COLUMBIA POWER TECHNOLOGIES
power from the next wave

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1 PURPOSE

This document summarizes the Columbia Power Technologies (CPower) System Performance Assessment (SPA) and Levelized Cost of Energy (LCOE) goals and projections under DE-EE0006399 (Project LandRAY) for the latest StingRAY wave energy converter (WEC) design. To determine Project goal achievement, three power take off (PTO) configurations—the baseline geared PTO module (GP1), the actual Project direct-drive PTO module (DDP1) and the next-generation direct-drive PTO module (DDPx)—and associated costs are compared using the StingRAY v3.2 WEC design. The WEC models with DDP1 (DDS1) and with DDPx (DDSx) are compared against the WEC model with GP1 (GS1) to determine Project success. A forward-looking LCOE assessment will be made at the end of the Project using DDPx, which incorporates Project learning.

To understand progress during the Project, separate time-domain models will be run on DDS1, reflecting the current knowledge and understanding of the DDP1 PTO at three Project stages: pre-Project (DDS1-p), intermediate–Project (DDS1-i) and final (DDS1-f). These three Project-stage models of the DDS1 WEC will be assessed, in order to gauge the improvement of SPA and LCOE purely as a function of Project performance, i.e., validated improvements of the CPower PTO design.

2 SYSTEM ASSESSMENTS

To accurately assess LCOE and SPA goals and to follow DOE request, the Project metric analysis and comparisons are driven by the five different PTO design models: baseline geared (GS1), three direct-drive models (DDS1-p, DDS1-i & DDS1-f) and the next generation model (DDSx). Annual Energy Production (AEP) computations require time-domain model results at each of these assessment stages. However, the StingRAY v3.2 WEC has developed substantially since the Project was originally proposed, which at that time used performance and design data understood in June 2013. Running computationally-intensive time-domain AEP models on the most recent StingRAY WEC design, as opposed to the original June 2013 design, is the only avenue that provides useful forward-looking LCOE information to both CPower and DOE. AEP calculations for GS1 and DDS1 assume common learning curve and performance gains.

As explained below, the 2020 WEC models for GS1 and DDS1 both use currently-understood technology improvements from the most recent modeled StingRAY v3.3 WEC and performance improvements from advanced controls. No future technical improvements beyond this are included. Economies of scale (learning curve) and the performance improvements are uniformly applied to the GS1 and DDS1 models to determine the 2020 WEC LCOE data. Any changes in LCOE between GS1 and DDS1-(p, i, f) models are only due to improvements related to the Project, and not to learning curve or technical improvements.

DDS1-f and DDSx are the systems that target the Project SPA and LCOE goals. Due to National Wind Technology Center (NWTC) size constraints and Project budget limitations, the LandRAY test article is scaled down in diameter, torque and nameplate rating from the DDS1 system. The diameter of the LandRAY test article is effectively the same as the expected size of CPower's first intended offshore WEC deployment at WETS, but the LandRAY test article is smaller than the projected PTO used in DDS1. All SPA and LCOE calculations for the GS1 and DDS1 models employ a generator that is full size and rating.

2.1 System Definitions

The five assessment models are mapped in section 2.1.6 for alignment with the SOPO systems and defined as follows:

2.1.1 GS1

The GS1 WEC system employs a gearbox to step up rotational speed of the permanent magnet generator (PMG). The efficiency, mass, inertia and cost of the gearbox-based PTO are used in the GS1 WEC assessment. This is the baseline system to be compared against the new PTO improvements and learning. Time-domain models will not be run on this device, to avoid unproductive use of modeling resources.

Instead, CPower estimates of GP1 efficiencies from prior investigation are applied to the performance of the DDS1-p system.

2.1.2 DDS1-p

This is the DDS1 WEC design with the direct-drive DDP1 PTO as understood prior to Project commencement. The DDS1-p WEC uses a forecasted performance model of the pre-Project direct-drive rotary (DDR) PMG. The efficiency, mass, inertia, availability and cost of the pre-Project DDP1 are used in the DDS1-p WEC assessment.

2.1.3 DDS1-i

This is the DDS1 WEC design with the direct-drive DDP1 PTO as designed, manufactured and understood at the Go/No-Go (GNG) decision point. The intermediate-stage DDS1-i WEC uses a more-accurate forecasted model of the PTO, that incorporates the latest information available at the time of GNG Project assessment. The efficiency, mass, inertia, availability and cost as understood at the GNG are used in the DDS1-i WEC assessment. DDS1-i performance is used for comparison against GS1 and DDS1-p.

2.1.4 DDS1-f

This is the DDS1 WEC with the direct-drive DDP1 PTO as designed, manufactured, built and tested. The final-stage DDS1-f WEC uses the most-accurate forecasted performance model of the DDP1 information, with the latest experimental information available at the close of the Project. The efficiency, mass, inertia, availability and cost as understood at the final-stage of the Project are used in the DDS1-f WEC assessment. DDS1-f performance is used for comparison against GS1, DDS1-p and DDS1-i.

2.1.5 DDSx

This is the improved DDSx WEC with the next-generation direct-drive PTO, envisioned as a result of the Project effort. An improved PTO will be proposed, using likely design improvements identified during the Project, as a function of Project learning. The efficiency, mass, inertia, availability and cost of the improved PTO, and forecasted WEC improvements beyond the base WEC model, will be used in the DDSx WEC assessment. DDSx performance is used for comparison against GS1, DDS1-p, DDS1-i and DDS1-f.

