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Comparison of Direct-Drive Power Takeoff Systems for Ocean Wave Energy Applications

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***Abstract*—This paper presents a comprehensive power takeoff (PTO) analysis program conducted as a collaborative research effort between Columbia Power Technologies, Inc., Oregon State University (OSU), and the U.S. Navy. Eighteen different direct-drive technologies were evaluated analytically and down-selected to five promising designs. Each of the five prototypes was simulated, modeled in SolidWorks, and built at the 200-W peak level and tested on OSU's wave energy linear test bed. The simulations were validated with the 200-W experimental results and then scaled up to 100 kW, with full 100-kW designs including costs, maintenance, operations, etc., to estimate the cost of energy (COE) for each PTO buoy system at utility scale.**

***Index Terms*—Generators, oceanic engineering and marine technology, permanent magnet machines.**

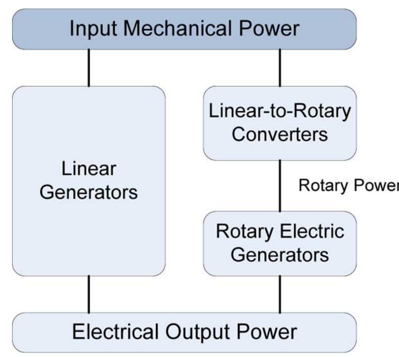

Fig. 1. Power flow for linear and linear-to-rotary systems.

I. Introduction

An extremely abundant and promising source of energy exists in the world's oceans in the forms of wave, tidal, marine current, ocean thermal energy conversion (OTEC), and salinity. Tidal systems include both barrages and turbines for tidal currents, while marine current systems employ turbines in nontidal ocean flows. Among these forms, significant opportunities and benefits have been identified in the area of wave energy extraction. Waves have several advantages over other forms of renewable energy in that the waves are more available and more predictable with better demand matching [1]. Wave energy also offers higher energy densities, enabling devices to extract more power from a smaller volume at consequently lower costs and reduced visual impact [2].

To fully explore ocean wave energy as a strong contributor to renewable energy portfolios around the world, the technical and economic feasibility of converting wave energy into usable electric power needs to be thoroughly evaluated. This paper presents a comprehensive comparison of direct-drive power takeoff (PTO) systems for point absorber wave energy applications. In the wind industry, direct drive refers to the elimination of gearboxes or other mechanical conversion systems, whereas for wave energy applications the term "direct" drive describes the direct coupling of the buoy's speed and force to the generator without the use of hydraulic fluid or air. By eliminating intermediate stages of conversion such as hydraulic, pneumatic, or pumped water, direct-drive systems have the potential for higher efficiencies and increased reliability, which may result in a lower cost of energy (COE).

Common direct-drive approaches employ either a linear electric generator or a linear-to-rotary mechanism, as illustrated in Fig. 1. A key element of this investigation was the comparison of linear generators with linear-to-rotary devices for wave energy applications. In general, linear generators have few mechanical failure modes, implying high reliability and reduced maintenance requirements [3]. Linear-to-rotary mechanisms

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TABLE I
EIGHTEEN DIRECT-DRIVE TECHNOLOGIES EVALUATED. (DOWN-SELECTED FIVE DEVICES ARE SHOWN IN BOLD)

Linear Electric Generators	Linear-to-Rotary Mechanisms
1. Sync, permanent magnet (PM), longitudinal, air gap coil w/ homogenous iron	**9. Rack & Pinion (double)** (designed/built with a single rack for proper scaling)
2. Sync, longitudinal, Vernier hybrid	**10. Traction Tire/Wheel**
3. Sync, PM, longitudinal, embedded coil (built previously at 10 kW, included in COE analysis)	**11. Windlass Spindle**
4. Sync, PM, longitudinal, air gap coil w/ back-iron (built previously at 50 W)	12. Slider-Crank
5. Sync, reluctance, longitudinal	13. PM Helical
6. Sync, hybrid, transverse, Vernier	14. Belt or Chain (reference)
7 Async, induction, longitudinal	15. Roller Screw or Ball Screw
8. Async, doubly-fed, longitudinal	16. Hydraulic System
	17. Hose Pump System
	18. Rack & Pinion (Single)

benefit from increased relative motion and the utilization of off-the-shelf rotary electric generators. An additional focus of this research was to determine the most promising type of rotary electric generator for use in wave energy applications. This overall research process led to the investigation of direct-drive rotary (DDR) systems that enable the energy in the wave to be directly converted into rotary motion.

This paper begins with a first-order analytical evaluation of 18 direct-drive PTO systems from which five promising devices were identified. The five devices were simulated, modeled in SolidWorks, built and experimentally tested on a wave energy linear test bed at low-power levels (200-W peak). The simulation models were verified with the experimental results and scaled up to 100 kW, including full 100-kW designs, with the goal of estimating COE for each PTO buoy system at utility scale.

