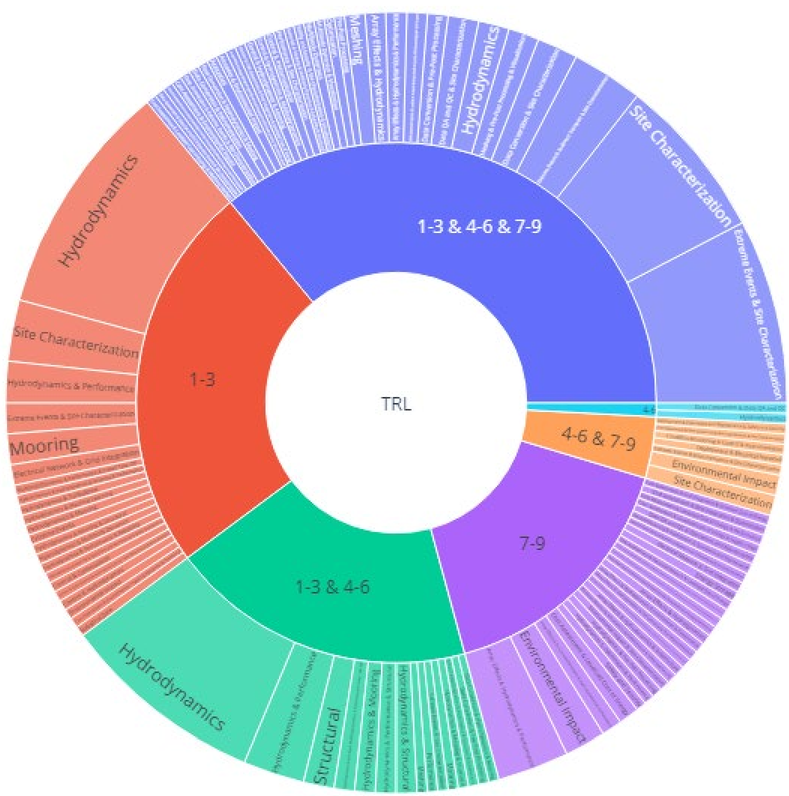

Figure 49. Sunburst diagram showing relationship between TRL and discipline

B.2.1. Wave Case Study

Within WEC numerical modeling, the field is generally split into three distinct domains: low-, mid-, and high-fidelity modeling:

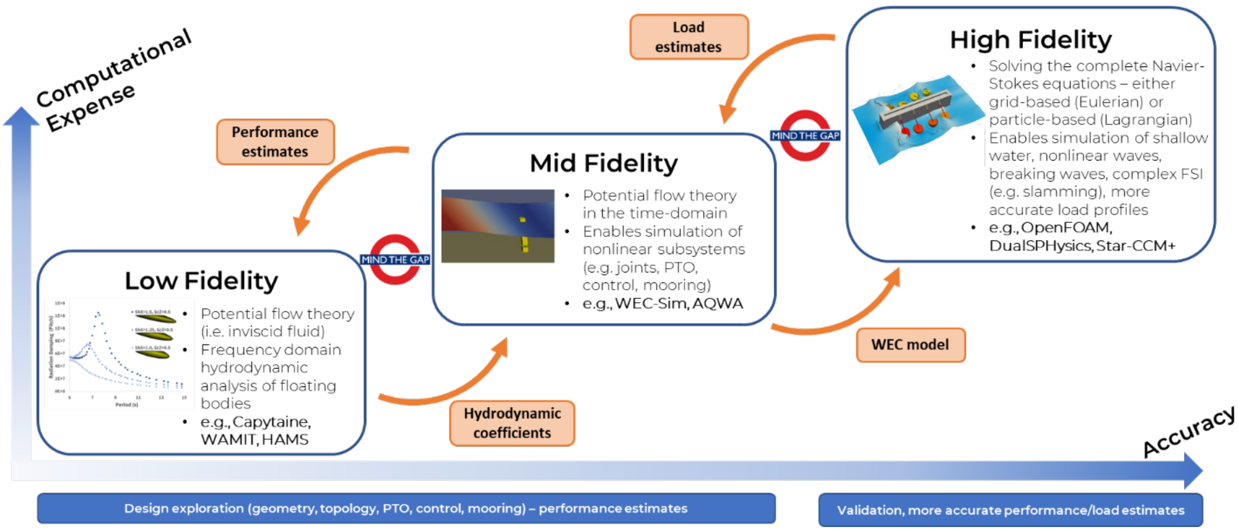

Figure 50. Interoperability case study for wave energy

However, interoperability between the three domains is typically poor. In recent decades, the emergence of software APIs has enabled greater software interoperability. Within WEC numerical modeling, commonly used open-source meshing, BEM, and optimization software (e.g., PyGmsh, Capytaine, WecOptTool) have developed Python APIs, but mid- and high-fidelity tools have not. Hence, there is currently no way to call open-source low- and mid-fidelity tools from within the same loop.