2.1.6 System Definitions mapping to SOPO

Table 1: System Configuration Table

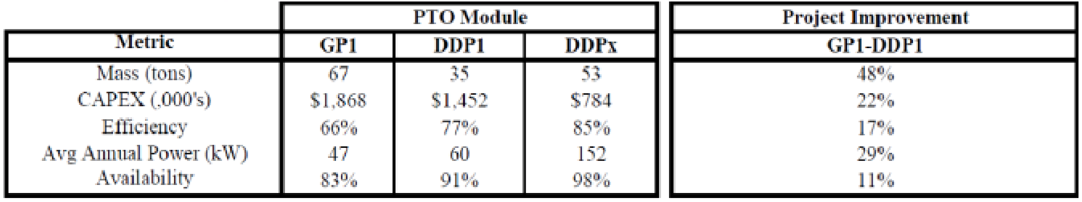
System - configuration	PTO Configuration	Project Stage	Model Assessment Identifier	System Notes
GS1	GP1	Pre-Project	GS1	Baseline PTO, modified DDS1-p WEC model is used and has more PTO mass and higher center of gravity (CG)
DDS1	DDP1	Pre-Project	DDS1-p	DDR PMG prior to Project start
DDS1	DDP1	GNG	DDS1-i	Incorporates latest understanding of DDP1 at GNG
DDS1	DDP1	Post-Test	DDS1-f	Incorporates latest understanding of DDP1 post-Test
DDSx	DDPx	Post-Test	DDSx	Incorporates all knowledge gained for next-generation DDPx and improved WEC

3 SPA GOAL

The PTO Module has inherent capacity to demonstrate material improvements against baseline measurements for both System Performance Advancement (SPA) Goals – Power-to-Weight Ratio (PWR) and Availability – in addition to substantial LCOE reductions. CPower expects to reduce PWR and LCOE by approximately 80% each and to increase Availability by 18%, through successful implementation of the PTO Module.

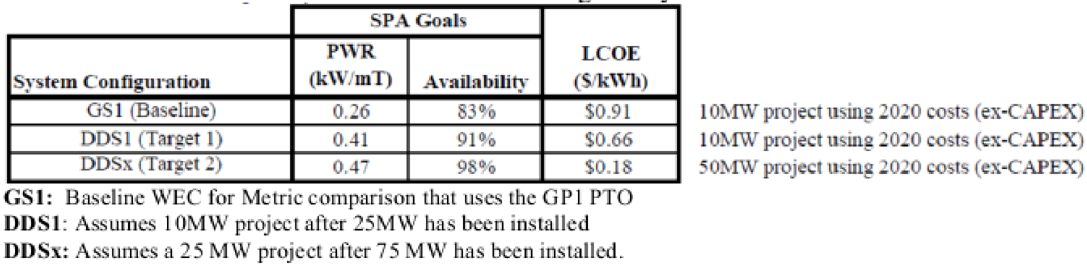
The following tables are from the SOPO:

Table 2. Baseline and Target Component Metric Values and Anticipated Project Metric Improvement (Single PTO)



	PTO Module			Project Improvement
Metric	**GP1**	**DDP1**	**DDPx**	**GP1-DDP1**
Mass (tons)	67	35	53	48%
CAPEX (,000's)	$1,868	$1,452	$784	22%
Efficiency	66%	77%	85%	17%
Avg Annual Power (kW)	47	60	152	29%
Availability	83%	91%	98%	11%

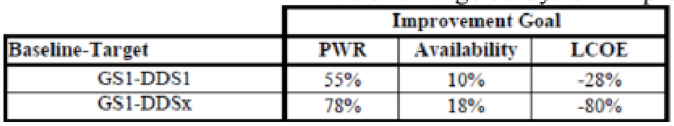
Table 3. Baseline and Targeted Systems Goal Values



	SPA Goals			
System Configuration	**PWR (kW/mT)**	**Availability**	**LCOE ($/kWh)**	
GS1 (Baseline)	0.26	83%	$0.91	10MW project using 2020 costs (ex-CAPEX)
DDS1 (Target 1)	0.41	91%	$0.66	10MW project using 2020 costs (ex-CAPEX)
DDSx (Target 2)	0.47	98%	$0.18	50MW project using 2020 costs (ex-CAPEX)

GS1: Baseline WEC for Metric comparison that uses the GP1 PTO
DDS1: Assumes 10MW project after 25MW has been installed
DDSx: Assumes a 25 MW project after 75 MW has been installed.

Table 4. Targeted System Improvements



	Improvement Goal		
Baseline-Target	**PWR**	**Availability**	**LCOE**
GS1-DDS1	55%	10%	-28%
GS1-DDSx	78%	18%	-80%

Further detail on the Targeted Systems Improvements is contained within the original proposal:

"… the LCOE figures for all systems are based on an Oregon wave resource and not the DOE model wave resource."

For this Report and to conform to DOE guidance, annual array output is set to 260,000 MWh/yr, versus the project size described in Table 3 above, and all metrics are provided for the DOE Reference Site of Humboldt, CA.

4 LCOE MODEL

The LCOE model used in this analysis is compliant with DOE Guidelines [doe_lcoe_reporting_guidance_2015_10_09.docx.][1]

$$LCOE = ((ICC \ x \ FCR) + AOE) \div (AEP_{net} \div 1{,}000)$$

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[1] http://en.openei.org/community/document/mhk-lcoe-reporting-guidance-draft

The LCOE model components are described below. The assumptions used in the LCOE model are discussed in Section 6. CPower has error-checked its LCOE model with the data supplied in NREL's 2011 Cost of Wind Energy Review.[2]

4.1 Annual energy production (AEP)

AEP computation methodology is in accordance with DOE Guidelines, except some variance in approach is taken for efficient use of modeling resources. This variance is fully explained in Attachment 1.

