Test of a Novel, Commercial-Scale Wave Energy Direct-Drive Rotary Power Take-Off at the NREL National Wind Technology Center

Cooperative Research and Development Final Report

CRADA Number: CRD-14-571

NREL Technical Contact: Jonathan Keller

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Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-5000-76906
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Cooperative Research and Development Final Report

Report Date: May 4, 2020

In accordance with requirements set forth in the terms of the CRADA agreement, this document is the final CRADA report, including a list of subject inventions, to be forwarded to the DOE Office of Science and Technical Information as part of the commitment to the public to demonstrate results of federally funded research.

Parties to the Agreement: Columbia Power Technologies, Inc. (currently known as C·Power)

CRADA number: CRD-14-00571

CRADA Title: Test of a Novel, Commercial-Scale Wave Energy Direct-Drive Rotary Power Take-Off at the NREL National Wind Technology Center

Joint Work Statement Funding Table showing DOE commitment:

Estimated Costs	NREL Shared Resources a/k/a Government In-Kind
Year 1	$65,000.00
Year 2, Modification #2	$370,000.00
Year 3, Modification #3	$41,755.00
Year 4, Modification #4	$150,000.00
TOTALS	$626,755.00

Abstract of CRADA Work:

The National Renewable Energy Laboratory (NREL) will work with Columbia Power Technologies [C-Power] to support work under US DOE DE-EE-0006399, "Build and Test of a Novel, Commercial-Scale Wave Energy Direct-Drive Rotary Power Take-Off Under Realistic Open-Ocean Conditions." Work will include a review of their design for a novel wave energy direct drive generator. After review, the system will be prototyped and tested in the NREL National Wind Technology Center (NWTC) 5MW dynamometer and data will be recorded and analyzed. Conclusions from data analysis will be used to improve the design prior to completing a version of the system for ocean deployment. Additionally, NREL will work with Columbia Power Technologies [C-Power] to quantify the system levelized cost of energy (LCOE) and analyze the system in agreement with US DOE System Performance Advancement (SPA) goals 1 and 2.

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Summary of Research Results:

At the time this report was prepared, one PI for the CRADA was no longer with NREL so this report was prepared by another, who despite best efforts, were only able to find limited information on the results from the CRADA. The following is a summary of the research results from the CRADA based on that information.

Columbia Power Technologies (C·Power) and engineers from the NWTC collaborated under CRADA 14-571 from December 2014 to December 2018 with funding awarded from DOE Funding Opportunity Announcement (FOA) 848 [1,2]. The objectives of the work were to demonstrate the technical feasibility of the prototype version of the novel C·Power wave energy direct-drive generator, called the LandRAY, in the NWTC 5MW dynamometer; inform design decisions prior to installation of a novel generator on a wave energy device intended for open-ocean deployment; and quantify the projected levelized cost of energy for the novel generator. Mark McDade was the original NREL Principal Investigator (PI) for the project; however, upon his retirement in May 2017, Jonathan Keller assumed the role as the NREL PI. (C·Power changed PIs during the project as well. Ken Rhinefrank was the original PI. Joe Prudell was named PI in July '18.) Through the course of the project, multiple tasks were completed and are summarized in this final report for the CRADA. Task descriptions in this report follow the numbering in the Statement of Project Objectives (SOPO) developed by C·Power for the FOA award and the Joint Work Statement of the CRADA.

Note: The original NREL shared funding was $476,755.00. Modification #4 for $150,000.00 was a plus-up that came from DOE to our AOP to finish the work. It is included here because it is unlikely to be captured anywhere else.

Task 2.0 Dynamometer Site Preparation and Planning

The initial project tasks were focused on design development, review and planning for characterization of the LandRAY in the NWTC 5MW dynamometer by both C·Power and NREL. This activity included review of the:

- LandRAY assembly procedures, logistics, operations, transportation, emergency and safety plans, and disassembly procedures
- interfaces between the LandRAY electric plant, supervisory control and data acquisition (SCADA), cooling system, floor mount and drive coupling, and instrumentation and the dynamometer facility
- dynamometer facility characteristics and procedures such as the nontorque system frequency response, startup and shutdown procedures, and emergency control and safety requirements
- LandRAY hardware and software interface specifications for operation in the dynamometer
- preliminary LandRAY test plan.