II. Analytical Characterization

Based on a comprehensive literature review of direct-drive device mechanisms, 18 technologies were identified for potential point absorber wave energy applications. As seen in Table I, the 18 technologies consisted of eight linear generators and ten linear-to-rotary mechanisms. A first-order analytical comparison of these 18 wave energy generator mechanisms was conducted in order to down-select to promising devices that could be comprehensively simulated and experimentally tested at small scale (200-W peak), and then scaled up to 100-kW designs. This analytical comparison and down-select process is described in Sections II-A and II-B.

A. Evaluation/Decision Matrix Method

An evaluation/decision matrix was developed to enable a systematic approach to the evaluation and down-selection process. This type of matrix approach for evaluating systems with a large degree of complexity is a preferred method in industry and is presented by Pugh [4]. Pugh's method employed in this work included the following four steps: 1) choose criteria for comparison; 2) select alternatives to compare; 3) generate scores; and 4) compute final selection.

For the criteria by which each of the wave energy direct-drive technologies would be evaluated (step 1 above), a comprehensive list of stakeholder requirements was generated. This included a list of wave energy stakeholders and the various criteria that were important to each in a wave energy device. From this stakeholder requirements document, the criteria were weighted. The requirements were then consolidated into logical groupings, resulting in 60 line items, and were used as the evaluation criteria in the final evaluation/decision matrices.

Due to the high degree of complexity of this evaluation it was necessary to construct several matrices comparing the various components involved in a complete wave energy conversion system. These submatrices included linear-to-rotary mechanisms, rotary generators, linear generators, bearing systems, force transmissions, mooring systems, and survival mechanisms. Though it would be simpler to evaluate the direct-drive mechanism in a standalone manner, this complete system design approach was necessary to determine the impact that the direct-drive mechanism had on the overall system, thus the integrated system effects were taken into account.

According to Pugh's method, a single well-known and well-characterized reference device is chosen as a datum. This datum is used to compare all other devices against. Row by row and column by column, each device was given a rating for each of the criteria. The ratings given were $+1$, 0, or -1 based on how well they compared to the reference for the given criterion. A rating of $+1$ indicated that the device performed more favorably than the reference datum for that criterion. Ratings of 0 signified no significant variation between the two machines' performance in that criterion, while -1 signified less favorable device performance than the datum. This process led to several iterations of additional research and investigation to establish an overall ranking for the most promising devices and subsystems.

B. Evaluation/Decision Process

The evaluation process was a highly iterative process in which the most promising direct-drive systems were identified. The process benefited from all previous effort in establishing the evaluation matrix as well as considerations of component-specific information. The final ranking from the evaluation matrix revealed many strong designs. To make the down-selection, system-level considerations needed to be included.

The process followed the flow diagram presented in Fig. 1, where a direct-drive mechanism was selected and then outfitted with the various system components, e.g., force transmission, field excitation [permanent magnet (PM) versus direct current (DC)], bearing system, mooring system, and survival mechanism, until an entire system had been specified. At that point a review of the system began from the top where components were reevaluated for their ability to function in the larger system.

The evaluation process in itself revealed new methods of comparison. Selecting from the rotary generators, it became clear that it would be possible in the hardware stage to use various generators interchangeably. This method allowed each of the most promising linear-to-rotary devices to be coupled with each of the most promising rotary generators resulting in numerous possible system configurations. Such a "tournament"-style comparison revealed the best components from each group.

The evaluation process ranked the linear-to-rotary mechanisms and the linear generators independently. The remaining highest ranked mechanisms from each category were compared and five promising devices were selected. As shown in bold in Table I, the following direct-drive PTO approaches were chosen to be comprehensively simulated, modeled in SolidWorks, built, and experimentally tested: rack and pinion, traction tire/wheel, windlass spindle, Vernier hybrid linear generator, and the air-gap linear generator. The synchronous, PM linear generator with embedded coil (Table I, item 3) also scored very well. For this generator design the copper coils are placed inside slots in a well-defined magnetic circuit. Since this device had been built and tested previously by Oregon State University (OSU, Corvallis) at the 10-kW level [5], it was also included in the simulation and scaling stages to provide the energy capture and COE estimates presented in Sections VII-A and VII-B.

III. PTO Design and Build

The hardware design and build of the down-selected five direct-drive PTO approaches are detailed in the following sections.

A. Rack and Pinion, Traction Tire/Wheel

The rack and pinion and traction tire/wheel systems were designed as a single test platform which allowed for the testing of both the rack and pinion and the traction tire/wheel PTO devices. The rack and pinion prototype was designed with a single rack for proper scaling.

