Triton–C
Final Detailed Design Summary

DE-FOA-0001418: Demonstration of an Advanced Multi-Mode Point Absorber for Wave Energy Conversion
Award Number: DE-EE0007819.0000
Principle Investigator: Tim Mundon. Ph.D.
Submission Date: November 5, 2019

Milestone 6
Deliverable 6

Following drawings provided (see Index in Reference for more detail):
17115.01-100-002_Triton-C General Arrangement

Document Version Control

Version	Version Date	Summary of Changes	Author
R0.1 (Draft)	5/8/19	Initial Draft	KDS
R0.6	07/01/19	TRM Comments	TRM
R0.7	8/28/2019	KDS Comments	KDS
R1-0	11/01/2019	Final Release	TRM

Review

Name	Role	Approval	
Balky Nair	CTO		
Tim Mundon	Chief Engineer	TRM	
Kate Stinson	Engineering Project Manager	KS	

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Executive Summary

This document presents an overview of the final detailed design package for the Triton-C wave energy converter. A number of accompanying documents are provided for more detail on the individual system and subsystems. Each of those documents will refer to (and present) specific engineering documentation and drawings. Taken as a whole, these documents should provide a complete and comprehensive guide to the final design and construction of the Oscilla Power Triton C WEC Prototype.

Table 1. Detailed design package master document list

Document	Details/Revision
Triton-C Detailed Design Summary (This document)	R7
Triton-C Detailed Design Report - Power Take Off	R0-1
Triton-C Detailed Design Report - Reaction Ring	R0-1
Triton-C Detailed Design Report - SCADA System	R0-2
Triton-C Detailed Design Report - Surface Float	R0-1
Index to Drawings and Documents in Design Package	

Key Issues & Challenges

The cost estimates for some subsystems are substantially higher than preliminary estimates suggested during FEED stage. The effect of this is that we will require some vendor negotiation or reductions within other subsystems and components in order to allow completion within the budget. Other subsystems costs were essentially similar to FEED predictions.

Table 2. Subsystems and components with substantial cost increases over FEED

Subsystem	FEED Estimate	Final Price	Cost Overrun	Detail / Mitigation
Hull	$400,000	$549,000	$149,000	Additional cost came from a more complex drivetrain foundation and the addition of cooling systems. A simpler drivetrain foundation was used instead, which may result in a reduction in cost.
Hydraulic System	$229,000	$541,000	$312,447	Specialist heat exchangers and custom accumulators were required which resulted in a large part of this cost overrun. Limited mitigation options for equivalent system performance.
Reaction Ring	$317,263	$489,000	$171,736	Perceived construction risk resulted in vendors doubling quotations over FEED level. Moving away from a concrete ring to a simple steel construction will be completed for around half the cost.

The designs presented in this package represent the preferred system design and do not take into account any of the suggested mitigations identified above (with the exception of the hull)

While cost mitigations for the Hull and Hydraulic systems are not obvious without impacting prototype performance, the proposed mitigation for the reaction ring would be done without impacting prototype performance. While a steel reaction ring does not aid in de-risking a proposed concrete construction (which may be lower cost in the long run), it will be functionally identical, and can be constructed for less than half the cost, based on initial quotations. Design work for this is currently being completed internally by OPI.

