Review of WEC-Sim Development and Applications

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Abstract—**WEC-Sim (Wave Energy Converter Simulator) is an open-source code for simulating wave energy converters, which has been actively developed and applied to simulate a wide variety of device archetypes, and has become a popular tool since its release. This paper reviewed the development efforts and the usage of WEC-Sim. The publications considered in this study have been broken down into six topic areas, namely feature development, experimental validation, device modeling, control modeling, PTO and grid modeling, and novel applications, which even includes some non-wave energy applications. This review paper has also attempted to recognize the contributions of the broader WEC-Sim development effort, meaning not only the internal WEC-Sim development team but also the external efforts from the academia researchers and technology developers around the world. The growing trend of external applications of WEC-Sim has demonstrated the broader acceptance of the open-source code, and how WEC-Sim has been used in a certain topic area also highlights the potential future development needs.**

Index Terms—**WEC-Sim, Numerical Modeling, Applications, Feature Development, Wave Energy**

I. Introduction

WEC-Sim is a numerical modeling code that has the ability to model the dynamics of wave energy converter (WEC) systems that are comprised of rigid/ flexible bodies, power-take-off (PTO) systems, and mooring systems. It uses a radiation and diffraction method, where the hydrodynamic forces are often obtained from frequency-domain boundary element method models, to solve the device system dynamics in the time domain [1, 2].

In 2014, WEC-Sim was released as open-source software by National Renewable Energy Laboratory (NREL) and Sandia National Laboratories (Sandia) [3, 4]. WEC-Sim can be used to predict, analyze and optimize WEC dynamics and power performance. Since its release, WEC-Sim has become a popular tool for WEC numerical modeling across academia and industry, for many different device types - and even for some non-wave energy applications. This paper investigates the usage of WEC-Sim since its release.

The literature considered in this study is restricted to English-language publications; the countries of the lead author's institution are shown in Figure 1. Over the period of 2013 - March 2021, 95 publications featuring WEC-Sim were found - the publications over time is shown in Figure 2, with the breakdown shown between conference, journal and NREL/SNL publications (a mixture of conference and journal papers). Figure 2 shows how early WEC-Sim publications were led by the code's lead developers; NREL and SNL. But over time, external authors have grown considerably, with recent years especially showing increased numbers of journal publications. 2017 and 2019 show increased numbers of conference publications due to EWTEC taking place, which has helped promote WEC-Sim and disseminate WEC-Sim research.

The papers have been categorized according to the main field of study (these categories align with those used by WEC-Sim's Tethys Engineering Signature Project page [5]), and the type of device modelled (categories shown in Table I). Many papers have considerable overlap between categories (e.g. 'development' and 'validation'), hence some judgement has been used to determine the 'main' aspect of the paper.

Although the majority of publications discovered were from academia, it is important to note that some of these publications were made in conjunction with device developers. Furthermore, some device developers use WEC-Sim but do not publish their models and results; hence these users are not represented in this review.

WEC-Sim has been used for a variety of purposes and a range of different devices - including some floating offshore wind turbines (FOWTs) and hybrid FOWT-WEC systems. However, the most commonly modeled device topology is a point absorber, with the most popular study on this topology focusing on control systems (Table I). Many of these studies

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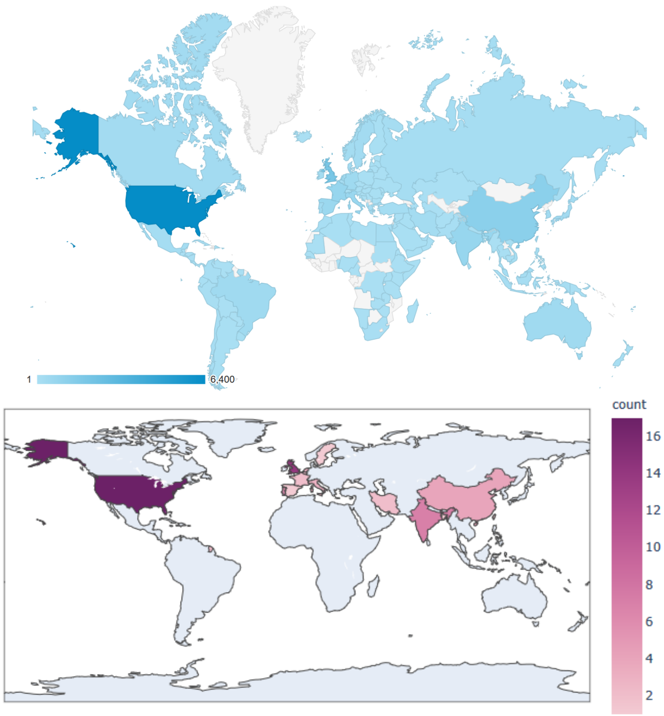

Fig. 1. Top: WEC-Sim users from Google Analytics between Nov 18, 2016 and April 14, 2021. Bottom: WEC-Sim-related publications by country of lead author's affiliation (excluding publications from NREL and Sandia).