The rack and pinion and traction tire/wheel PTO systems had linear and rotary bearings in common. The linear bearing was designed as a low-friction surface using vertical bars of ultra-high molecular weight polyethylene (UHMW) plastic providing a low frictional coefficient. The low-friction guide rail bars are shown in Fig. 2 between the pillow block bearings. There is a second set of pillow block bearings on the back side of the linear-to-rotary portion, supporting a reaction wheel, which provides a back force against the rotary-to-linear engagement area. The traction wheel, or pinion, converts the linear force into rotational torque, which is coupled to the gearbox. The 15 : 1 gearbox converts the high-torque low-speed power input from the pinion to a higher speed, lower torque output to a permanent magnet direct current (PMDC) generator. The output torque

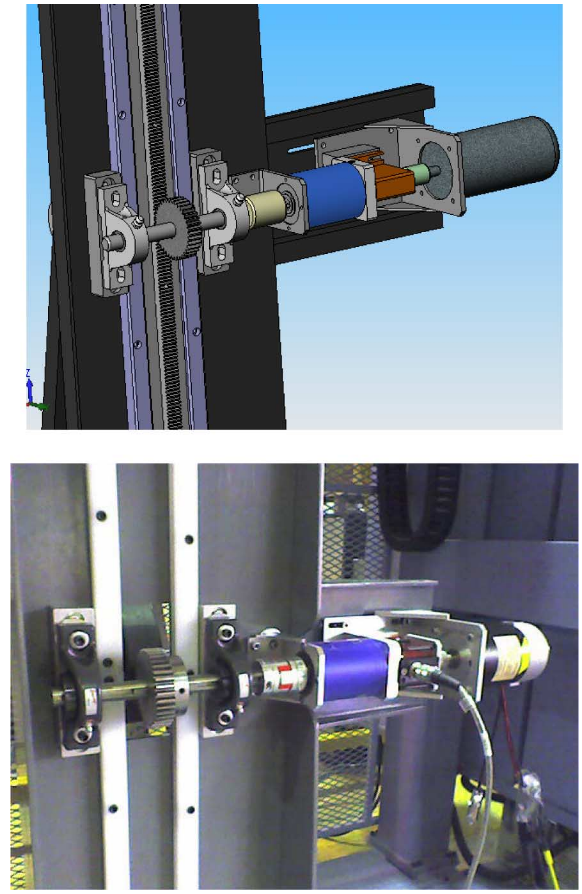


Fig. 2. Rack and pinion PTO model and hardware.

from the gearbox is monitored via the high-resolution torque sensor, shown in red in the top figure of Fig. 2. The outputs of the torque sensor and generator are recorded in real time congruently with the power, force, and speed inputs of the linear test bed. The high-efficiency gearbox was tested separately, to establish a baseline bidirectional performance and characterization which was used to validate the simulations.

B. Windlass Spindle

The design of the windlass spindle PTO system uses a spring return system shown in Fig. 3. Rewind of the spindle may also be performed by controlling the generator as a motor, using active feedback controls. For a larger scaled PTO system, the energy storage required for the spindle rewind was decided to be electrical due to the limited availability of large and reliable mechanical storage devices. The electrical control would also provide a more precise and controlled rewind than a large mechanical spring return.

The 200-W peak windlass spindle was connected directly to the linear test bed with a second spool connected via a nylon belt to the return springs. The linear force was converted via the spindles-to-rotary torque input into the 30 : 1 gearbox. The gearbox, torque sensor, and PMDC generator were identical to the components used for the rack and pinion and traction tire. Using electrical rewind would eliminate the need for springs and would provide a highly compact design.

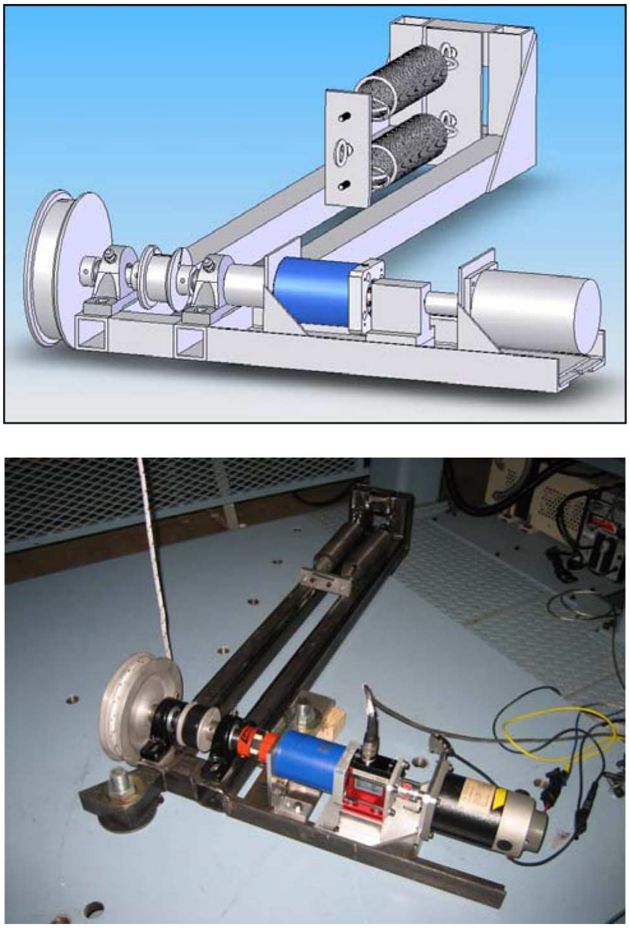


Fig. 3. Windlass spindle PTO model and hardware.