Mid- and high-fidelity models both involve solving device dynamics in the time-domain, and generalized multibody dynamics solvers (e.g., Simscape Multibody, Project Chrono) have proved to be a good option for modeling a wide range of devices. However, high-fidelity fluid-structure interaction solvers (DualSPHysics, Proteus) have been coupled with Project Chrono, whereas Simscape Multibody has not. Hence, to simulate a device at the mid- and high-fidelity levels requires building two separate device models. Using a common multibody solver could help to improve interoperability between mid- and high-fidelity WEC numerical modeling software and streamline the WEC numerical modeling process.

B.2.2. Tidal Case Study

For current energy conversion there are many data interoperability bottlenecks. Beginning with data collection, bathymetric, sedimentary and metocean data is generally collected from disparate sources with nonstandard formats. Often, these data can require manipulation to merge different data sets. This is a challenging manual activity, which is often delegated to third parties. Improving data interoperability could reduce cost and increase efficiency of simulation for current energy conversion and marine renewable energy.

Data interoperability is also critical for the operation of CEC arrays. Knowledge of the condition of the devices, current and future metocean conditions, projected costs and availability of crew and equipment, and logistical simulation must be combined to optimize the most cost-efficient and safe periods for undertaking maintenance. Being able to programmatically access this data would allow automatic solution of this complex challenge and reduce the risks associated with operations and maintenance for marine renewable energy arrays.

B.2.3. Questions

- Do you agree with our assessment of the areas of low interoperability between software?
- Does our example problem seem realistic? Are there other examples of specific coupling problems that could lead to benefit if solved?
- Do you think new standards should be developed for certain marine energy data? Which types of data would this cover?
- Is dependence on commercial (paid) packages for open-source software a barrier to adoption of software?
- Can you provide examples of low interoperability between software?
- Would marine energy data standards improve interoperability?

B.3. Software Quality

Definition: Identify software gaps for marine-energy-specific applications and improve existing software accuracy and usability.

B.3.1. Open-Source BEM Case Study

An example for wave energy is open-source BEM. NEMOH was the default open-source BEM solver for many years. However, despite being relied on by the wave energy community, NEMOH did not have long-term funding and was no longer supported. There were several known issues with NEMOH that went unresolved for years.

To address some of these issues, and to convert Fortran-based NEMOH to Python, Capytaine was developed. Capytaine was quickly adopted by the wave energy community as the default OSS BEM solver. However, it also did not have long-term funding, and for a period was unsupported. With support from DOE WPTO, SNL and NREL funded the lead Capytaine developer to continue supporting the software. Since its renewed support, Capytaine has seen an increase in adoption, and many of the known issues have been resolved.

This highlights an example where just because software exists, does not imply "no need." In fact, this example highlights the need to leverage existing support, through continued support and improvement [34].

B.3.2. Software Coverage

The marine energy software database was analyzed for categories without records to identify gaps. Just because a software category has a gap (i.e., doesn't have a record), doesn't mean it is an area of need. Conversely, categories with abundance (i.e., have many records) can be areas of need. However, these gaps provide useful insight into the software landscape, and are used to frame the Next-Generation Marine Energy Software Workshop breakout group discussion.

Figure 51 shows the relationship between Discipline and TRL. The left-hand side is for all software in the database, and the right-hand side is for marine energy software. Low coverage is shown in dark colors, and high coverage is shown in light colors. Figure 52 shows the relationship between Technology and Life Cycle.