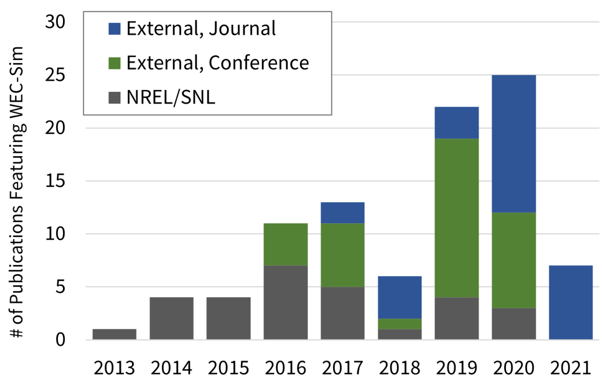

Fig. 2. Number of WEC-Sim publications found from January 2016 - March 2021.

have taken advantage of WEC-Sim's application library, where 'off-the-shelf' WEC models are available to be combined with separate PTO/control models. WEC-Sim's full integration in MATLAB/Simulink can also be leveraged to good effect for this particular application.

Experimental validation studies have been conducted with a range of different device topologies; building confidence in WEC-Sim's versatility and ability to accurately model a range of different device types.

Do to space limitations, not all of the papers listed in Table I are discussed here. This paper gives an introduction to the main development efforts undertaken in WEC-Sim, and an overview of how WEC-Sim has been used (i.e. categories of study and types of WEC devices) by the wave energy community worldwide.

II. Feature Development

There have been numerous significant development to WEC-Sim since its initial release in 2014. Being an open-source software, WEC-Sim has done well to encourage development both internally and externally. Many users modify and release version of the code with various improvements, often also open-source. These internal and external development span a wide range of features from improvements in dynamics and mooring, to various nonlinear considerations, to new wave features to a wide breadth of applications contained in a parallel repository. Some of those major features added to WEC-Sim over its lifetime, both internal and external to the NREL/Sandia WEC-Sim development team, are highlighted here.

A. WEC-Sim Team Development

WEC-Sim has been continuously developed since its initial release in 2014. Describing each and every modification is an enormous task and spans a wide range of applications. This section is limited to a brief description of major WEC-Sim features created and integrated into the source code by the internal development team.

The initial development efforts of WEC-Sim include processing the hydrodynamic coefficients from the BEM solvers, the capabilities of modeling multibody dynamics as well as the constraint modules that are used to define the degrees of freedom and represent the various type of joints, transnational and rotational PTOs. As part of the initial release in 2014, Yu et al. [3] simulated a two-body point absorber and two oscillating surge devices using WEC-Sim to demonstrate the use of the code, and Ruehl et al. [4] carried out a verification and validation study by comparing the WEC-Sim simulated RM3 results to those obtained from ANSYS AQWA, OrcaFlex and those obtained from existing experimental wave tank tests.

While WES-Sim was developed based on linear wave theory, WEC-Sim is often referred to as a weakly nonlinear time-domain model, which allows for the nonlinear hydrostatic and Froude-Krylov forces to be included based on the instantaneous water surface elevation and body position. The two nonlinear forcing terms are calculated by integrating the static and dynamic pressures over each panel along the wetted body surface at each time step. The feature of calculating nonlinear buoyancy and Froude-Krylov wave excitation forces were developed in 2015. As demonstrated by Lawson et al. [14], these instantaneous nonlinear force calculations are essential to capture dynamic behavior for a body with non-uniform cross-sectional area (e.g., ellipsoid), particularly for large amplitude motion scenarios.

Throughout the years, a set of features were introduced in WEC-Sim, including 1) a state-space model that converts the fluid memory kernel to a state-space form, which provides a substantial computational benefit [20]; 2) the use of Morison elements to provide

TABLE I
OVERVIEW OF 95 PUBLICATIONS FEATURING WEC-SIM, ORGANIZED BY FIELD OF STUDY AND DEVICE TYPE. COLOURS MATCH FIGURE 2.