The analysis within this Report contains data for both the Humboldt, CA DOE Reference Site and for Stonewall Bank, OR, which was used in the original proposal analysis. Stonewall Banks source data was downloaded from the NDBC website for station 46050 (Stonewall Bank).[3] The hourly records covered the period from 1996 to 2008 (13 years) with an 82% return rate. Spectra were downloaded, and Hm0 and Te were calculated directly from spectra for each sea state.

The Humboldt site has a less-desirable spectrum of waves, that is sub-optimal for wave energy due to long periods and shorter waves, as compared to Stonewall Bank and numerous other more favorable sites. CPower recommends that the DOE consider use of Stonewall Bank or a site with similar characteristics for the model resource.

To establish the initial pre-Project AEP on the DDS1-p WEC, CPower has performed time-domain modeling. For the GS1 system, CPower will use assumptions on efficiency and availability to estimate its TAEP, but as explained earlier, will not use time-domain models on system GS1. TAEP calculation details are reviewed in Attachment 1, and TAEP results are included in Attachments 3, 4 and 5. AEP is computed from TAEP as follows:

$$AEP = TAEP \times (availability) \times (Trasmission\ efficiency)$$

4.2 Installed capital Costs (ICC)

ICC is calculated per DOE guidance. The completed DOE CBSs for GS1, DDS1-p and DDS1-i for both Humboldt and Stonewall Bank are contained in Attachment 2.

While ICC and O&M are reported within the DOE CBS format, CPower requests DOE consideration of an Alternative CBS. CPower has historically employed an alternative hierarchy to certain elements of the Draft Generalized Cost Breakdown Structure (CBS) for MHK Projects dated August 1, 2014.[4] CPower's hierarchy follows a more-traditional naval architecture structure and includes the device and all components upstream of the sea-floor umbilical interface as part of the WEC. The Balance of Station (BOS) includes all components downstream of the interface, through to the grid interconnect. CPower has integrated its hierarchy into the 2nd level of the DOE's CBS (Alternative CBS), which is shown in Figure 1.

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[2] http://www.nrel.gov/docs/fy13osti/56266.pdf

[3] http://www.ndbc.noaa.gov/station_history.php?station=46050

[4] http://en.openei.org/community/document/mhk-cost-breakdown-structure-draft

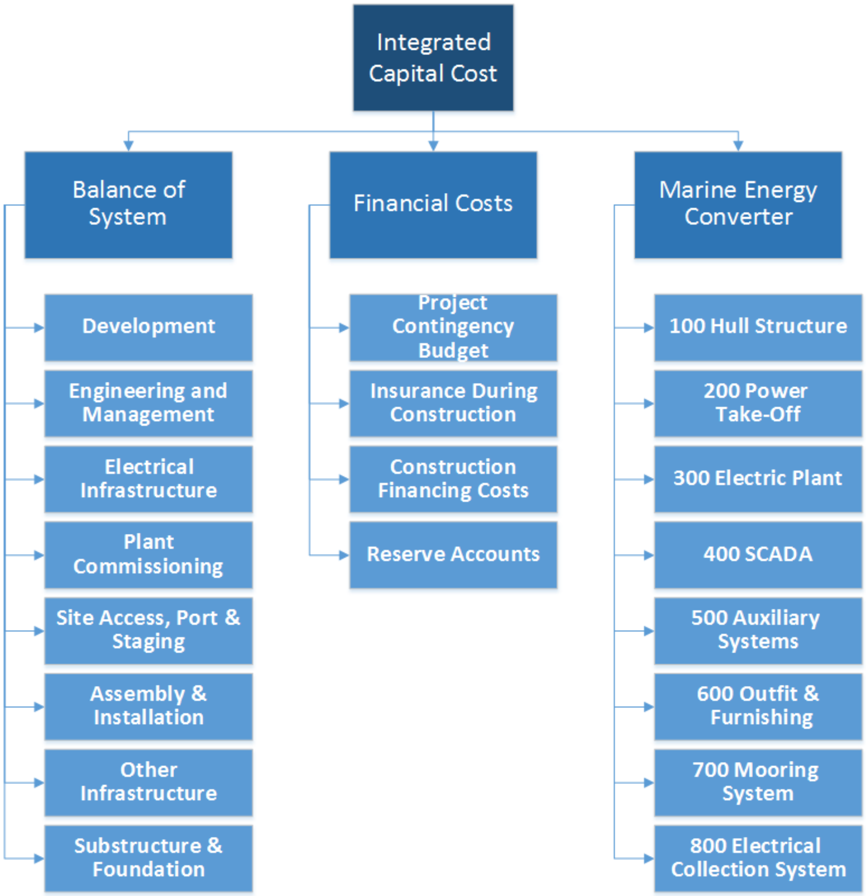

Figure 1: Alternative CBS

4.3 Annual Operating Expense (AOE)

AOE is calculated per DOE guidance. See Attachment 1.

4.4 Fixed Charge Rate (FCR)

The FCR is calculated to be 10.8% and is calculated per DOE guidance.

5 SPA GOAL APPROACH

5.1 PWR - SPA Goal 1

From the DOE, PWR guidance under FOA 848:

"Power to Weight Ratio (PWR) is defined as the ratio of effective power to weight in air of the device (see eqn. below). Improvement in PWR can be achieved by increasing the energy capture and conversion efficiency of the device or by reducing its weight. PWR drives cost throughout the life cycle, impacting device capital cost, handling equipment size and cost, difficulty of installation, deployment, and recovery. Applicants must quantify baseline system PWR value, and the target system PWR value for a single system that can be achieved via component technology innovations developed in this FOA."

$$PWR = \frac{Rated\ Capacity\ (kw)\ x\ CapacityFactor}{Weight\ in\ Air\ (metric\ tons)}$$