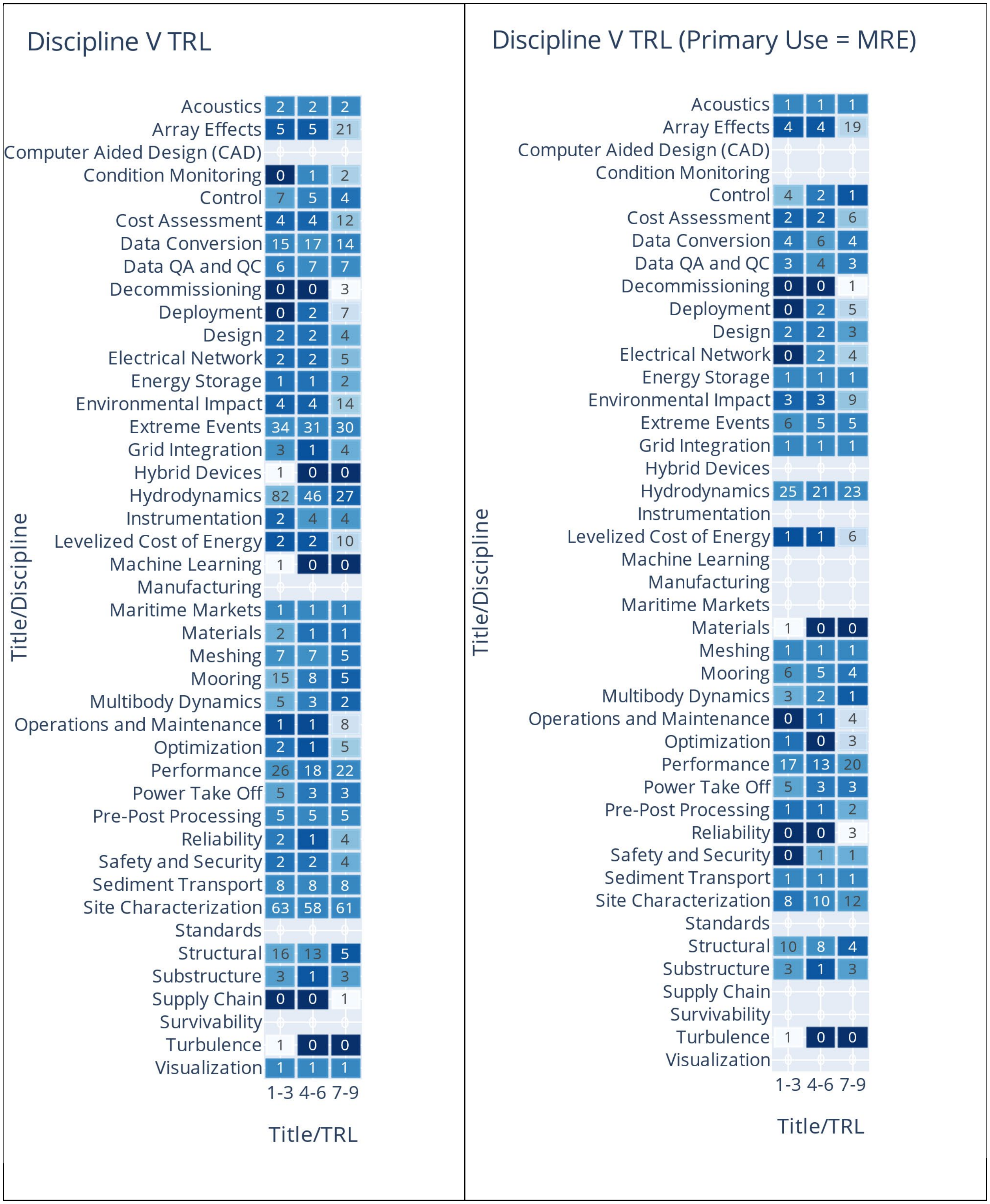

Figure 51. Discipline versus TRL for (Left) all software and (Right) marine energy software