This device benefits from its simple and scalable design. Fewer moving parts reduce the number of total failure modes. Sealed rotary bearings were needed to transmit power from the spindle to the gearbox housing located inside the buoy.

C. Vernier Hybrid Linear Generator

The synchronous longitudinal Vernier [6]–[8], hybrid linear generator is a unique design that required a large number of custom-machined parts in its construction. The design incorporated hours of electromagnetic modeling, as well as SolidWorks modeling in an iterative process, to arrive at an optimized electromechanical design. The active section, which contains three coils and a magnet assembly, is mounted to two linear guide bearings. On either side of the active section, magnet steel laminations are specially designed, which change the reluctance of the magnetic circuit, to create flux variations, which induce the sinusoidal output voltage in the coils. Each coil works independently and is electrically spaced 120° apart, to produce a three-phase output. The three molded coils are visible in Fig. 4.

During the construction, eddy current loops were identified and eliminated. The magnetic circuit was designed to minimize cogging forces, while optimizing the magnet volume. The magnets used were high-energy density Neodymium Iron Boron (NdFeB), rated at 40 MegaGauss Oersted (MGOe). This overall design allows for the more costly components (magnets and coils) to be located on the same side, reducing the size of the required active region.

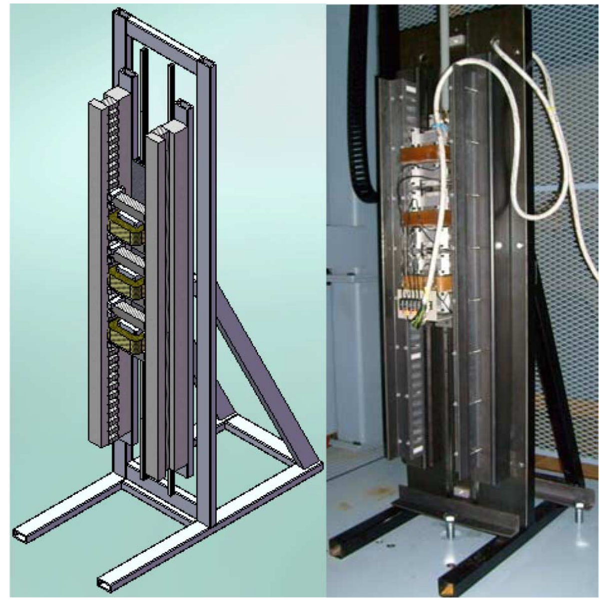


Fig. 4. Vernier hybrid generator PTO model and hardware.

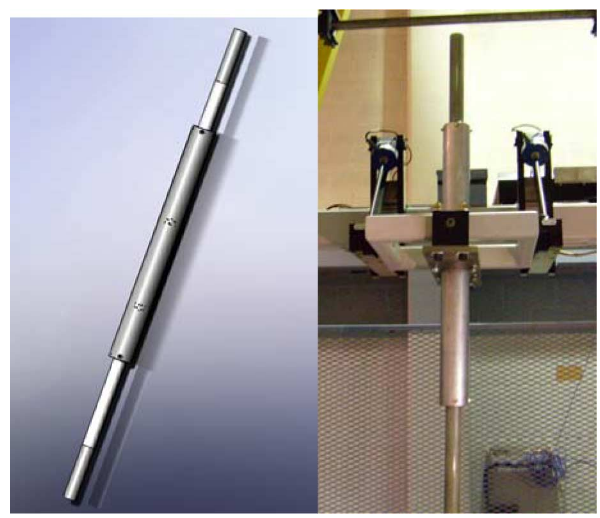


Fig. 5. Air-gap linear generator PTO model and hardware.

D. Air-Gap Linear Generator

The longitudinal flux air-gap linear generator device (Fig. 5) is a three-phase linear generator design, using improved air-gap material. This design uses copper coils on the inner diameter with a magnetic field assembly on the outer diameter. The magnetic flux concentrates towards the center coils due to the reduced air-gap material reluctance and the presence of a homogeneous back-iron material.

IV. PTO Testing on Linear Test Bed

The wave energy linear test bed (LTB) is capable of testing devices with average power ratings ranging between 50 W and 20 kW. The LTB can drive the device under test (DUT) with a

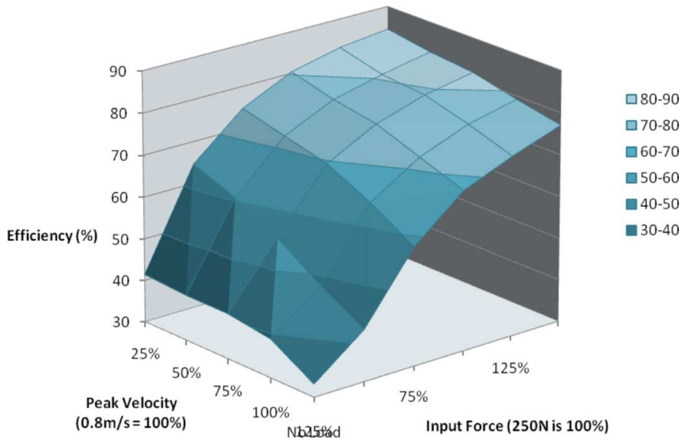


Fig. 6. Rack and pinion efficiency trends with speed and force variation.

peak speed of 2 m/s to a total stroke of 2 m. It has a generator driving force of 20 000 N [4500 pounds-force (lbf)] at 1 m/s and 10 000 N (2250 lbf) at 2 m/s.