Figure 1 shows the planned dynamometer test setup of the C·Power Power Take-Off (PTO) module and the interface with the dynamometer non-torque loading system, test stand, and dynamometer strong floor [3,4].

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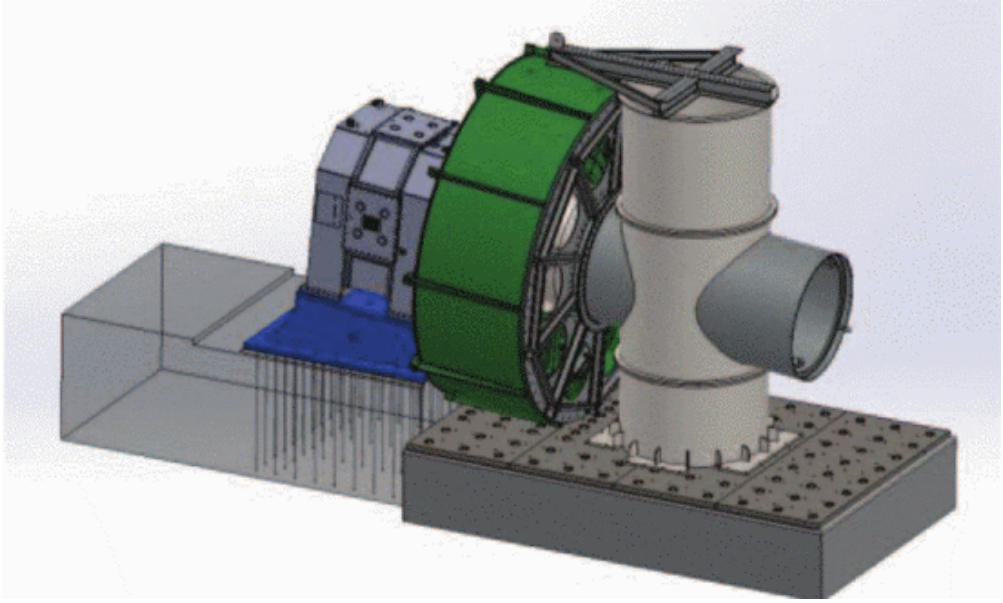

Figure 1. LandRAY dynamometer test setup [3,4]

Task 3.0 Design completion, review and build approval

In this task, NREL worked with C·Power to conduct a design review of the generator and all interfaces associated with the 5 MW dynamometer and provided guidance on those designs. The review considered the overall design integration of the state and rotor to the rest of the machine with the intent of identifying possible areas of risk. The review also informed C·Power-led test planning. The LandRAY System Level Design Review, also led by C·Power, was conducted in April 2014 and covered these topics. The test plan was written to consist of main bearing testing, secondary bearing testing, shaft seal testing, stator cart testing, electrical commissioning, PTO no-load testing, PTO loaded testing, real seas testing, fault testing, extreme seas testing, post testing characterization, and noise testing.

Task 5.5 Interim SPA goal assessment

NREL provided an initial consultation of the use of the marine hydrokinetic cost breakdown structure. This consisted of an informal assessment of:

- methodologies for assessing performance and reliability, used to confirm power-to-weight ratio (SPA goal 1), and PTO and sub-systems availability for system availability (SPA goal 2)
- consulting on the use of the marine hydrokinetic cost breakdown structure and DOE's LCOE guidance documentation
- developing appropriate cost assumptions for key system cost drivers not directly affected by the innovative component technology
- identifying and estimating system-wide cost impacts resulting from the innovative component technology
- quantifying LCOE for the baseline values of the performance metrics

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- quantifying the reduction in LCOE resulting from the proposed component technology's improvements to the SPA
- developing a transparent and comprehensive cost of energy analysis for inclusion in the impact analysis, including a clear presentation of how the improvements to the SPA goals resulting from the improvement to the component technology contribute to the reduction in LCOE.