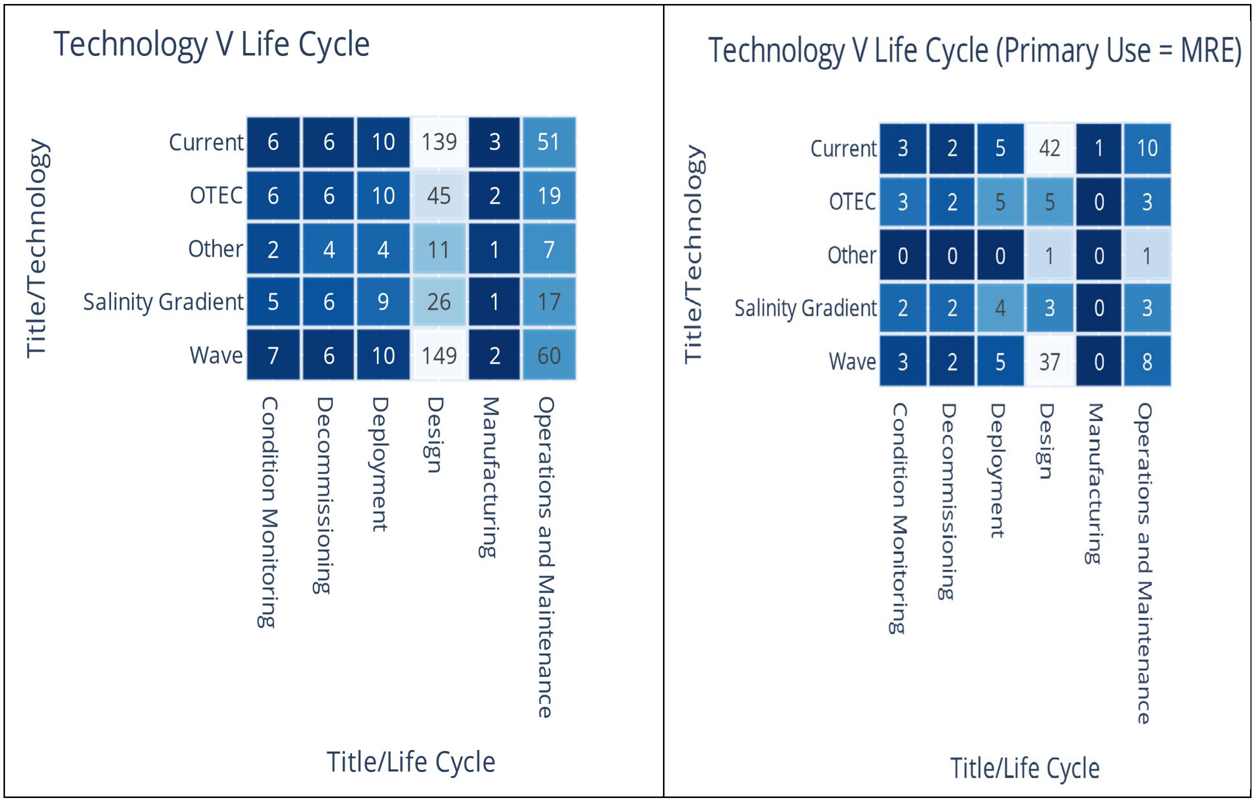

Figure 52. Number of software per technology and life cycle: (Left) all software, (Right) marine energy software

B.3.3. Questions

- Do you agree with our assessment of disciplines that are lacking high-quality, validated, or popular software products?
- Do you have experience where the outputs of software did not match reality?
- Is there software which you would like to use but are inaccessible? What reasons make the software difficult to use?
- Do you agree with the areas of low software coverage that we believe would benefit from adding new software? What are the reasons for your answer?
- Are there any areas of marine energy development where you do not use software? If so, would any of these areas benefit from new software?
- Are there any areas of marine energy development where there are insufficient software choices available? What functionality would you like a competing software in that area to deliver?
- Have you wanted to use software but could not (e.g., lack of support or access issues)?
- What applications lack high-quality, validated, software?

B.4. Productivity

Definition: By utilizing advanced software and hardware architectures, like parallel central processing units (CPU)/GPU or machine learning, software can produce higher fidelity and/or a higher volume of outputs

New scientific computational and solution frameworks are revolutionizing many fields of science and engineering. These hardware and software innovations (1) allow us to do things we were doing more ***efficiently***, and (2) open up the door to ask and solve new, **different problems**. How can we incorporate emerging hardware and software technologies in scientific computing into marine energy software? Some of these scientific computing trends include:

- Hardware
  - Parallelization (e.g., HPC)
  - GPUs
  - Other advanced architectures.
- Software
  - Control co-design (e.g., WecOptTool, CT-Opt)
  - Machine learning
  - Differentiable programming
  - Other?

These have the potential to allow us to solve problems much more efficiently, allowing us to explore more of the design space (previously would be not explored due to time constraints). Or it could allow us to formulate the problem completely differently, for example by expanding the design space by removing structural barriers inherent to the framework (e.g., control co-design, machine learning).