For the PTO testing on the LTB, a test plan was developed, which focused on key performance criteria including: power rating, efficiency, force, and speed characteristics. Each device was run through a sinusoidal position profile with peak speeds from 25% to 125% of the rated peak speed of 0.8 m/s (0.2–1.0 m/s). A stroke length of 0.5 m was specified, and at each speed data were collected for six load cases: no-load to 125% of the rated peak force input (250 N).

Systems utilizing rotary components were put through additional tests to characterize losses in each stage of conversion. These collected data went into a performance matrix of the loaded conditions for each device to aid in performance characterization. With each performance matrix, a surface plot was created to show efficiency trends with speed and force variation for each device. An example in Fig. 6 provides a 3-D graph showing this relationship for the rack and pinion system. Additional tests to determine friction, mass, inertia, and loss were also performed with the LTB, to collect data that were used to further improve the simulations.

For each test case, data were collected for five cycles of the input position profile at a 1-kHz sampling frequency. Collected data included the following: position, speed, and acceleration of LTB carriage; left, right, and combined load cell data; motor shaft speed and torque for linear-to-rotary systems; output DC voltage and current for linear-to-rotary systems; and output three-phase alternating current (AC) voltage and current for linear generator systems. From these recorded data, postprocessing allowed the calculation of input force and power from the LTB, output mechanical shaft power and output electrical power for the linear-to-rotary systems, and output electrical power for the linear generator systems. Efficiencies were then calculated based on the input mechanical power from the LTB and output power from the conversion device. For linear-to-rotary systems this output power was mechanical shaft power at the output of the mechanical conversion, and for linear generator systems this output power was electrical power produced by the machine. The overall hardware efficiency results are provided in Table II.

TABLE II
HARDWARE EFFICIENCY RESULTS

Rack and Pinion

	Applied Force:	noload	50%	75%	100%	125%
Peak Velocity	25%	41.44	64.60	74.73	80.35	83.11
	50%	40.77	60.66	72.13	77.61	80.46
	75%	40.76	55.30	69.58	75.78	79.45
	100%	39.25	48.28	64.52	71.93	76.47
	125%	33.14	42.40	58.28	68.15	72.95

Traction Tire/Wheel

	Applied Force:	noload	50%	75%	100%	125%
Peak Velocity	25%	28.72	46.27	62.60	70.19	73.48
	50%	29.29	38.37	56.80	66.61	70.37
	75%	29.45	33.32	53.19	63.61	67.90
	100%	28.91	34.06	49.49	60.87	66.48
	125%	28.70	33.16	45.41	57.73	64.92

Windlass Spindal

	Applied Force:	noload	50%	75%	100%	125%
Peak Velocity	25%	46.31	75.43	81.80	84.55	
	50%	46.20	72.80	80.52	83.21	
	75%	47.48	72.76	80.20	83.54	
	100%	46.64	69.73	78.92	82.64	
	125%	41.31	66.09	76.17	79.76	

Vernier Hybrid Linear Generator - Active Loading

	Applied Force:	noload	50%	75%	100%	125%
Peak Velocity	25%	0.00	33.97	11.30	-19.19	
	50%	0.00	53.66	44.77		
	75%	0.00	59.52			
	100%	0.00	62.55			
	125%	0.00				

Airgap Linear Generator - Resistive Loading

	Applied Force:	noload	50%	75%	100%	125%
Peak Velocity	25%	0.00				
	50%	0.00	16.38			
	75%	0.00	40.29	9.53		
	100%	0.00	51.84	32.47	11.85	
	125%	0.00	55.05	41.93	28.05	

V. ROTARY TESTING AND MACHINE SELECTION

This research also endeavored to determine the most promising type of rotary electric generator for use in wave energy applications. For linear-to-rotary direct-drive wave energy converter (WEC) prototypes, the direction of rotation of the generator changes as the buoy heaves up and down in the ocean. The rotary testing investigated the bidirectional performance of the following four machines: PMDC, PM synchronous, induction, and synchronous reluctance. The comparison focused on the electrical characteristics of the machines, while noting the mechanical attributes. The end result established the efficiency rating for the DDR generators, with respect to bidirectional operation.

The results from this and subsequent testing [9] show that the induction and reluctance motors were not efficient enough for consideration for this type of bidirectional operation. Brushed-type PM machines can be efficient, but have increased maintenance requirements due to the brushes. Based on the overall efficiency with consideration of the entire testing matrix of operating points, the rotary PM synchronous machine exhibited the best performance.