This LCOE analysis activity resulted in the SPA goal improvement assessment listed in Table 1 [5]. These metrics and the associated cost breakdown structure and theoretical annual energy production metrics are described elsewhere [6].

Table 1. LCOE Metric Improvements

Metric Improvements					
PWR		Availability		LCOE	
Targeted	Actual	Targeted	Actual	Targeted	Actual
55%	60%	10%	11%	-28%	-31%

A project Go/No-Go Decision meeting was held in December 2015 with C-Power, NREL, and DOE [5]. As a result, LandRAY components were shipped to NREL. Most components arrived at the National Wind Technology Center (NWTC) in January 2016. The M2G system was shipped to NREL January 2016. The majority of the LandRAY (housing, rotor, shafts, bearings, electro-magnetics, and support equipment) was shipped from the Ridgefield, WA pre-assembly site in April 2016 and arrived early May 2016. The test stand was proof tested during the last two weeks of June 2016 at RMS Crane in Denver and was shipped to NREL-Flatiron at the end of June 2016.

Task 7.0 PTO assembly and installation at test facility

The latter half of the project was focused on characterization of the LandRAY generator in the NWTC 5MW dynamometer facility. After delivery of the LandRAY components and associated hardware to the NWTC, NREL and C·Power personnel assembled the LandRAY equipment in the high bay and connected it to the dynamometer as shown in Figure 2. During the assembly process tests and inspections of the assembled system were conducted and some modifications and additional work were required to confirm adherence to design tolerances and specifications. Once assembled, verification procedures were followed to assure sub-system specific measurements, inspections and tests performed as designed, and confirm readiness for safe testing. NREL provided the cooling pump and heat exchanger with variable frequency drive, and water for filling the reservoirs in the system.

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Figure 2. LandRAY generator assembly (left) and dynamometer test setup (right). Photos by Mark McDade, NREL 44103 and Dennis Schroeder, NREL 48856

Task 8.0 Verification and validation

A C·Power test plan and test objectives were developed and reviewed prior to start of validation testing. Testing then commenced in October 2016 [7]. These extensive validation tests were intended to confirm the structural, electromagnetic and thermal numerical models of the generator are accurate and under startup, acceleration, deceleration, steady-state and stochastic clockwise and counter-clockwise motions in controlled conditions. In contrast to at-sea testing, the dynamometer enabled full control of speed and displacement inputs and measurements of the generator behavior were significantly easier to acquire. Measurements including voltage, current, power, shaft torque, shaft position-speed-acceleration, structural loads, rotor temperature, stator temperature, cooling system temperatures, vibration, air-gap clearance and more were recorded and confirmed to be within specification. An example of power, torque, and speed measurements acquired during real seas testing are shown in Figure 3 and Figure 4. These measurements were used for detailed analysis of performance, efficiency, reliability, SPA goals and LCOE.