However, the marine energy industry has been slow to adopt any of these trends. One complicating factor is that existing tools are not set up to exploit these new and evolving technologies. Interested users are left to program entire frameworks for themselves.

Some possible solutions include:

- Moving toward popular (used outside marine energy) open-source tools, like OpenFOAM, Project Chrono, etc. These codes have extensive user bases and are open source, and therefore usually have good coupling to utilize these new/emerging hardware and software solutions. However, these are often coded in compiled languages (for efficiency/speed) which are not very accessible to most scientists/engineers. These would require significant effort to make them compatible with marine energy.
- Moving toward an open-source programming language. Currently MATLAB is very popular in marine energy software. However, the closed-source nature of it makes it difficult to couple with other software and use these emerging trends. There are modern, high-level (dynamic) languages that are open source and are frequently used for these emerging technologies. These include:
  - Python: originally not a scientific tool, but with the release and popularity of NumPy has become the most popular scientific/engineering dynamic language as well as the most popular machine learning language.
  - Julia: Newer open-source dynamic language which exploded in popularity after V1.0 release in 2018. Like MATLAB, it is meant for scientific/engineering applications. It was developed

with differentiable programming and machine learning in mind and is easy to run in different architectures (e.g., GPUs, supercomputers, etc.).

- Waiting until current frameworks catch up with these trends. If using these trends in hardware/software is not a current priority, eventually even closed-source frameworks like MATLAB will catch up (there is an inherent lag when developing closed-source software). There might be more pressing issues/gaps that need to be solved in marine energy software.

B.4.1. Questions

- Is progress hampered by the speed of computation of certain problems? For what type of problems does this issue arrive?
- Would the complexities and costs involved with using advanced architectures (e.g., GPUs, parallelization, supercomputers) be an acceptable trade-off for increased speed/volume of computation?
- Which emerging trends in software solutions (e.g., machine learning, differentiable programming, control co-design, etc.) would you like to see incorporated into marine energy? If these were incorporated, would you see yourself utilizing these new solution approaches?
- Would you be willing to learn a completely new programming language or modeling framework to access these emerging trends in hardware and software solutions?

B.5. Backup Questions

- Do you agree with the selection of topics?
- Within the themes, do you agree with our analysis of the existing software landscape?
- What software does your organization use through the design process/life cycle?
- What software is used to assess risk and failure modes of your system (e.g., refer to Metrics)?

APPENDIX C. AFFINITY DIAGRAM

Table 26. First-Level (Green), Second-Level (Pink), and Third-Level (Blue) Themes

I want to leverage state-of-the-art computational resources		
	I need faster numerical modeling tools	
		Speed is important for multi-physics simulations
		We need faster high fidelity models
		Speed is important for high fidelity simulations
		Simulation speed may not be a barrier
		Simulation time is a constraint that could affect results accuracy
	I want to use GPUs but need help	
		Using GPU could be useful, but it is not easy to implement
		I see a future role for graphics processing units
		There's work being done for GPUs, but there's more to do
	I want to use cloud computing for simulations	
		Having a cloud machine with multiple programs installed could be beneficial to the whole industry
		Different conventions used between codes can make interoperability challenging
		Cloud computing can help engineers to get results much faster
		Interest for linearization at system level
	I want to do co-design and use digital twins	
		Desire to use digital twins for co-design
		Co-design is important but has practical limitation

	I want to use Machine Learning (ML) but don't know how	
		People are excited about ML, but current level of knowledge/expertise in marine energy is a barrier to adoption
		ML can be used to perform high fidelity simulations and optimization much faster
		ML needs to be properly understood in order to be used effectively
		ML should not be used as a replacement to understand the physics of a system
		Some people are skeptical of ML
		ML tools, workflows and public examples need improvement
	I want to use state-of-the-art optimization tools	
		We can leverage modern computing resources (both hardware and software) to perform optimization studies more effectively
		Optimization is different depending on the detail level
		Low-fidelity models are necessary for optimization
	I need to perform hardware-in-the-loop (HIL) simulations	
		Desire for hardware-in-the-loop software integration
		Desire to leverage Hardware/Software integration efforts
		Desire for open-source hardware-in-the-loop (HIL) software
I need to overcome existing software limitations in order to advance marine energy technology		
	I need software to model current energy converters	
		I need software to model current energy converters
		I need to use Tidal Bladed but it's no longer supported