VI. Integrated System Modeling

A numerical model was built and verified for each of the final PTO devices. The goal of the modeling was ultimately to predict the amount of energy each system would produce at utility scale in a realistic wave climate to also enable COE estimates. Matlab/Simulink was used for the electrical/mechanical modeling of the PTOs while OrcaFlex was used for hydrodynamic modeling.

A. PTO Modeling

The most decisive component of the system model is the PTO model. A simulation model was developed for each of the hardware models to accurately characterize the performance of the respective PTOs. The models represent the interactions with all of the system components. These include mechanical parameters (masses, inertias, radii, and frictional coefficients) as well as electrical parameters (flux, reluctance, voltage, impedance, current, etc.). In the position-input modeling approach each subpart of a mechanical system (e.g., gears, rack, shafts) is treated as a lumped mass that accelerates as a result of the sum of the forces acting on it. This allows for a block-oriented modeling approach. Each block has forces as an input, and outputs acceleration, speed, and position. The second modeling approach, which was used for energy capture calculations, took the position-input models and rearranged the equations such that they took both force and speed inputs and output a predicted power.

The rack and pinion and traction tire modeling were very similar to one another. The major sub-blocks are the rack (traction surface), pinion (traction tire) shaft to gearbox, gearbox, shaft to generator, and the generator. The generator was modeled as a brushed DC machine with a resistive load. For a fixed load, this provided a generator torque proportional to speed.

The windlass spindle modeling was similar, but had some extra complexities. Because of the tension provided by the return springs, the system does not rest at a force-neutral point. In addition, the rope that acts as the power transfer mechanism is assumed never to go slack.

The Vernier hybrid and air-gap linear generators were a bit different. The mass components were not separate from the electromechanical energy conversion components. The air-gap linear generator was modeled using standard direct-quadrature (DQ) theory. The Vernier hybrid machine was modeled using a three-phase position and current-dependent flux linkage model.

B. Position-Input Power Takeoff Modeling

The purpose of the position-input step is to validate the model against the wave energy LTB hardware results. To do this, the same position profile applied during LTB testing was used in the simulations and the resulting data were compared for accuracy. Each simulation model was designed using the same parameters and power level as the low-power (200-W peak) hardware prototypes. The simulation parameters were adjusted as necessary such that the low-power simulation results matched the low-power hardware results. Verified simulations helped illustrate the inner workings of the devices. This allowed the authors to scrutinize individual component performance to improve future designs. Using this tool effectively can eliminate more expensive and laborious prototyping. Fig. 7 is an example of the close correlation between the experimental results and the simulation results for the rack and pinion system, comparing the mechanical force exerted on the system.

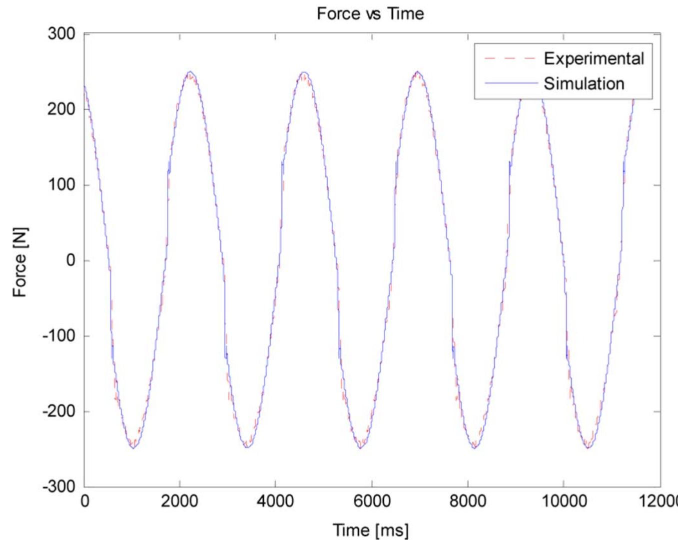


Fig. 7. Experimental versus simulation results.

C. OrcaFlex Hydrodynamic Modeling

An important stage in this overall modeling process was to generate the PTO position and force time series in a realistic wave climate. For this the authors chose the statistically average August wave climate for a location off Newport, OR. A basic, one-degree-of-freedom (DOF) hydrodynamic model can easily be implemented in Simulink, but it was deemed that a full DOF hydrodynamic buoy model would be required for accurate results. Therefore, OrcaFlex was used to generate the buoy position and force data.

Hydrodynamic refinements were made to improve the capture efficiency of the buoy/spar design. By using OrcaFlex in this way the authors were able to change many design characteristics and determine how the power capture ability was affected. There are also numerous control laws that can be used to control the energy capture of the generator. Some of these include: speed proportional, reactive, constant force, and constant power. Due to the limited flexibility of OrcaFlex's generator modeling capability, the authors were not able to simulate a reactive control approach. Simulations using both the speed proportional approach and the constant current approach were both run. In all cases for the wave following buoy being modeled, the constant force control captured more total energy.