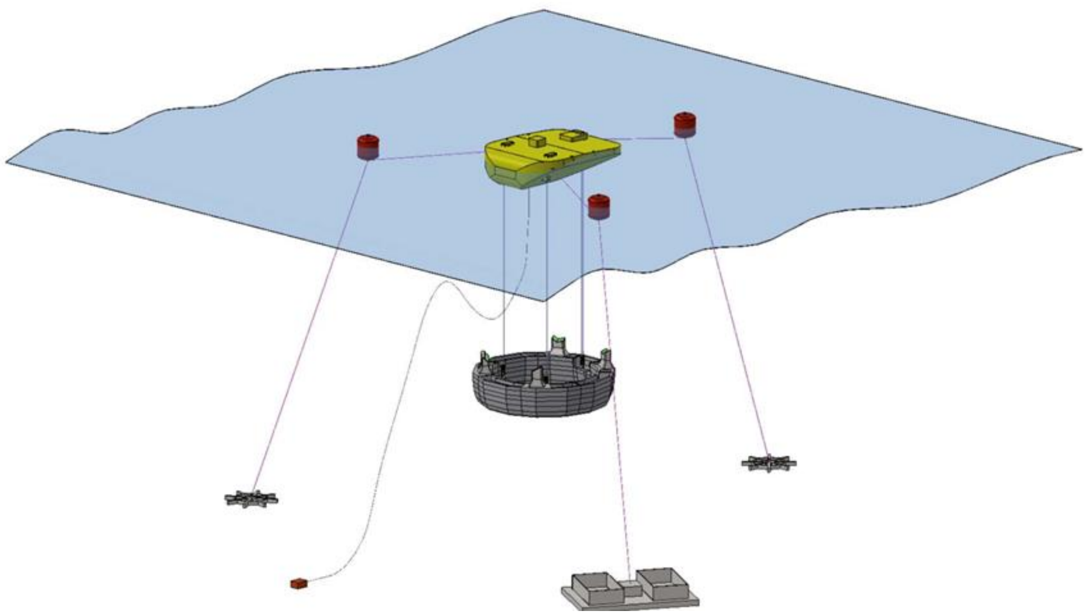

Figure 1: Triton-C Wave Energy Converter as would be deployed at WETS, HI.

Detailed Design Package

The Triton C system can be described by the key parameters in and Table 4. Overall system performance has been determined based on updated numerical model output from the described final design. Design wave conditions and loads are as previously reported[1] and have not changed.

Table 3. FEED and Final Detailed Design Package

	FEED design	Final Detailed Design
Overall System Displacement	72.3m^3	78.6m^3
Length Overall (LoA)	10m	10m
Beam	7.67m	7.67m
Installation Draft	3.7m	4.97m
Operational Draft	24.5m	20.0m
Surface Float Mass	27.4T	40.3T
Reaction Structure (Ring) Mass	79.6(in air), 45.2 tonnes (submerged)	74.1(in air), 38.6 tonnes (submerged)
Nameplate Rated Power	100kW	100kW

Installation Draft Refers to the maximum depth below the waterline when in the installation configuration, i.e. when the reaction ring and float are rigidly connected.
Operational Draft is the depth to the bottom of the reaction ring from the waterline in still water conditions while in the operating configuration.
Nameplate rated power refers to the maximum 30 min mean output of the generator system, rather than the expected output at the WETS site. For more information on the expected performance during deployment, see the following section on performance.