Where,

- *Rated Capacity (kW) is the expected power that the system is designed to produce.*
- *Capacity factor is a ratio of the actual power produced at a site to the power produced by the device if operating at rated capacity, over a given time (typically one year).*
  - *Capacity factor used for both the baseline and target values shall be for the same site and assumed resource.*
- *Weight in Air (metric tons)*
  - *Includes all weight that impacts logistics and handling*
  - *Does not include weight of cables, moorings, or any other components assembled on-site.*
  - *Permanent ballast is included.*

PWR will be computed according to the above equation using AEP and both Active mass and Dry mass for the 2020 WECs. To achieve these DOE objectives, the following approaches will be used:

5.1.1 Power

The 2020 WEC is assessed for AEP at each site using the approach discussed in section 4.1. From this AEP calculation and associated data, the following will be extracted:

$$Rated\ Capacity\ (kW) = Maximum\ average\ power\ delivered\ to\ grid\ over\ a\ ten\ minute\ period$$

$$Capacity\ Factor = \frac{site\ specific\ AEP}{8760\ hours\ x\ Rated\ Capacity}$$

$$PTO\ efficiency\ (at\ Rated\ Capacity) = \frac{Rated\ Capacity}{rated\ shaft\ input\ power}$$

5.1.2 Active mass (metric tons)

Total WEC mass included all necessary structural hardware and equipment from the WEC-side mooring attachment, but excluding water ballast and permanent ballast. This will be used to compute Active PWR.

5.1.3 Dry mass (metric tons)

Total WEC mass included all necessary structural hardware and equipment from the WEC-side mooring attachment, including permanent ballast, but excluding water ballast. This will be used to compute Dry PWR.

5.1.4 Displacement (metric tons)

Provided for reference, this is the Total WEC mass including all necessary structural hardware and equipment from the WEC-side mooring attachment, including permanent ballast and water ballast. Each WEC time-domain analysis uses the same WEC structure, the total displacement of each WEC model must be equal in order to keep the same WEC waterline (elevation in the water column). Variations in PTO mass are accounted for by adding or removing permanent ballast to keep displacement equal for all models.

5.2 PTO Availability - SPA Goal 2

No deviation from the DOE approach is expected. From the DOE, PWR guidance under FOA 848:

"Availability is the percentage of time a system is operable over the service life of the system (see equation below). Availability encompasses factors of reliability such as Mean Time Between Failure (MTBF), time to repair, and planned maintenance. Therefore, achieving a high availability percentage along with reduced number of maintenance visits per year results in lower LCOE through 1) an increase in the system's annual delivered energy; and 2) overall reduced Operations & Maintenance (O&M) cost of the MHK system through reduced component repair and replacement costs, and reduced logistic and labor costs associated with mobilizing vessels and crews to perform maintenance. Applicants must define their baseline and target availability for a single system, and planned and unplanned maintenance visits per year that can be achieved via component technology innovations developed in this FOA.

$$Availability = \frac{Operable\ Time}{Operable\ Time + Down\ Time}$$

$$Availability = \frac{Service\ Life -\ Down\ Time}{Service\ Life}$$

Where,

- *Operable Time = Service Life – Down Time*
- *Down Time should at a minimum take into consideration:*
    - *Mean Time Between Failures (MTBF) of critical components*
    - *Number of maintenance visits per year (planned and unplanned)*
    - *Weather windows for maintenance visits*
    - *Time to retrieve and redeploy the system*
    - *Mean Time To Repair (MTTR) of critical components"*

5.2.1 Component Service life

The component service life is defined as the median time period for which critical components are designed to be serviced. Critical components are those considered to be at risk of failure over the WEC service life. This applies to all systems, sub systems, support equipment and vessels required for support. The PTO is designed for a 20-year life, but some components have a shorter service life.

5.2.2 WEC Service life

The WEC service life is defined as the design life of the WEC before major overhaul or decommissioning. The WEC is designed for a 20-year life, but some components have a shorter service life. To normalize different component lives, down time will be adjusted to the WEC service life as appropriate.

5.2.3 MTBF

Mean Time Between Failures (MTBF) of each critical component is component service life divided by the number of failures.

$$\text{Componenet MTBF} = \frac{component\ service\ life}{number\ of\ component\ failures}$$

5.2.4 MTTR

Mean Time To Repair (MTTR) is a component-specific parameter for each critical component. MTTR is the total corrective maintenance time for a single component and does not include WEC retrieval and redeployment times, those are included when computing total WEC downtime.

5.2.5 Component Down Time (CDT)

Each critical CDT is computed individually in the referenced spread sheets [DDS1-p MTBF MTTR Service life PTO V2.xlsx] for the entire service life. Component service life may be different from WEC service life and overall downtime is scaled accordingly.

$$CDT = \frac{WEC\ Service\ life}{component\ sevice\ life} \times \text{number of component failures} \times \text{MTTR}$$

5.2.6 System Down Time (SDT)

Sub system down times (SDT) are computed individually in the referenced spread sheets [DDS1-p MTBF MTTR Service life PTO V2.xlsx.]

$$SDT = \text{number of components} \times \text{CDT}$$

5.2.7 Down Time (DT)

DT is the total projected system downtime during the WEC service life and is the summation of all SDT's. That is to say, all down time from all components and sub systems during the service life is summed and reported as total down time (DT). A summation of DT for each subsystem is totaled in the referenced spread sheets [DDS1-p MTBF MTTR Service life PTO V2.xlsx] and includes a time estimate for WEC Recovery and Deployment Time (RDT). RDT assumes a fixed time for recovery, refit and deployment and is added to all other component down times, thus a more-extended repair period is included in DT; the five-year recovery allows for planned refit of components that have a five-year service live. It is initially assumed that a five-year period between recovery and deployment will be planned, and this will be adjusted once more operational data is collected. If calculated Recovery Events are more than once every five years, it is assumed that refit is performed during those recoveries. If Recovery Events drop below once in five years, the DT will be adjusted to once in five years unless data supports otherwise.