	I need better PTO and control system modeling tools	
		I need open-source, customizable control software
		For initial PTO design & opt available software is sufficient for me
		I need PTO modeling tools that allows me to develop detailed custom models
	I need better high fidelity modeling tools for marine energy devices	
		I need software with better accuracy of low-mid fidelity models
		Improving OpenFOAM usability (e.g., UI/UX and examples) would be useful for me
		High fidelity modeling software barriers (e.g., development cost, validation) are challenging for me
		"High-fidelity" is a broad term
	I need new marine energy software	
		I need to model flexible bodies
		I need software to model more WECs including hybrid devices
		I need to model nonlinear waves (e.g., shallow water)
	I need WEC-Sim improvements (e.g., imitations/improvements)	
		I want WEC-Sim to be faster and to provide support for extreme conditions
		WEC-Sim models can be difficult for me to validate
		WEC-Sim's dependency on MATLAB is a problem for me
	I need OpenFAST developed for current energy converters	
		I need improved UI/UX for OpenFAST
		I need continued investment and support for OpenFAST

		I need OpenFAST to be verified and validated for current energy converters
		I need new OpenFAST features for current energy converters
	I need fast and interoperable BEM software	
		I've run into known limitations with Boundary Element Method solvers
		I need differentiable BEM for gradient based optimization
		I need interoperable hydrodynamic libraries (e.g., across platforms)
	I need low cost mooring design tools (large value added)	
		I need mooring and anchor design tools to reduce the associated high risk and uncertainty during installation
		I want access to more mooring modeling approaches other than linearized matrix and lumped mass
		I need reliable software for mooring design
		I want to leverage mooring systems from related fields (e.g., offshore wind)
		I need mooring costs from both a design and purchase consideration
		I need reference mooring designs (i.e., catenary, tension leg, etc.)
		Using MoorDyn for wave energy would be useful for me
		I want improved interoperability between different software tools, e.g., MoorDyn/OpenFOAM
	I need arrays and grid integration models	
		I need industry standard grid integration tools
		I need to model WEC arrays
	I need optimization tools	
		I need better optimization methods

		I need software to optimize for material selection
		I need software to optimize design for manufacturing
		I need software to optimize structures
	I need interoperable marine energy software (e.g., like wind energy)	
		I need to develop custom wrappers to integrate software
		I need interoperable system and subsystem (e.g., systems engineering) models
		I need interoperable finite element analysis models
		I need multi-fidelity modeling frameworks
		I need interoperable hydrodynamic and structural models
		I need improved and interoperable meshing tools
		I need interoperable multi-fidelity models
		I want to learn from interoperability of wind turbines models
		I need interoperable computational fluid dynamics and structural analysis models
		I need interoperable controls models
		I need to leverage high-fidelity models inform engineering models
		I think that sometimes tools won't be interoperable
I want to advance marine energy technology, but data access is a barrier		
	I need access to data repositories for balance of system components	
		I need PTO designs and operational data

		I need mooring designs, cost estimates, and performance data
		I need data assimilation (and extrapolation) methods
		I need access to data on bathymetry and sediment
	I need established data standards to build trust in and improve interoperability between software	
		I need standard software inputs & outputs
		I need pre and post-processing scripts for compatibility with IEC Data Standards
		I need standardized data formats for hydrodynamic coefficient calculation (BEM)
		I need standardized data formats for resource assessment data
	I need access to installation, operations, maintenance (IO&M) data and experience	
		I need access to operations and maintenance (O&M) data
		We need more IO&M experience as knowledge is currently limited
		I need IO&M lessons from related industries
		I want more access to Mermaid which is great commercial software for IO&M cost optimization
		I need IO&M tools
		I want condition monitoring tools
		I need a free and open-source cost optimization tool (comparable to Mermaid)
		I use custom IO&M tools (not generalizable to others)

	I need access to quality data for model verification and validation	
		Difficult for me to know the accuracy of model results
		I need to do better at model verification and validation
		I need data for validation and uncertainty quantification (UQ)
	I need access to cost data to improve cost modeling, optimization, and analysis	
		My cost optimization for balance of system relies on sparse data and black box models
		I need more access to economic and manufacturing data
		I need access to design for manufacturing data
		Xometry is a great Solidworks plugin to assess design cost for me
		I need access to more subject matter expertise
		I need cost optimizations
	I need reliability tools that consider failure modes and rates	
		I need defined and standardized reliability models
		I have a need to quantify extreme events with respect to risk and insurance
		I need software to model failure models and rates
		I need a tool like Xometry that includes failure rates
		I need access to data for failure modes and rates
	I need to have confidence in my results	
		I need to have confidence in the tools in my toolbox