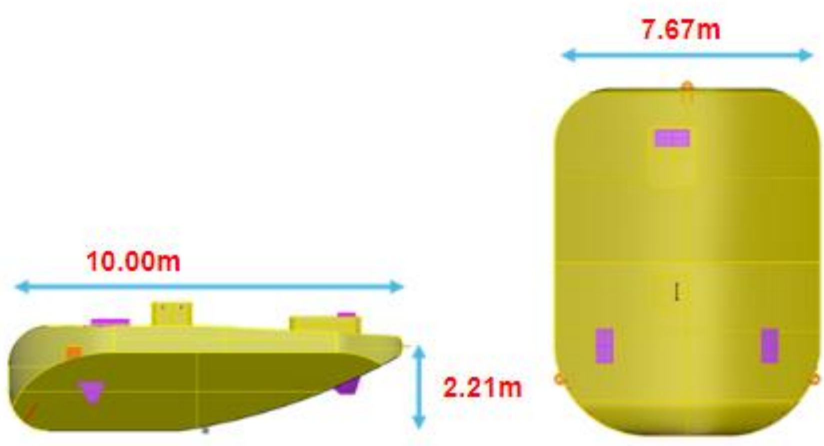

Figure 2: Triton-C surface float: hull dimensions

[1] *Triton C Numerical Modeling Report R1-5*

Table 4. Drivetrain specification values

Property	FEED Value	Detailed Design Value
Tendon Load Torque (mean/max)	75kNM / 195kNm	75kNM / 185kNm
Maximum tendon angle	68˚	60˚
Maximum sheave speed (typical/design)	<50 rpm / 132 rpm	<50 rpm / 94.7 rpm
Gearbox ratio (generator/spring)	1:19 / 1:6.57	1:19 / 1:6.57
Design hydraulic pressure	350 bar	40 bar, 350 bar (LP/HP)
Maximum damping torque	62.7 kNm	62.7 kNm
Achievable apparent spring constant (min/design)	2.7 to 10.7 kNm/rev	1.5 to 4.5 kNm/rev
Maximum stroke (operational/extreme)	+/- 458 degrees / +687, -458	+/- 458 degrees / +687, -458
Peak instantaneous power	> 750kW	> 750kW
Storage Capacity (Supercapacitors/Batteries)	896 Whr	1143 Whr / 24.5 Whr
Maximum average export†	100kW	30kW

† With the grid inverter located on-shore and the DC bus extended across the subsea cable, the maximum export power will be limited to around 30kW.

As a result of the design development from FEED to detailed engineering, there were some differences. The key changes between the FEED design and the final detailed design of the system can be summarized as:

Achievable Spring rate

The highest spring rate proposed in the FEED could not be achieved. The spring rate is dictated by the flow into the accumulator and the size of the external gas volume attached to it. It is therefore limited by the pressure rating of the hydraulic/pneumatic system. For a spring rate of 4.5 kNm/rev and a displacement of greater than three meters, the design pressure of 350 bar will be exceeded. This means that the highest spring, which is achieved with a single 19-liter external gas volume, should not be used in the largest sea state, as it would cause excessive pressure. Higher spring rates, as proposed in the FEED, would mean that design pressure is exceeded at significantly smaller displacements and are therefore not practical in this system.

Maximum Export Power

The 250kW rating of the existing subsea cable power relies on an export voltage of 4kV. However, operation at this voltage was not feasible within the Triton C due primarily to transformer weight and size. The 480v AC produced by the Triton C without a transformer would be limited to an export power of less than 10kW due to the voltage drop/current limits of the cable[2]. As a solution, we selected to move the grid inverter onshore and then export DC voltage from the Triton C. This allows a higher voltage drop to be tolerated across the cable and allows us to increase the power export capacity to around 30kW.
However, as the cost of the subsea cable and grid interconnection hardware and operations are a substantial proportion of the budget, and given the cost overruns noted above, it may

[2] *Cable export power capacity is limited by voltage drop across the cable. As supplied voltage reduces, current increases linearly, but the voltage drop losses increase with the square of the current, hence the substantial reduction in power when moving from 4kV->480V.*

be necessary to forego the export connection altogether in order to allow construction of the system within the available budget. This will be determined during the procurement process. While the grid connection is ideal, it is not essential to the project objectives.

Float Mass
As the design developed, the mass of the components within the hull increased above FEED estimates. This was due primarily to the hydraulic systems and was mitigated as much as possible by selection of lightweight components (composite accumulators/tanks/etc.), but it was not possible to fully mitigate the increased weight. To maintain representative performance, the reaction ring mass was reduced so that the complete system retains the same waterline. Future versions of the Triton C would be able to achieve lighter masses through composite hull construction, refined design and component selection.

Subsystems and Components (Design Package Organization)

The Triton-C wave energy device comprises the following electrical, mechanical, hydraulic and hydrodynamic systems that are fully described in the other documents with this package. To help understand the function of each component and its contribution to the overall function of the system, Figure 3 provides a visual guide to the various sub-systems and assemblies.