$$DT = \sum_{k=0}^{n} CDT_k + (RecoveryEvents \times RDT)$$

$$\text{where; n} = \text{every critical component}$$

$$RecoveryEvents = Ceiling\left[\frac{\sum_{k=0}^{n} CDT_k}{AverageMTTR}\right]$$

where; $AverageMTTR =$ Average of all component MTTR's

Table 5: Down Time (DT) and Availability

System - configuration	DT (hours)	Service life (20yr*8760hr)	Availability (%)
GS1	29,784	175,200 hr	83
DDS1-p	13,201	175,200 hr	92.5
DDS1-i	13,201	175,200 hr	92.5
DDS1-f	-	175,200 hr	-
DDSx	-	175,200 hr	-

6 LCOE MODEL ASSUMPTIONS

To conform to the 2020 deployment scenarios for GS1 and DDS1 outlined in Section 3, the assessment models, including baseline, are adjusted to reflect the expected performance and capital cost levels of a 2020 WEC. For this analysis, the 2020 WEC is assumed to benefit from the economies of scale resulting only from projected installed capacity for a wave farm capable of producing 260,000 MW/yr. In addition, performance improvement is included for technical improvements understood at the time of this Report. The performance improvements are described in Section 6.8 and are uniformly applied to all WEC models, including baseline.

The following high-level assumptions direct the approach for SPA and LCOE reporting:

6.1 WEC Capital Costs

Capital costs for the GS1 are shown in Table 6. The capital costs for DDS1 prototypes are shown in Table 6a. The costs for all three WEC models are the same except for the PTO. The GP1 PTO, which is 138% heavier than DDP1, is estimated to cost 22% more than DDP1.

Experience curves are applied to the first prototype capital costs for all prototypes, including GS1, to determine 2020 WEC costs. The improvement rate calculations are done in accordance with National Energy Technology Laboratory (NETL) guidelines as referenced in the DOE guidance. To calculate the production unit number for determining the aggregate improvement, i.e., how far down the experience curve, all design models use the last unit in the array. No other estimate of previously installed capacity is included.

Table 6 shows the experience curve rate assumptions for the various sub-systems and the resulting effect on capital costs. The rates are assigned to each sub-system grouping based on CPower estimate as to the potential savings available over time. All are within the 1-12% range discussed in DOE LCOE guidance, except for structure. The latest models for the next StingRAY design v3.3 suggest an experience rate above 15%. This is due to a more-cost-effective hull structure and substitution of lower-cost ballast material. StingRAY v3.2 uses steel ballast, while v3.3 will use concrete and seawater. The projected mass decrease from v3.2 to v3.3 is 64%, not including any other potential benefits from economies of scale.

Table 6: GS1 WEC Capital Costs and Experience Curve Effects

Sub-System	1st Unit Cost	Learning Rate	Cumulative Effect	nth Unit Cost
100 Hull Structure	$9,862,767	15.5%	70%	$2,919,169
200 Power Take Off	$3,295,820	10.0%	53%	$1,698,745
300 Electric Plant	$1,064,100	10.0%	34%	$698,156
400 SCADA	$107,132	10.0%	34%	$70,289
500 Auxiliary Systems	$251,749	7.0%	25%	$188,321
600 Outfit & Furnishing	$56,510	2.5%	10%	$51,067
700 Mooring System	$1,736,150	10.0%	34%	$1,139,088
800 Electrical Collection System	$95,750	7.5%	27%	$70,098
	$16,469,978			$6,834,934

Table 6a: DDS1-p, -i, -f WEC Capital Costs and Experience Curve Effects

Sub-System	1st Unit Cost	Learning Rate	Cumulative Effect	nth Unit Cost
100 Hull Structure	$9,862,767	15.5%	70%	$2,919,169
200 Power Take Off	$2,701,492	10.0%	53%	$1,421,252
300 Electric Plant	$1,064,100	10.0%	34%	$698,156
400 SCADA	$107,132	10.0%	34%	$70,289
500 Auxiliary Systems	$251,749	7.0%	25%	$188,321
600 Outfit & Furnishing	$56,510	2.5%	10%	$51,067
700 Mooring System	$1,736,150	10.0%	34%	$1,139,088
800 Electrical Collection System	$95,750	7.5%	27%	$70,098
	$15,875,650			$6,557,440

6.2 Installation Costs

WEC installation costs are estimated to be $200,000 per unit in 2020. This includes transportation to deployment site via tug of $30,000, single-point mooring installation of $25,000, unit load, deployment & tie-in of $45,000, and certification/commissioning expenses of $100,000. The WEC is not expected to require specialized equipment during deployment. Tug cost is expected to be $10,000 per day with ½ day to prepare the WEC for transportation, two-day roundtrip to/from staging/assembly facility to deployment location and a half-day to deploy the WEC.

Shoreside infrastructure installation costs are estimated to be $5,000/unit.

6.3 Infrastructure Costs

The cost per WEC from the downstream umbilical connection to the grid interconnect is estimated to be $60,000/unit in 2020.

The export cable is expected to cost $400,000/km with a 10km distance from the sub-sea pod to grid interconnect. The sub-sea pods are estimated to cost $150,000 each with the capability for 10 unit connections. On-shore facilities are estimated to cost $10,000/unit.

6.4 Failure rates

Prior to deployment of the WEC, components are assumed to have been culled for infant mortality, through quality control (QC) inspections and shipyard testing.