Field	Device Type			
	PA	OWSC	Atten	Other/Multiple
Development	Wang 2020 [6] Wang 2020 [9] Wave Energy Scotland 2016 [12] Faraggiana et al. 2019 [15] Michelen et al. 2016 [17] Sirnivas et al. 2016 [19]	Wang and Wang 2018 [7] Wang 2019 [10] Scriven et al. 2019 [13] Forbush et al. 2020 [16]		Palm and Bergdahl 2017 [8] LaBonte et al. 2013 [11] Lawson et al. 2014 [14] Yu et al. 2014 [3] Tom et al. 2015 [18] Tom et al. 2015 [20] Coe et al. 2016 [21] Guo et al. 2017 [22]
Validation	Hughes et al. 2019 [23] Faraggiana et al. 2020 [27] van Vlijmen et al. 2019 [30] Tosdevin et al. 2019 [32] Martin et al. 2020 [33]	Choiniere et al. 2017 [24] Laporte-Weywada et al. 2019 [28]	So et al. 2017 [25]	Agati et al. 2016 [26] Pozzi et al. 2017 [29] Bosma et al. 2019 [31] Ruehl et al. 2014 [4] Wendt et al. 2001 [34]
Novel Devices	Wei et al. 2017 [35] Krishnendu and Balaji 2020 [39] Krishnendu and Ramakrishnan 2020 [43] Krishnendu and Ramakrishnan 2021 [47] Rosenberg and Mundon 2016 [49] Martin et al. 2017 [51] Wei et al. 2017 [52] van Rij et al. 2017 [53] Tom et al. 2018 [54]	Chow et al. 2018 [36] Yu et al. 2014 [40] Yu and Jenne 2017 [44]	Chandrasekaran and Sricharan 2020 [37] Sricharan and Chandrasekaran 2021 [41] Pardonner et al. 2020 [45]	Albert et al. 2017 [38] Li et al. 2018 [42] Li et al. 2018 [46] Li et al. 2019 [48] Clark and Paredes 2018 [50]
Control	Hillis et al. 2020 [55] Hillis et al. 2020 [56] Stock and Gonzalez 2020 [57] Yetkin et al. 2021 [58] Hillis et al. 2019 [59] Ling 2019 [60] Shi et al. 2019 [61] Tona et al. 2019 [62] Artal-Sevil et al. 2020 [63] Bora Karayaka et al. 2020 [64] Stock et al. 2020 [65] Tona et al. 2020 [66] Zadeh et al. 2020 [67]			
PTO & Grid	Vijayasankar and Samad 2021 [68] Cruz et al. 2019 [69] Tran et al. 2019 [70] Chandrasekaran and Sricharan 2020 [71] Tran et al. 2019 [70]	Cruz et al. 2019 [69]		
Novel Apps	Mahmoodi et al. 2020 [72] Paredes et al. 2020 [74] Rollano et al. 2020 [76] Tang et al. 2020 [78] Fernandez et al. 2021 [77] Manuel et al. 2016 [80] Atcheson et al. 2019 [81] Ballard et al. 2020 [82] van Rij et al. 2017 [83] Van Rij et al. 2019 [84]	Balitsky et al. 2019 [73] Amini et al. 2020 [75] Fernandez et al. 2021 [77] Scriven et al. 2020 [79]		

additional hydrodynamic damping and inertia [85]; 3) coupling with MooDyn, which is a lumped-mass-based mooring model, to improve WEC-Sim's mooring dynamics modeling capability [19]; and 4) PTO-Sim, which is an additional WEC-Sim library, was developed to model the WEC's conversion of mechanical power to electrical power. [86, 87]. PTOs are modeled as a simple linear spring-damper systems in the initial release of WEC-Sim. PTO-Sim accounts for the efficiency losses of the PTO systems and is capable of modeling various types of drivetrains, including both hydraulic or direct-drive systems, making WEC-Sim a complete wave-to-wire model.

The two major WEC-Sim features developed recently are generalized body modes and passive yaw. Historically, WEC-Sim has only concerned itself with the forces on and response of rigid bodies. The generalized body mode feature allows WEC-Sim to additionally model bodies with general, flexible modes [22]. These modes are analyzed in a boundary element method solver that can also handle such modes (WAMIT, Nemoh, etc), and then may be incorporated into a WEC-Sim simulation. These modes can include bending, torsion, expansion, and more, allowing for device structural loading and flexible WEC devices to be modeled with WEC-Sim.

The passive yaw feature was integrated into WEC-Sim in 2020 by Forbush et al. [16]. The passive yaw feature allows WEC-Sim to interpolate BEM coefficients to a device's instantaneous yaw orientation. This is especially important for highly direction-dependent devices such as the RM5, which Forbush et al. demonstrated. The result of this feature is that an RM5 device will naturally yaw to the most influential incoming wave direction and absorb more power. Previous to this implementation, a flap-type WEC would see very large torques when forced by an off-direction wave. This feature allows WEC developers to explore the forces on and power generation of direction-dependent devices with higher fidelity.

Between these major WEC-Sim development, notable features include the addition of improved paraview visualizations, wave gauges, various wave spectrum discretizations, continuous integration unit tests, and a host of documentation improvements. WEC-Sim also now includes mean drift and current forces, drag bodies, PTO end stops, parallel computing capabilities. Many new features of WEC-Sim are demonstrated in the WEC-Sim Applications repository which holds examples of many code features.