		I want to leverage verification & validation metrics from other sectors
I need to consider many factors and trade-offs when developing or using new marine energy software (e.g., language, architecture, license)		
	I want to use low-level programming languages like C++ for simulation software and use APIs for better interoperability	
		I need to use low-level programming languages (C++, Fortran) for computationally expensive software
		I need to use APIs to get different software talking to each other
	MATLAB is a barrier for me	
		MATLAB packages are too costly for me
		MATLAB licenses costs are a barrier for me
		MATLAB is a barrier to productivity (e.g., parallelization and high performance computing) for me
		MATLAB is a barrier to interoperability for me
	MATLAB is beneficial to me	
		MATLAB has offers me free licenses
		I like that MATLAB has an established user base and support
		I want to continue to use MATLAB
	I want to transition to Python, from MATLAB	
		My university is switching from MATLAB to Python
		I think future graduates will be more familiar with Python than MATLAB
		I need to stop developing software in MATLAB
		I've spent a lot of development time making Python code available to MATLAB users

	I want to learn new programming tools and skills, but it can take time	
		I'm willing to learn new skills and use the best programming language(s) for the job
		I think it's more cost effective to stick with existing tools (i.e., resistant to change)
	I need custom software due to lack of technology convergence	
		I need to develop custom software to solve problems
		I use custom cost of energy models due to wide range of technologies
		I need to develop custom models due to my custom PTO
	I need long-term software development, support (i.e., funding) and clear objectives	
		I think software development is a continual process (i.e., no end)
		I think supporting open-source software long-term is challenging but important
		Commercial software does not guarantee me long-term support (i.e., funding)
		I think software development approaches must balance a wide range of needs
	I need to understand tradeoffs and limitations between different software	
		I need SME expertise to correctly apply software
		I think selecting the "right" software is challenging
		I'm using software outside of its intended application
		I need a better understanding existing software limitations
		I need a tool to easily compare software

	I need to overcome commercial software limitations (e.g., cost, interoperability, and productivity)	
		Interoperability is difficult with commercial software (e.g., no incentive, close-source) for me
		Closed source code can be a black box to me
		Parallelization is difficult to achieve with commercial software for me
		Licenses costs are a barrier to adoption for me
		Commercial licenses can be too expensive for me
	I want to use industry-standard commercial software for some things - like structural analysis	
		I need to use commercial structural analysis software
		I need validated techno economic studies (e.g., against design and standards)
		I need updated foundation designs
		I think commercial software is worth the cost
I need open-source software that is trusted, free, and easy to use		
	I need easy-to-use open-source software (OSS)	
		I think the learning curve is tolerable if the software is useful
		I need OSS with a less steep learning curve
		I need to rely on software development subject matter experts (SMEs)
		I need to consider software adoption factors beyond cost
		I need improved OSS user interface (UI)
		I need improved OSS documentation

		I need improved OSS training and user experience (UX)
	I need multi-platform, free open-source software (FOSS)	
		I need free open-source software (FOSS)
		I need open-source software that reduces the cost barrier
		I need Operating System (OS) interoperability
	I need trusted open-source software (OSS)	
		I need open-source software bugs unresolved
		I need open-source software
		I need easy-to-modify open-source software

APPENDIX D. OPEN-SOURCE SOFTWARE BUSINESS MODELS

WPTO made strategic investments in marine energy software over the past decade, but they cannot fund software development and maintenance indefinitely; thus, the long-term sustainability of these software packages must be considered. Many of the WPTO-funded software projects are released as open-source software (OSS), where OSS refers to "software that is released under a license in which the copyright holder grants users the rights to use, study, change, and distribute the software and its source code." OSS business models[22] are an active field of research in the field of software engineering. This appendix provides an overview of the state-of-the-art research in this area.

Here is a non-exhaustive list of common OSS business models based on [35]-[39].

D.1. Dual Licensing

Refers to a business model where the software is available under an open-source license but also under separate proprietary license terms. Customers can be attracted to a no-cost and open-source edition, then be part of an up-sell to a commercial enterprise edition. Further, customers will learn of open-source software in a company's portfolio and offerings but generate business in other proprietary products and solutions, including commercial technical support contracts and services.