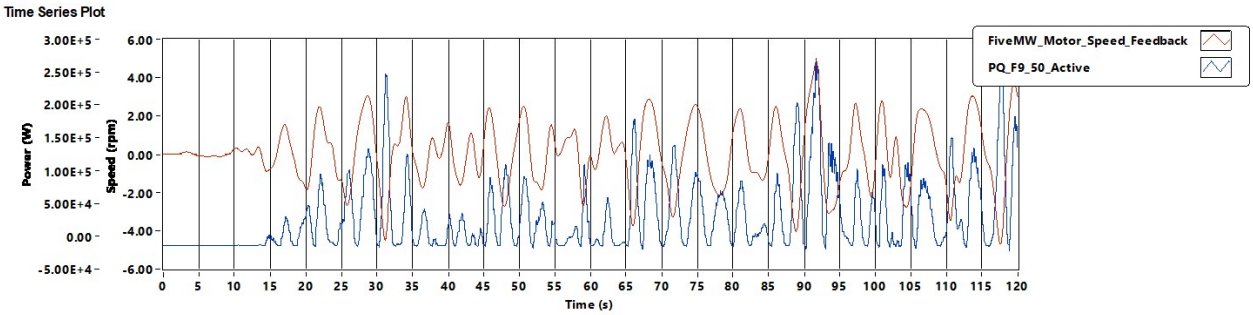

Figure 3. LandRAY generator power and speed during real seas test.

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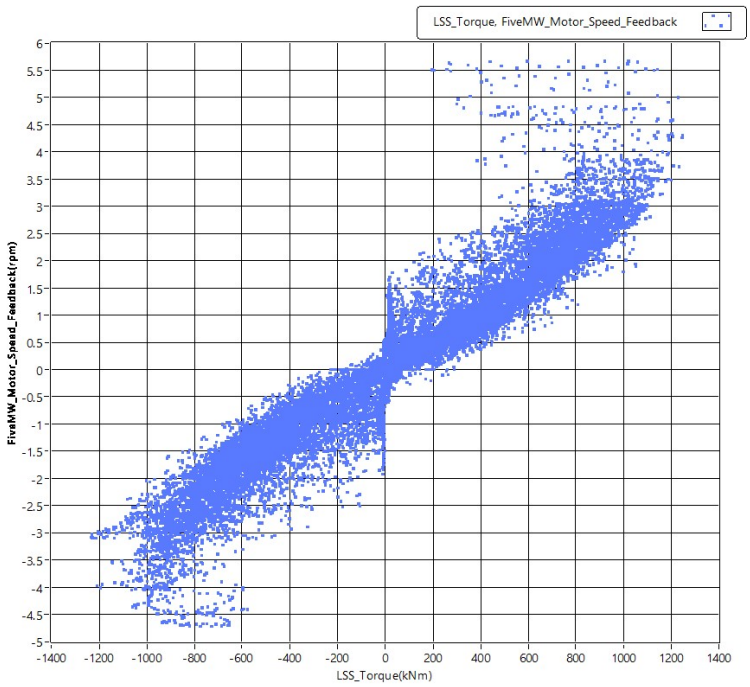

Figure 4. LandRAY generator torque and speed during real seas test.

Task 9.0 Disassembly and ship

The data sets were quality checked and confirmed complete [8], prior to disassembly and removal of the equipment from the dynamometer [9]. The desired LandRAY parts were returned to C·Power. Shafts, bearings and electro-mechanics were shipped in Dec ’18 upon completion of testing, decommissioning, and salvage. M2G was shipped in May ’19; it had remained in place to facilitate possible UL testing.Other components like the housing and rotor structure were disposed of and the test stand remains at the NWTC per agreement for anticipated future work.

Task 11.0 Data analysis and final test report

NREL assisted C·Power with the creation of the final report on metrics and SPA goals primarily as described earlier in Task 5.5, and with questions regarding post-test data analysis associated with NREL instrumentation.

Conclusions:

Columbia Power Technologies (C-Power) and NREL collaborated under CRADA 14-571 from December 2014 to December 2018 to demonstrate the technical feasibility of the prototype version of the novel LandRAY wave energy direct-drive generator and quantify the projected levelized cost of energy. Validation testing was performed in the NWTC 5MW dynamometer and used to inform design decisions prior to installation of another generator in an open-ocean deployment. The outcome of the testing was that the generator operated as designed, that no unexpected flaws existed in the mechanical, electrical, or control systems, and that the generator was ready for deployment. Final results of the project were reported by C·Power to the Water Power Technologies Office.

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

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Subject Inventions Listing:

None

ROI #:

None

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DOE Program Office:

Office of Energy Efficiency and Renewable Energy (EERE), Wind and Water Technologies Office

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