B. External Development

WEC-Sim is designed to allow for custom modifications and to be redistributed by any contributor; this was a primary motivation for its Apache 2.0 open-source license. Many developers external to the WEC-Sim team have used this route to implement features in their own versions of the code. Most of these features have not been implemented in the main fork of WEC-Sim, but may be available by contacting the appropriate author.

Structural Modeling and Mooring: Several externally developed features are concerned with mooring and structural dynamics within WEC-Sim. In 2017, Palm, Eskilsson and Bergdahl implemented their in-house mooring code MooDy into WEC-Sim. MooDy allows for higher-order finite elements, snap loading and explicit time stepping in the mooring solver, greatly expanding WEC-Sim's mooring capabilities [8]. There is an early open-source release of the two codes coupled together. In 2020, Scriven developed the ability to couple WEC-Sim with the structural dynamics solver Code_Aster [79]. This feature enables coupled hydro-elastic simulations in the time-domain. This coupling intends to predict device displacement and forces with higher accuracy, but does not give detailed stresses on a device. The inclusion of structural dynamics for the MegaRoller device is 13 times more computationally expensive than nonlinear WEC-Sim, but their analysis showed that structural dynamics can affect the predicted peak PTO loads and device response by over 10%.

Nonlinear Considerations: Many other externally developed WEC-Sim features focus on improving the accuracy of wave forces on a device. In 2018 and 2019, Wang and Wang used WEC-Sim's wave elevation import feature to introduce a non-linear 2nd order wave force by importing the wave elevation and integrating the wave pressure over a body [7, 10]. In 2021, this work was extended to expanded to investigate the performance of a point absorber in a multi-directional, second order nonlinear sea state [88]. This allows WEC-Sim to account for waves that are asymmetric in both the vertical and horizontal directions. Atechson, Johannesson and Svensson conducted a variation mode and effects analysis on the variables affecting the uncertainty of PTO load forces in WEC-Sim [81]. This work included adding a WEC-Sim feature to account for wave slap and slam corrections. When analyzing the axial PTO force for a scaled-down RM3, they found that variation in WEC-Sim parameters (mooring, hydrodynamics, viscous forces, PTO coefficients) accounts for significantly less uncertainty than the ultimate limit state method. Individual WEC-Sim input parameters were also more precise than the uncertainty from slap and slam correction and scatter from environmental conditions. Also in 2019, Faraggiana, Masters and Chapman implemented a directional wave distribution in WEC-Sim [15]. Of the external contributions listed in this subsection, this is the only feature currently implemented into the main WEC-Sim repository. This feature has greatly expanded WEC-Sim's capabilities by allowing for any arbitrary directional wave distribution to influence a device's motion.

III. Experimental Validation

As the computational power available to researchers continues to grow, a greater percentage of research and development will move more and more towards modeling software. The effort to build a representative numerical model is generally much faster and significantly less costly than building a physical scale model, fabricating and instrumenting said model, and reserving sufficient time at a wave tank to collect quality data to inform the next steps in concept development. Generally a numerical model allows the user to run and test a greater number of design variations operating under a wide range of environments or conditions. However, the confidence in any numerical model is built upon the expectation that the model is able to predict performance of a physical device to a sufficient level of accuracy. Therefore, the developers of any numerical model should continue to validate their code against available experimental data which includes as many operating conditions and environments as possible.

WEC-Sim is no exception. Since its initial release in December 2014, the development team has attempted to take any opportunity to validate the code against available experimental data. These efforts are highlighted by the use of WEC-Sim in several international collaborative tasks and competitions. For example, the first competition WEC-Sim participated in was the hydrodynamic modeling competition organized by the University of Maynooth Center for Ocean Energy Research (COER) [89]. This blind competition, where only the device specifications and test conditions were released, challenged competitors to predict the dynamic response of a floating rigid-body which was then compared to wave-tank data. COER compared numerical simulation submissions against the experimental results and ranked competitors based on their accuracy with WEC-Sim taking first place. Following participation in COER's competition, the WEC-Sim development team became a founding participant and co-organizer for the International Energy Agency (IEA) Technology Collaboration Programme for Ocean Energy Systems (OES) Wave Energy Conversion Modelling Task. The IEA OES Task 10 is focused on the verification and validation of numerical modeling approaches for simulating wave energy converters to provide accurate estimates of WEC power performance. As described in [90], IEA OES TASK 10 participants compared their numerical simulations against physical model tests of a heaving semi-submerged sphere to compare WEC dynamics, power output, and hydrodynamic loading. As the confidence in the code grew within the wave energy community, WEC-Sim was selected for development of a 1:20 scale Wavestar numerical model in support of the Wave Energy Converter Control Competition (WECCCOMP). The objective of WECCCOMP was to maximize the WEC performance through innovative control strategies to be completed through numerical and then experimental implementation. In support of the numerical simulation stage, a WEC-Sim model was validated against experimental data using several system identification processes [54]. Although not in support of WECCCOMP, the numerical model was then expanded to model a scaled Wavestar array. The WEC-Sim array simulations were then compared against experimental test to evaluate the influence of array spacing on the WEC array hydrodynamics [91].