6.5 Operations and Maintenance

CPower has devised a bottoms-up approach to calculate potential 2020 O&M costs, and no learning rate is applied. The methodology breaks O&M into onshore monitoring, visual inspections, planned on-site minor maintenance, unplanned on-site minor maintenance, unplanned in-port major maintenance, and in-port refitting. The cost of the maintenance procedures is a function of estimated vessel cost ($800-1,500/day), labor cost ($80/hour), material cost ($4,000-50,000/repair), days per repair (1-10), and number of annual occurrences. No special-purpose O&M vessels are required. In-port costs also include a facilities charge of $1,000/day. Onshore monitoring is expected to be $4,000/WEC/yr.

For DDS1 WECs, 65% of the WECs in the array are expected to need unplanned in-port repairs each year. Additionally, all WECs undergo six periodic visual inspections, one planned minor repair and one unplanned maintenance procedure each year. The high volume of unplanned in-port maintenance for the DDP1 generator is expected to remove the need for additional planned major and minor on-site repairs. This is because the normally-planned periodic maintenance will be performed during the unplanned in-port repairs. Expected improvements to DDPx will allow more on-site repairs and fewer unplanned in-port repairs.

Until more data is collected, it is also assumed that the WEC will be recovered once every five years for inspections, regular maintenance and refit, prior to redeployment. Weather windows for recovery and deployment are location-, equipment- and WEC-specific and require a deployment-specific design to accurately quantify, but in this case each are assumed to be two weeks, and a two-week refit period assumes replacement parts are readily available on-site; total down time for refit is assumed to be six weeks. The in-port refitting cost and unplanned major repair costs have been equalized to facilitate the O&M calculation. This is done by averaging the costs of the three refits and ten unplanned in-port repairs.

Unplanned major repairs frequency is determined by MTBF analysis. All others are estimates.

Costs are a function of vessel day rate, labor rates, number of repair workers, material, facilities, frequency, and time to repair. These are outlined in Table 7. Within the CBS, these O&M costs are adjusted for tax deductibility (O&M*(1-T)), where T is equal to the Effective Tax Rate as provided in the DOE guidance. See Section 6.6.1.

Table 7: 2020 O&M Cost Components per O&M Event

	Onshore Monitoring	**Visual Inspections**	**Minor**	**On-Site**	**In-Port**
Vessel Cost		$800	$800	$800	$1,500
Labor Cost	$4,000	$1,280	$1,920	$1,920	$4,200
Material Cost			$4,000	$4,000	$50,000
Days		0.25	1.0	1.0	3.0
Number/Yr		6.0	1.0	1.0	0.65
Cost	$4,000	$3,120	$6,720	$6,720	$43,900

6.6 Financial assumptions

6.6.1 Taxes

Effective tax rate is 39.6% as per DOE guidance. .

6.6.2 Depreciation

Service life is 20 years and MACRS deprecation duration is 5 years as per DOE guidance. No other financial incentives are included in the LCOE model.

6.6.3 Inflation

Inflation factor is 2.5% as per DOE guidance.

6.6.4 Discount Rate

The Discount Rate is 7% as per DOE guidance.

6.7 Soft Costs

Soft costs are estimated to be $872,534 per WEC. The soft cost components are:

- Construction Insurance = 1% of installed capital costs
- Surety Bond (Decommissioning) = 3% of installed capital costs
- Construction Finance Factor = 1.034 of installed capital costs [5]
- Procurement Contingency = 5% of uninstalled WEC and BOS costs
- Installation Contingency = 30% of deployment and installation costs

6.8 Output Improvement

Output improvement over time is calculated in the same manner as experience curve improvements. For GS1 and DDS1, the GP1 and DDP1 performance and efficiency, respectively, is used for the 2020 WEC. No changes in output from PTO improvements outside of the Project are included in the output improvement rate of 10.6%, which is set in order to meet known improvements explained below. Table 8 Output Improvement shows results of performance increases from improvements due to currently-understood hydrodynamic improvements and advanced controls. The new v3.3 models showed a 63% improvement in output using linear damping. Additionally, 2020 WECs are assumed to have more advanced controls than the linear damping used in the 2015 GS1 and DDS1 models. In its 2013-14 Phase I SBIR project on advanced controls, CPower determined that advanced controls would likely improve performance from 50-150%.[6] Combined with the v3.3 performance improvement and the advanced controls, future hydrodynamic improvements point to an aggregate improvement of 225%. This does not include improvements from unquantified technical advances, and the output improvement is applied uniformly across the GS1 and DDS1 WEC models.

Table 8: Output Improvement (Humboldt, CA)

Sub-System	1st Unit TAEP (MWh)	1st Unit AEP (MWh)	Improvement Rate	Cumulative Effect	nth Unit AEP (MWh)
GS1	467	388	10.6%	225%	**872**
DDS1-p	547	499	10.6%	225%	**1,122**
DDS1-i	596	544	10.6%	225%	**1,223**
DDS1-f					
DDSx					

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[5] Construction Finance Factor assumes 7% real interest rate, with 80% of capital spent in first year of 3 year construction plan.

[6] *Wave Energy Converter Performance and Cost Optimization Through Novel Control Strategies*, March 2014

Table 8a: Output Improvement (Stonewall Bank, OR)

Sub-System	1st Unit TAEP (MWh)	1st Unit AEP (MWh)	Improvement Rate	Cumulative Effect	nth Unit AEP (MWh)
GS1	585	486	10.6%	225%	**1,092**
DDS1-p	685	625	10.6%	225%	**1,405**
DDS1-i	743	678	10.6%	225%	**1,524**
DDS1-f					
DDSx					

6.9 Transmission losses

The LCOE model assumes relatively short distances from array to grid interconnect of 10 km, so expected loss within the model is negligible.

6.10 Array Capacity

Current DOE guidance calls for a project capable of producing 260,000 MWh/yr.