- Maintain a free, open-source version
- Fee is charged for a proprietary version
- Examples(s): MySQL.

D.2. Proprietary Extensions

- Refers to a business model where the OSS is available as source code only, while executable binaries are only available to paying customers (e.g., proprietary extensions, modules, plugins, or add-ons). This business model requires a permissive software license. Some companies provide the latest version available only to paying customers.
- Maintain a free, open-source version
- Fee is charged for optional add-ons, plugins, or binaries
- Example(s): Red Hat Enterprise Linux.

D.3. Professional Services

Refers to a business model where the OSS is available free and open source, and development and maintenance is supported through selling services, such as training, technical support, or consulting.

- Maintain a free, open-source software
- Fee is charged for training, support, and consulting
- Examples: DirectCFD support for OpenFOAM.

[22] Also referred to as "software sustainability" and "commercial open-source software."

D.4. Software As a Service (SaaS)

Refers to a business model where the OSS is available free and open-source and subscriptions for online accounts and server access are sold to customers is one way of adding value to open-source software.

- Maintain a free, open-source software
- Fee is charged for access to online accounts and servers
- Examples(s): Robot Operating System (ROS).

D.5. Partnership With Funding Organizations

Refers to a business model where the OSS includes partnerships with other companies. Sometimes a commercial version may be sold to finance the continued development of the free version. Governments, companies, or other nongovernmental organizations may develop custom in-house modifications to software, then release that code under an open-source license.

- Release free, open-source software
- OSS is funded through grants/stipends
- Examples(s): WEC-Sim.

D.6. Voluntary Donations

Refers to a business model where developers accept donations. Some users may pool money together for the implementation of a desired feature or functionality.

- Open-source code is freely available
- Users of the code donate to its continued development and maintenance
- Examples: SourceForge.

D.7. Case Studies

Software sustainability is an active field of research encompassing the social, technical, environmental, and economic aspects of software that enable it to endure and continue to meet stakeholder needs. On the economic front, new OSS business models are still emerging. Many OSS business models do not fit into a single approach listed above; OSS often includes elements of multiple business models.

5.1.2. OpenFOAM

For example, OpenFOAM is an OSS commonly used for computational fluid dynamics (CFD) [40]. It is used worldwide for automotive, manufacturing, and marine energy applications, among countless others. OpenFOAM uses several of the business models listed above. OpenFOAM is developed and maintained by CFD Direct. The approaches include having “companies fund new functionality in OpenFOAM through contracted development and support with CFD Direct.” (i.e., partnership with funding organizations), and providing “maintenance plans are available to businesses to support the cost of ongoing maintenance of OpenFOAM, giving priority to issues that affect them most” (i.e., voluntary donations). Additionally, the primary OpenFOAM developer, CFD Direct, provides “OpenFOAM Training including their acclaimed Essential, Applied and Programming CFD courses, delivered as scheduled classes, on-site and as live virtual training.” (i.e., professional services), and access to the CFD Direct Cloud, "the leading cloud CFD solution, providing a configured environment with OpenFOAM" (i.e., software as service).

D.7.1. ParaView

Another example is ParaView, an OSS commonly used for postprocessing data visualization, has been used for marine energy applications, and was originally funded by DOE [41]. ParaView maintains a free OSS version of the software under a BSD license and has adopted several of the above business models. ParaView is developed and supported by Kitware, Sandia National Laboratories, and the Army Research Laboratory (i.e., partnership with funding organizations). They also maintain "other licenses that are applicable because of other packages leveraged by ParaView or developed by collaborators" (i.e., dual licensing), and "there are specific packages for the ParaView binaries available on paraview.org that have applicable licenses" (i.e., proprietary extensions).

D.7.2. Additional Case Studies

Additional OSS case studies of commonly used OSS (e.g., LINUX, Python, and major Python packages like Pandas, NumPy, etc.), and case studies of software developed at the national labs (e.g., CUBIT and Dakota) could be explored in the future.

Lessons can also be learned from business models adopted by the open-access community at large (e.g., Wikimedia, open-access journals), and from development and maintenance of facilities [42]. Parallels can also be made with data access since databases must also be developed and maintained. Many of the OSS business models listed above also apply to data. For example, data may be freely available adhering to FAIR data standards, and the same data may be available through a paywall with value-added products [43].