WEC-Sim validation efforts have also been led and experimental tests completed by academic institutions exploring their own or unique WEC concepts. Several recent validation effort were completed in the OH Hinsdale Wave Research Laboratory at Oregon State University (OSU). The first effort was completed to evaluate the accuracy of using WEC-Sim to model an oscillating water column [92]. A comparison of numerical and experimental data found good agreement between the tested and simulated OWCs performance, except near-resonant frequencies. WEC-Sim's accuracy in predicting OWC performance in regular waves was within 5%, when off resonance, while for a sample irregular sea state the error in power performance was near 2.0%. The second validation campaign consisted of using WEC-Sim to model a floating oscillating surge wave energy converter (FOSWEC) [93]. The 1:33 scale FOSWEC was tested in the OSU directional wave basin and measured data was compared against WEC-Sim numerical simulations. Unique to this test was the design of a constraint platform that could constrain different degrees of freedom to represent a variety of operating conditions with varying dynamics. Comparisons showed generally good agreement between numerical and experimental results, but also highlighted areas where WEC-Sim could be further developed to improve accuracy across a wider range of operating conditions. The testing of OSWEC-like concepts has also been completed at the University of Maine. This experimental validation campaign investigated the performance and load shedding capabilities of a variable geometry oscillating surge wave energy converter (VGOSWEC) that utilizes adjustable geometry to control device hydrodynamics [94]. The VGOSWEC test article was designed such that the main body of the OSWEC held five horizontal flaps spanning the interior of the frame. These flaps could be adjusted, opened or closed, to change the shape and accompanying hydrodynamics. A 1:14 scale model was built for wave tank tests to measure the VGOSWEC motion response in regular waves and as well as fixed tests to measure the moment induced by incident waves. Although restricted to the frequency domain, numerical results compared well against wave tank test data providing confidence that WEC-Sim is capable of modeling unique WEC concepts.

Although WEC-Sim has been advanced and utilized by academic and research institutions, an additional measure of success is the adoption and use by wave energy developers. These entities rely on accurate device performance predictions to guide design decisions in preparation for wave tank tests or open ocean deployments to advance their design concepts. Though there are fewer published examples of these validation efforts, one can still find several examples of developers finding confidence in using WEC-Sim to predict device performance. For example, the National Renewable Energy Laboratory partnered with Ocean Power Technologies (OPT) to conduct a validation and optimization study for OPT's PowerBuoy [83]. WEC-Sim models were built to represent four design variations of OPT's PowerBuoy that were validated against experimental power output and fatigue load data provided by OPT. The validated WEC-Sim models were then used to simulate and predict the power performance and system loads for each of the four design variations to guide OPT's PowerBuoy development. In addition, Colombia Power Technologies (CPTs) partnered with Oregon State University to develop a WEC-Sim model of CPTs 1:7 scale SeaRay WEC [25]. WEC-Sim results were compared against the SeaRay open ocean experimental data. WEC-Sim predictions for power output and device motion were compared across 285 trials of varying sea states to evaluate the accuracy of linear hydrodynamics in true operating conditions. Comparison of numerical against experimental results found that WEC-Sim over predicted power performance up to 24% and the range of motion between -9% to 17% between the fore and aft floats. Another recent example of wave energy developers using WEC-Sim in validation studies is a collaboration between a consortium of universities in the United Kingdom and Marine Power Systems to model the WaveSub [27]. The WaveSub is a submerged WEC generating energy from the relative motion between multiple floating bodies. A WEC-Sim time domain linear potential flow model was developed to match experimental results from a 1/25 scale wave basin experiment. Comparisons between numerical and experimental results showed that decent matching could be achieved after incorporating additional viscous and frictional terms. After including these tuning parameters, the final difference in average power between simulations and experiments peaked at 10% while predicted device movement has even better matching.

Although validation efforts to date have shown good agreement between experiments and WEC-Sim, given the current diversity of WEC concepts we should consider each test a unique and separate instance potentially requiring updates or new capabilities to be developed within WEC-Sim to model novel concepts. Furthermore most of the documented validation efforts have focused on rigid body dynamics and although WEC-Sim has the capability to model generalized body modes there is a lack of experimental data to validate against. The WEC-Sim development team welcomes any opportunity for collaboration to validate the performance of the code against experimental data and to potentially advance WEC-Sim's capabilities for improved accuracy. The reader is directed to visit the WEC-Sim Signature Project portal on Tethys Engineering [5] to gain access to available published works and find additional examples of experimental validation efforts.