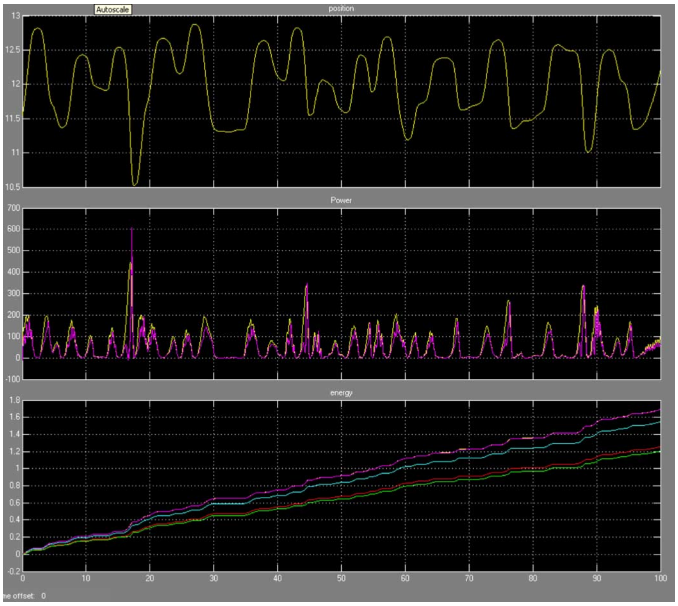


Fig. 8. Energy capture simulation results for the rack and pinion system.

D. Energy Capture Modeling

The results from the validated PTO models and the realistic position and force time series from the OrcaFlex hydrodynamic models were combined to predict power output and energy capture for each of the PTO systems (energy capture estimates at utility scale are provided in Section VII-A). The initial simulation modeling and validation was done with only a position input. Therefore, the simulation model for each power takeoff was rearranged such that it accepted a force and speed as inputs, and the output was instantaneous power. This power was then integrated to obtain a predicted energy capture during the period.

Fig. 8 shows simulation results of the rack and pinion system and illustrates the energy capture modeling. The top graph shows the relative position of the linear generator; this is the relative position between the buoy and spar. The center graph shows the instantaneous power captured by the PTO. The line in yellow is the mechanical input power and the violet is the electrical output power. The bottom graph is the total energy captured by the system. This example for the rack and pinion shows energy into the system (yellow), the pinion (violet), the gearbox (blue), the generator (red), and finally the electrical energy captured (green). This modeling dissection helped validate all of the subsystems in the PTO and can show where improvements to efficiency can be made.

VII. 100-kW Concept Designs and Insights

A key goal of this PTO comparison research was to identify devices that were economically feasible at utility scale. For this reason comparisons were made regarding cost, reliability, maintainability, and survivability at the 100-kW scale. It is assumed that 100 kW is a rating large enough to be considered utility scale, while still within a reasonable scaling range for comparison using assumptions extrapolated and experience gained from the developed hardware and software models.

To properly characterize the technologies, each device was advanced through a conceptual 100-kW design. The designs focused on the significant components involved in a large-scale direct-drive WEC. These designs use some first-order simplifications, while retaining sufficient detail to identify major components and material volumes. Spring boarding off these 100-kW designs, estimates for energy capture and overall COE were compared for the different PTO systems (see Sections VII-A and VII-B).

For systems rated above 10 kW, the point absorber shell and construction costs are of greater concern. The heaving point absorber approach hinges on a reliable linear coupling mechanism and sealing system between the buoy and spar. A low-power ($<$10 kW) PM linear generator can be implemented using a sea water gap between the armature (in the spar) and the magnet section (heaving buoy section), thus significantly simplifying the design of a low-power WEC. However, at higher powers, the mechanical tolerance requirements dictate that the air gap becomes too large and the electromagnetic material costs become unacceptable. Thus, higher power designs require an advanced linear-mechanical force coupling solution and a linear seal, which is expected to be a high-maintenance item for high-power linear machines. These limitations led to the consideration of a DDR power transfer mechanism for improved system reliability.

In addition, a point absorber WEC solution that only captures the heave component of the wave energy only harnesses half of the energy compared to a WEC that is designed to capture both heave and surge [10]. During this investigation, it became apparent that by implementing a large diameter DDR generator, the absorbing body of a WEC can be designed to convert both heave and surge wave energy directly into rotary motion to harness twice the energy of point absorbers operating solely in heave. Therefore, analysis of a 100-kW PM DDR system was added to this investigation, and included in the energy capture and COE estimates provided in Sections VII-A and VII-B. As discussed in Section II-B, also included in this analysis is the synchronous PM linear generator with embedded coil, built by OSU in a previous research effort.

A. Energy Capture Estimates

OrcaFlex was used to model (at 100 kW) the buoy response to the PTO and the incident wave climate using climate data from National Oceanic and Atmospheric Administration's (NOAA's) Stonewall Banks buoy (located 20 nm west of Newport, OR). These buoy response data were successfully coupled to the direct-drive Simulink models to provide first-order energy capture estimates at utility scale.