7 SPA AND LCOE ASSESSMENT

Results of the system assessment are described in this section. All figures in Table 9 and 9a System Improvement Metrics are for 2020 WECs at Stonewall Bank, OR as described above. All other Tables in this Section include data for Stonewall Bank, OR and Humboldt, CA. Details regarding Project SPA and LCOE goal achievement are covered in section 10, which will be completed during final reporting.

Table 9: Relative System Improvement Metrics (Stonewall Bank, OR)

Baseline to Target	PWR		Availability		LCOE	
	Targeted	**Actual**	**Targeted**	**Actual**	**Targeted**	**Actual**
GS1 to DDS1-p	55%	48%	10%	11%	-28%	-25%
GS1 to DDS1-i	55%	60%	10%	11%	-28%	-31%
GS1 to DDS1-f	55%		10%		-28%	
GS1 to DDSx	78%		18%		-80%	

Table 9a: Absolute System Improvement Metrics (Stonewall Bank, OR)

Baseline to Target	PWR		Availability		LCOE	
	Targeted	**Actual (Note 1)**	**Targeted**	**Actual**	**Targeted**	**Actual**
GS1	0.26	0.21	83%	83%	.91	.817
DDS1-p	0.41	0.32	91%	92.5%	.66	.612
DDS1-i	0.41	0.34	91%	92.5%	.66	.566
DDS1-f	0.41		91%		.66	

Note 1: Actual absolute values of PWR for all systems (GS1 and DDS1) have reduced due to a more-detailed design, mass increase and power decrease of the v3.2 WEC used in this assessment. As mentioned earlier, the v3.2 WEC design used in this proposal and SOPO criteria was from early 2013, while the v3.2 design used in this assessment was from mid-2015. The v3.2 WEC power production is now being estimated using more-accurate performance modeling techniques developed over the last two years, which have resulted in a reduction in WEC power absorption estimates. Factors contributing to this increase in WEC mass include: added structural reinforcements to the WEC hull, drive shafts for all PTO's changed from FRP to steel and ballast tank/lower spars changed from FRP to steel, in order to lower the WEC's CG. These power losses and mass increases are being addressed independently by CPower with the v3.3 WEC design revision. In spite of the reduction in PWR due to external Project influences on system DDS1, other improvements such as PTO availability and efficiency from this Project have helped keep the LCOE targets on track.

Table 9b: Project Array LCOE

	LCOE ($/kWh)	
System -configuration	**Stonewall Bank, OR**	**Humboldt, CA**
GS1	0.817	1.022
DDS1-p	0.612	0.765
DDS1-i	0.566	0.703
DDS1-f		
DDSx		

Table 9c: 2020 WEC SPA and LCOE Metrics (Humboldt, CA)

System configuration	**PWR (kW/ton)**	**Availability (%)**	**nth Unit AEP (MWh)**	**ICC ($/kWh)**	**AOE ($/kWh)**
GS1	0.17	83	**872**	0.969	0.053
DDS1-p	0.25	92.5	**1,122**	0.724	0.041
DDS1-i	0.28	92.5	**1,223**	0.664	0.039
DDS1-f					
DDSx					

Table 9d: 2020 WEC SPA and LCOE Metrics (Stonewall Bank, OR)

System configuration	**PWR (kW/ton)**	**Availability (%)**	**nth Unit AEP (MWh)**	**ICC ($/kWh)**	**AOE ($/kWh)**
GS1	0.21	83	1092	0.774	0.043
DDS1-p	0.32	92.5	1405	0.578	0.034
DDS1-i	0.34	92.5	1524	0.534	0.032
DDS1-f					
DDSx					

8 PRE-PROJECT SYSTEM SPA AND LCOE ASSESSMENT

Pre-Project system specifications and methods are described in this section. See section 2.1 for system definitions. A recap is provided in Table 10.

Table 10: PTO Specifications and Improvements

	PTO Module			Improvement	
	GP1	**DDP1-p**	**DDP1-i**	**Target**	**GP1 to DDP1-i**
Mass (tons)	67.00	28.20	28.20	48%	58%
CAPEX (1,000's)	$933	$781	$781	32%	16%
Efficiency	66%	72%	78%	17%	18%
Avg Annual Power (kW)	125	160	174	29%	39%
Availability	83%	92.5%	92.5%	11%	11%

8.1 GS1 system specification

Table 11: GS1 system specification

Parameter	units	Specification
PTO Availability	%	83
WEC Active Mass	metric tons	582.5
WEC Dry Mass	metric tons	914.6
WEC Displacement	metric tons	1,200.8
PTO Mass	metric tons	67
Rated Capacity	kW	370
Capacity Factor	%	33.7 = 1,093,000/(8,760*370)
Efficiency	%	66
Max Torque	MNm	1.5
Diameter	m	Not relevant
Length	m	Not relevant

8.2 GS1 PWR

$$PWR = \frac{Rated\ Capacity\ (kw)\ x\ CapacityFactor}{Weight\ in\ Air\ (metric\ tons)}$$

$$PWR\ active = \frac{370\ kw\ x\ 0.337}{582.5\ (metric\ tons)} = \ 0.21\ \frac{kW}{ton}$$

$$PWR\ dry = \frac{370\ kw\ x\ 0.337}{914.6\ metric\ tons} = 0.14\frac{kW}{ton}$$

8.3 DDS1-p system specification

To establish the initial pre-Project AEP on the DDS1-p WEC, CPower performed time-domain modeling as described in Attachment 1 and reported in Attachment 3. For the GS1 system, CPower will use assumptions on efficiency, inertia and availability to estimate its AEP.

CPwr will not use time-domain models on system GS1 (DDS1 with GS1 PTO). The GS1 PTO mass is heavier than the DDS1-p PTO, thus with more mass in the nacelle of the WEC, this forces less ballast to be used in the damper, creating a higher CG in the GS1 WEC. WEC modeling on system DDS1 has identified that a higher CG causes a reduction in energy production that is linear with an upward change in CG; for this reason, system GS1 WEC power extraction is reduced by 5.7% with respect to DDS1.