IV. Novel Device Modelling

The breakdown of novel device types studied using WEC-Sim is show in Figure 3. 15 publications investigating novel devices were found, with the most common type being the point absorber. But some studies have investigated an attenuator, OWSC, and even a hybrid WEC-FOWT systems - demonstrating WEC-Sim's versatility.

[39, 43, 47] used WEC-Sim to investigate the performance of a heaving buoy integrated within a breakwater. Good agreement is shown in the time-domain with

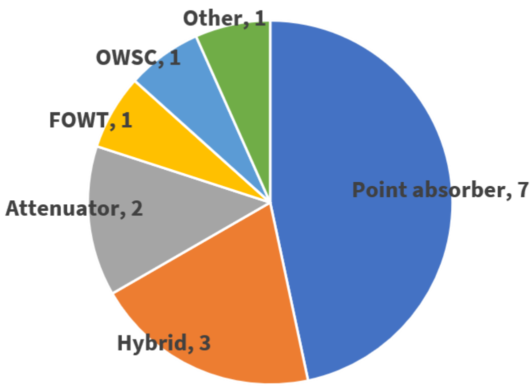

Fig. 3. Overview of novel device types studied using WEC-Sim.

experimental data (for regular waves) and the studies highlight the potential dual-benefits of this concept: absorbing incident wave energy to reduce reflections within the chambered breakwater (and thereby serve as coastal protection) and to provide clean energy to meet rising demand in India's coastal villages.

[51] focused on a two-body floating point absorber, and used WAMIT and WEC-Sim to explore different geometries for the submerged body; demonstrating how device geometry can greatly influence the performance of a WEC.

[35, 52] study a novel device called the 'ocean grazer', which uses multi-pump, multi-piston drivetrain to generate power from the waves. A large WEC-Sim model was developed that includes 10 floating bodies and 10 PTOs, all connected by joints in one multibody system - with hydrodynamic interactions included. The model has been used to investigate the power performance of each 'unit' in the drivetrain - to explore the characteristics of this concept. However, the computational expense of this model is highlighted as a potential limiting factor - with 1 day of computation time required to compute 200s of simulation time. As with most physics codes, there are many factors that can influence computation time. One of the most computationally expensive parts of WEC-Sim is the radiation convolution integral - especially when computing hydrodynamic interactions between multiple floating bodies. For this reason, WEC-Sim includes a state-space approximation to the convolution integral, which should significantly reduce computation time.

[36] used WEC-Sim to apply a parametric design study to an OWSC device, to understand the relationship between geometric properties and hydrodynamic characteristics. [41, 71] both use WEC-Sim to investigate a novel attenuator WEC, named the 'Bean Floating WEC' - due to the floats resemblance to kidney beans. The floats are connected to a central buoy, and configurations of 4, 6 and 8 floats have been modelled - hence the largest WEC-Sim model features 9 interconnected floating bodies, with PTO-Sim used to model the hydraulic PTOs in each arm.

[42, 46, 48] investigated a hybrid offshore renewable concept; featuring wave, wind and tidal. WEC-Sim is used as the main solver in this model, but in order to calculate loads on the wind and tidal turbines, WEC-Sim was coupled to the BEM code, WindSloke (which has been used to calculate both wind and tidal loads in these studies). [50] investigated co-locating wind and wave devices, in order to understand how they might interact hydrodynamically. In this study, WEC-Sim was actually used to model the floating wind turbine (FOWT) and the wave energy converter was modelled in SWAN in order to provided a modified wave spectrum input to WEC-Sim (accounting for the WEC's presence). WEC-Sim was coupled to MooDy in order to investigate the FOWT's mooring system; with results showing that co-location could help to reduce fatigue damage on FOWT mooring cables.

V. Control Modelling

WEC-Sim provides a useful simulation utility for investigation of control approaches because it readily incorporates the suite of MATLAB/Simulink controller and development tools. A controller that acts as the complex conjugate of the device intrinsic impedance is known to maximize mechanical power capture for idealized power-take-offs (PTO). While it is certainly possible to realize such a controller in simulation, practical barriers associated with its physical implementation and a community desire to model realistic PTOs imply that WEC controller investigation remains an active area of research. The WEC-Sim simulation environment is well-suited to this application, as WEC-Sim blocks can be customized to facilitate investigation of novel control strategies.