Energy capture for each system was affected by the total conversion efficiency as well as the systems' availability due to downtime and maintenance. The systems that suffered the most were those with higher mechanical losses and larger periods of downtime due to maintenance. The linear generators and the DDR device yielded promising results due to their high conversion efficiency and reliability. Fig. 9 shows the estimated annual energy capture for each device.

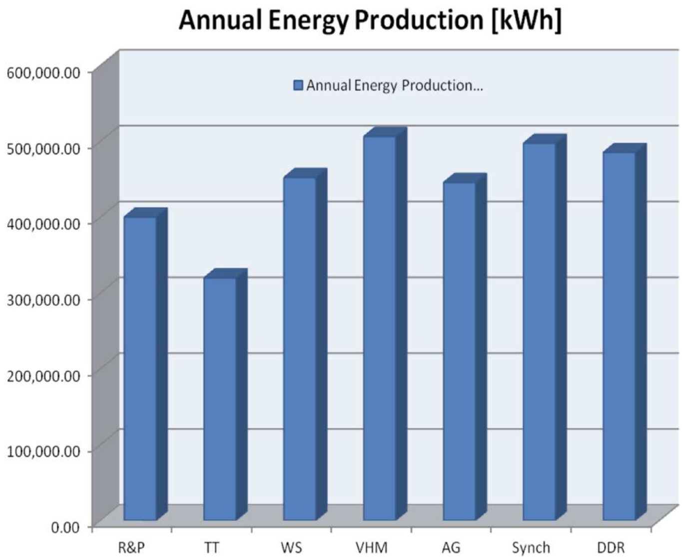
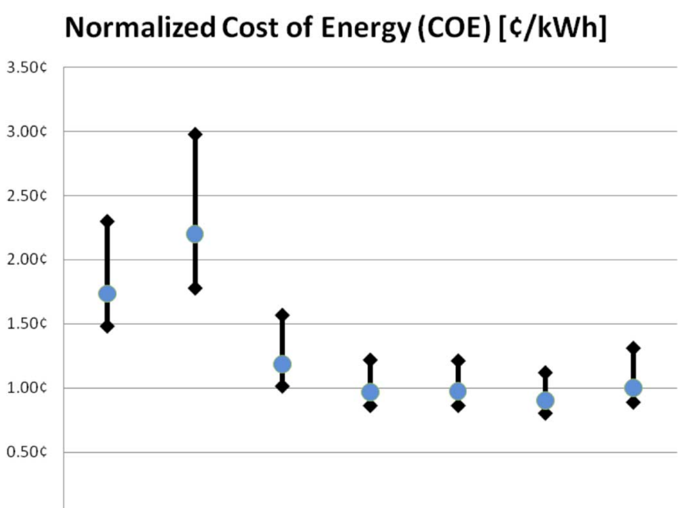


Fig. 9. PTO energy capture estimates for heaving point absorber WECs: rack and pinion (RP), traction tire (TT), windlass spindle (WS), Vernier hybrid machine (VHM), air-gap generator (AG), synchronous linear generator (Synch), and the direct-drive rotary (DDR) system.



	R&P	TT	WS	VHM	AG	Synch	DDR
High	2.30¢	2.98¢	1.56¢	1.22¢	1.21¢	1.12¢	1.31¢
Low	1.48¢	1.78¢	1.01¢	0.86¢	0.86¢	0.81¢	0.89¢
Mid	1.74¢	2.20¢	1.18¢	0.97¢	0.97¢	0.90¢	1.00¢

Fig. 10. Normalized PTO cost of energy estimates.

B. Cost of Energy

COE estimates provide key comparison information for the PTOs in this investigation. The systems that have the lowest COE are seen to have a greater potential for utility scale commercial viability. This paper provides a first-order estimate and many considerations must be taken into account to predict the actual installed COE due to commercial production and economies of scale.

Fig. 10 shows the COE estimates which are derived by combining present value capital and operations and maintenance costs with the annual energy capture. Values shown have been normalized to 1.0 cent per kWh on the mid DDR cost system to allow for relative percentage comparison. There is an associated tolerance band indicating the relative certainty of these predictions. It can be seen that the linear generators and the DDR device have lower predicted COE than that of the linear-to-rotary devices.

VIII. Conclusion

This paper presented a comprehensive PTO analysis program where 18 direct-drive technologies were evaluated and down-selected to promising designs, which were simulated, modeled in SolidWorks, and built at the 200-W peak level. These devices were tested on OSU's wave energy linear test bed enabling the simulations to be validated and then scaled up to 100 kW, including 100-kW concept designs to estimate COE for each system at utility scale.

Based on the results of this PTO down-select investigation it was concluded that for low-power wave energy applications (<10 kW) employing a heaving point absorber approach, a synchronous PM linear generator is a strong solution. At higher power levels, this topology will encounter air-gap tolerance and linear guidance challenges that will be very difficult to solve in a cost-effective way. At higher power levels (>10 kW) a DDR system was found to surpass linear and linear-to-rotary PTOs. Columbia Power Technologies, Inc. is now conducting a comprehensive DDR WEC development program including numerical modeling and scaled wave tank and intermediate scale field testing along the path to full scale development.

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