Table 12: DDS1-p system specification

Parameter	units	Specification
PTO Availability	%	92.5
WEC Active Mass	metric tons	506.9
WEC Dry Mass	metric tons	914.6
WEC Displacement	metric tons	1,200.8
PTO Mass	metric tons	28.2
Rated Capacity	kW	370
Capacity Factor	%	43.4 = 1,406,000/(8,760*370)
Inertia	kgm^2	112,046
Efficiency	%	72
Max Torque	MNm	1.5
Diameter	m	9.0
Length	m	0.86
Air Gap	mm	4

8.4 DDS1-p PWR

$$PWR = \frac{Rated\ Capacity\ (kw)\ x\ CapacityFactor}{Weight\ in\ Air\ (metric\ tons)}$$

$$PWR\ active = \frac{370\ kw\ x\ 0.434}{506.9\ (metric\ tons)} = 0.32\ \frac{kW}{ton}$$

$$PWR\ dry = \frac{370\ kw\ x\ 0.434}{914.6\ metric\ tons} = 0.18\frac{kW}{ton}$$

8.5 DDS1-p Availability

DDS1-p Availability is calculated in Attachment 6 [DDS1-p MTBF MTTR Service life PTO V2.xlsx.]

9 INTERMEDIATE SYSTEM SPA AND LCOE ASSESSMENT

Intermediate project system specifications and methods are described in this section.

9.1 DDS1-i system specification

Table 13: DDS1-i system specification

Parameter	units	Specification
PTO Availability	%	92.5
WEC Active Mass	metric tons	506.9
WEC Dry Mass	metric tons	914.6
WEC Displacement	metric tons	1,200.8
PTO Mass	metric tons	28.2
Rated Capacity	kW	391
Capacity Factor	%	44.5 = 1,525,000/(8,760*391)
Inertia	kgm^2	112,046
Efficiency	%	78
Max Torque	MNm	1.5
Diameter	m	9.0
Length	m	0.86
Air Gap	mm	4

9.2 DDS1-i PWR

$$PWR = \frac{Rated\ Capacity\ (kw)\ x\ CapacityFactor}{Weight\ in\ Air\ (metric\ tons)}$$

$$PWR\ active = \frac{391\ kw\ x\ 0.471}{506.9\ (metric\ tons)} = \ 0.34\ \frac{kW}{ton}$$

$$PWR\ dry = \frac{391\ kw\ x\ 0.471}{914.6\ metric\ tons} = 0.19\frac{kW}{ton}$$

9.3 DDS1-i Availability

DDS1-i availability is calculated in Attachment 7 [DDS1-i MTBF MTTR Service life PTO V2.xlsx.]

10 FINAL SYSTEM DESIGN SPA AND LCOE ASSESSMENT

To be completed along with final reporting. Final Project system specifications and methods are described in this section, along with an analysis of SPA and LCOE goal achievement.

GLOSSARY

AEP	Annual Energy Production
AOE	Annual Operating Expense
BOS	Balance of Station
CBS	Cost Breakdown Structure
CDT	Component Down Time
CG	Center of Gravity
CPower	Columbia Power Technologies
DT	Down Time
DDP1	Project direct-drive PTO module
DDPx	Next-generation direct-drive PTO module
DDR	Direct-Drive Rotary
DDS1	2020 StingRAY v3.2 WEC with DDP1
DDS1-i	2020 StingRAY v3.2 WEC with DDP1 as understood at GNG stage
DDS1-f	2020 StingRAY v3.2 WEC with DDP1 as understood at Project finish
DDS1-p	2020 StingRAY v3.2 WEC with DDP1 as understood pre-Project
DDSx	Improved 2020 StingRAY v3.2 WEC with DDPx as projected at Project finish
DOE	Department of Energy
FCR	Fixed Charge Rate
FOA	Funding Opportunity Announcement
GNG	Go/No-Go decision point
GP1	Baseline geared PTO module
GS1	2020 StingRAY v3.2 WEC with GP1
LCOE	Levelized Cost of Energy
MACRS	Modified Accelerated Cost Recovery System
MHK	Marine Hydrokinetic
MTBF	Mean Time Between Failure
MTTR	Mean Time To Repair
NETL	National Energy Technology Laboratory
O&M	Operating & Maintenance
PMG	Permanent Magnet Generator
Project LandRAY	Project DE-EE0006399
PTO	Power Take Off
PWR	Power-to-Weight Ratio
QC	Quality Control
RDT	Recovery and Deployment Time
SDT	System Down Time
SOPO	Statement of Project Objectives
SPA	System Performance Advancement
TAEP	Transmitted Annual Energy Production
WEC	Wave Energy Converter
PWR	Power-to-Weight Ratio
QC	Quality Control
RDT	Recovery and Deployment Time
SDT	System Down Time
SPA	System Performance Advancement
TAEP	Transmitted Annual Energy Production
WEC	Wave Energy Converter

ATTACHMENTS

Attachment 1 – Energy Production Assessment for DOE LCOE and SPA Reporting.pdf

Attachment 2 – DE-EE0006399 M13.1.1 LandRAY SPA Goal and LCOE Report-Attachment 2 PD v1.0 01-17-2016.xlsx

Attachment 3 – DDS1-p TAEP calculations.pdf

Attachment 4 – DDS1-I TAEP calculations.pdf

Attachment 5 – Final TAEP calculations.pdf

Attachment 6 – DDS1-p MTBF MTTR Service life PTO V2.xlsx

Attachment 7 – DDS1-i MTBF MTTR Service life PTO V2.xlsx