Example application cases showcase the utility of MATLAB control development tools in the context of WEC-Sim models. So et. al (2018) presents a discussion of several control techniques including passive damping, latching, linear quadratic Gaussian regulation, and a detailed WEC-Sim implementation of model-predictive control (MPC) [95]. Generally, MPC uses models of the device dynamics and an estimation of wave excitation force to develop an estimate of the WEC condition at future times: this estimate is then used to select an optimal control action at the current time via the minimization of a cost function. Of particular emphasis in this example is the incorporation of both hard and soft constraints in the MPC formulation [95]. Another example of novel MPC implementation in WEC-Sim can be found in [58]. This study investigates the effect of non-negligible actuation costs on controller action for a two-body point absorber. Notably, these MPC implementations are convenient in WEC-Sim as they can employ custom cost functions and employ optimizers native to MATLAB in the minimization of these functions. An additional example of this benefit, Glennon (2019) demonstrated a fuzzy logic controller and a non-linear MPC for a two-body point absorber [96]. For the fuzzy logic controller, an extensive set of customized Simulink blocks were used.

Optimal velocity control, an approximation of optimal complex-conjugate is demonstrated in [57] for both single and two-body point absorbers in WEC-Sim. This control approach employs prediction methods similar to MPC while formulating the top-level control actuation as familiar set-point tracking. The dynamic effects and control complexities introduced by the body-to-body interactions of the two-body case is emphasized. Hillis et. al (2020) provides an additional example of optimal velocity control including PTO load constraints for a completely submerged two-body device with a taut-mooring [55]. Accurately modeling the device mooring was of critical importance in this case to inform the PTO load constraint.

The Wave Energy Control Competition (WECC-COMP) was a competition in which teams proposed novel control strategies for a single-body WEC device modeled after the WaveStar device in WEC-Sim with a complex PTO linkage [97] [54]. Ling proposed an MPC, in which a Kalman filter and an auto-regressive model were employed to predict future device states to inform an optimal control action at the present time with constraints on PTO force and displacement [60]. The code-generation utilities of Simulink are particularly highlighted: as simulation is often a precursor to an experimental campaign, this functionality can streamline the transition between WEC-Sim and physical testing. A predictionless machine-learning approach to WEC control was proposed by [61]. A Bayesian optimization was used with a Gaussian process estimator of the controller objective function. The non-linear dynamics captured by the WEC-Sim model are particularly important in this context as, in the former case, they provide a realistic perturbation from any linearized device model, and in the latter, they can contribute to local non-convexities in the objective surface, an important test of robust control characteristics.

VI. PTO & Grid Modelling

WEC-Sim allows users to study the influence of PTO systems on the WEC performance. The users can incorporate complex models using Simscape blocks, or they can add simplified linear models to study the general characteristics of the PTOs. The PTO blocks in WEC-Sim can be modified by the user to model either a translational, rotational, mechanical, or hydraulic PTO.

Several examples of PTO modeling using WEC-Sim can be found on the academic literature. The influence of a linear power take off system on a complex multi-body WEC device was studied with a model developed using WEC-Sim [71]. The authors tested numerically five different WEC configurations. The influence of parameters such as shape diameter of floats, still water depth, and PTO damping were studied. In another study, the results for models of linear PTO systems in WEC-Sim has been validated experimentally using a test bench with good agreement between the results [24]. The device modeled in this paper is an OSWEC with adjustable geometry. One of the main conclusions of this study is that in absence of a PTO, the flap orientation did not have a considerable impact on power capture and structural loads.

The influence of wave forcing on the power estimation of a WEC array was studied in [76], a comparisson of different numerical models was developed in this paper using a complex WEC-Sim model. A linear based, time domain model is used to calculate the WEC hydrodynamics, the linear PTO damping and the restoring mooring force. An interesting example of using WEC-Sim for grid modeling was developed in [98]. The cost and effects of battery storage systems on power fluctuations and impact on the grid were modeled in this paper using WEC-Sim. The results of this study were used to estimate the battery storage capacity that is needed for a given power flow to the grid. It was demonstrated that the primary source of cost for the battery system is the instantaneous peak power. Another interesting example of the use of WEC-Sim to model PTO systems is the prediction of the dynamic characteristics of a submerged WECC device which is subjected to a PTO failure [70]. The significance of the PTO failure event on the WEC integrity and performance is discussed in the study.

The PTO system is simulated using linear models in the articles mentioned above. These models are useful to simulate general characteristics of the WEC device and the PTO. WEC-Sim allows the development of detailed models of each element of a PTO device. These models can be used to estimate relevant dynamic and performance characteristics on the components of the PTO such as loads, internal velocities, power inefficiencies, and power generation. The capabilities of WEC-Sim to model in detail PTO systems were described in [86] and [87]. A hydraulic PTO system was taken as a case study to described in depth the development of a complex model.

The PTO modelling capabilities of WEC-Sim have been improved over the last years. Currently, there is a dedicated package called PTO-Sim, which has been developed by the WEC-Sim team to model complex PTO systems in detail. Also, there is a huge interest of the WEC-Sim users regarding PTO simulations. Approximately 26% of the issues and questions in the WEC-Sim repository are related with PTO simulations.

VII. Novel Applications

In addition to those studies highlighted in the previous sections, many novel studies using WEC-Sim have been conducted. These studies focus on a wide variety of topics important to WEC implementation and the community at large including site analysis, analysis of structural damage, wave-to-wire models, and the effects of phase or uncertainty on PTO performance. Some novel studies published recently are highlighted in this section.

Site Analysis: In 2020, Mahmoodi et al. completed an analysis of WEC deployment in the Persian Gulf [72]. They analyzed performance of the RM3 point absorber with a compressible hydraulic PTO from the PTO-Sim module [86, 87]. Eight Persian Gulf locations based on a 20-year wave horizon were assessed. Also in 2020, Amini et al. assessed the deployment of an oscillating flap-type WEC in the Caspian Sea [99]. They used SWAN to obtain input waves, ABAQUS to find the optimal flap width and height at each site, and compare device performance to evaluate the optimal site for wave energy production.

Structural Damage Analysis: Some novel studies focused on analyzing various aspects of structural damage in WECs. Ballard et al. assessed the fatigue damage of a power umbilical for a point absorber [82]. Their results show more significant fatigue damage in shallow water due to higher umbilical curvature, and low fatigue damage when an umbilical is perpendicular to the incoming wave. Tang et al. investigated the effect of WEC component faults using WEC-Sim [78]. The authors implemented four electrical and three mechanical fault models into WEC-Sim constraint and PTO blocks. Their results show that the proposed graph-theoretic fault detection model works effectively to classify faults while being robust and simple to implement.

Additional Studies: Other novel studies include that of Manuel et al. in 2016, which quantified the effects of uncertainty on PTO performance [100]. The uncertainty of the RM3 point absorber's PTO extension and loading on performance was investigated, and a correlation between maximum extension and wave height was proposed.

Balitsky et al. created a wave-to-wire model by coupling WEC-Sim with Nemoh and the shallow water wave propagation model MILDwave [101]. They modeled wake effects in a WaveRoller array and found that predicted power output can decrease by up to 30% when wake effects are considered.

Rollano et al. studied how wave phase can influence power absorption in a RM3 [76]. They assessed three different wave models in WEC-Sim: phase-resolved wave height time series from FUNWAVE, wave spectra with no phase information from the FUNWAVE time series, and a phase-averaged linear SWAN spectra. They concluded that large wave events are underpredicted when no phase information is included. Some fluctuations in power absorption can only be captured with detailed wave phase information.

VIII. Summary

Since its original open-source release in 2014, the WEC-Sim software has been actively developed and applied to simulate a wide variety of device archetypes, and for diverse applications. WEC-Sim has been, and continues to be, developed jointly by the National Renewable Energy Laboratory and Sandia National Laboratories. Development and support of the WEC-Sim open-source code has been possible through continued support from U.S. Department of Energy Water Power Technologies Office. The WEC-Sim team at NREL and Sandia has supported development of the WEC-Sim code by adding new features, maintaining the software repository, responding to issues, resolving bugs, writing and updating documentation, and developing open-access applications of the WEC-Sim code [102]. However, to attribute WEC-Sim's development exclusively to the WPTO funded team at Sandia and NREL is incomplete. By nature of its open-source release, WEC-Sim has greatly benefited from the contributions of its external user-developers. The feedback and requests from users have driven the WEC-Sim team's development, but contributions from external uses have also provided numerous innovative new features, and novel applications. In this paper we've attempted to review the contributions and applications of these external user-developers.

WEC-Sim was developed and released under an Apache 2.0 open-source license with the intent to allow user-developers the option to incorporate code modifications into the main WEC-Sim repository (referred to as WEC-Sim master), or to allow for independent development and application of the WEC-Sim source code (on independently hosted forks). The result has been that many modifications of the WEC-Sim code have been submitted via a pull-request for inclusion into the master release, but many have not. The flexibility in application of WEC-Sim's Apache 2.0 open-source license was intentional, as the overarching goal of WEC-Sim development is to support and promote the development of the wave energy industry as a whole. The intent was to allow user-developers to submit code to the master repository if they desired, but are not required to so do. The WEC-Sim team is happy to see the extensive use of the software both to model diverse WEC archetypes and for applications beyond its original intent (of modeling WECs), The WEC-Sim team is equally pleased to see both the contributions made my external collaborators that make it into the master release of the code, and to see the modifications of the code that have been developed and maintained on independent forks. In the view of the WEC-Sim team these are all examples of successful execution of our goal, to develop an open-source software package that reduces the barrier of entry, is easy to use, easy to modify, and is extensible to broad applications. This review paper has attempted to do justice to the contributions of the broader WEC-Sim team, referring to the contributions and applications by those external to the WEC-Sim development team at Sandia and NREL.

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