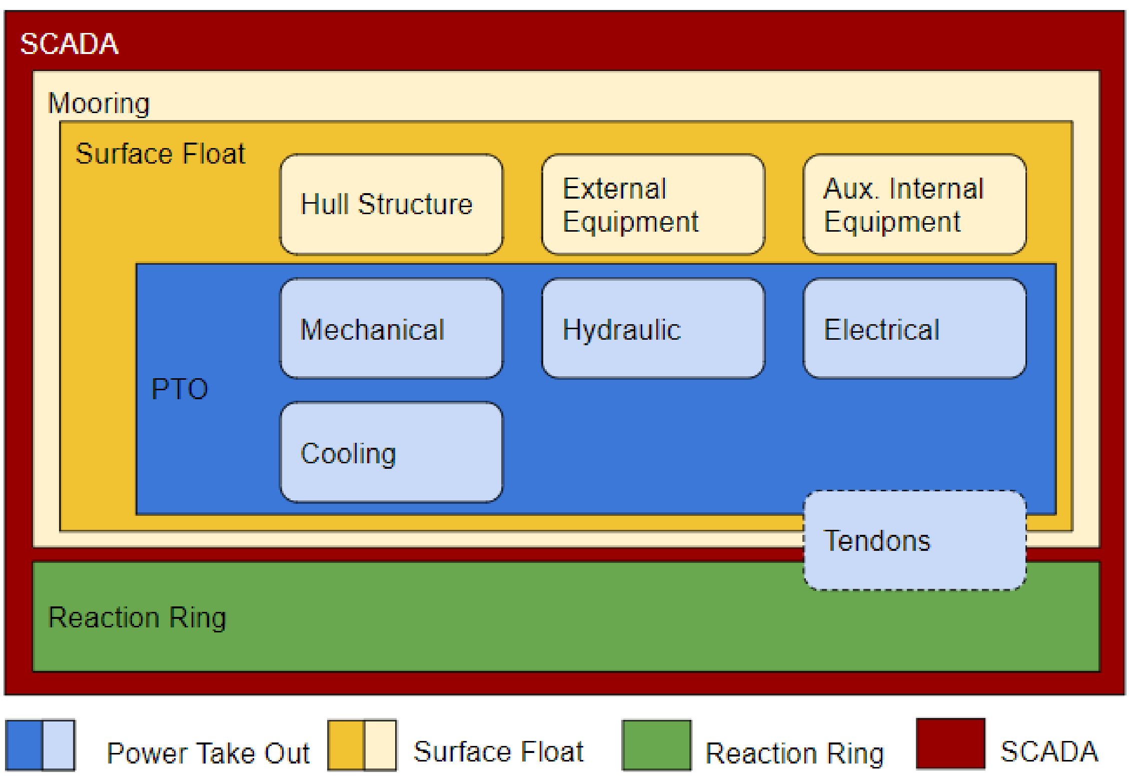

Figure 3: Triton-C system diagram

The four major systems within the Triton-C are the Power Take Off, Surface Float, Reaction Ring and SCADA system. The Power Take Off includes the related electrical, hydraulic, and mechanical power generation equipment across the three drivetrains. The Surface Float is the buoyant surface structural assembly which houses the PTO. The Reaction Ring is the submerged structural body and mass connected to the surface float. The SCADA system in the control monitoring, instrumentation, and communication data recording system.

Below is the outline list of reports and sections within the detail design package. These sections are divided by system and subsystem, highlighting major components within the Triton-C.

Triton-C Detailed Design Report: Power Take Off

a. Mechanical
    - Tendons and fairlead
    - Sheave
    - Gearbox
    - Brakes (Dynamic brake)
b. Hydraulics
    - HP/LP
    - Hydraulic motors (E-brakes)
    - Pressure relief valves
    - Skids and piping
c. Electrical
    - Generator
    - Float grid conversion
    - Battery system
    - Export and Umbilical
    - Onshore grid conversion

Triton-C Detailed Design Report: Surface Float

a. Mooring
    - Float, lines, shackles
b. Hull
    - Structural Assembly
        - Framing and shell
        - Mounting plates and foundations
    - External equipment
        - Hull surfaces: paint, draft lines, logos, non-skid
        - Deck mooring fittings
        - Mooring padeyes
        - Mast: navigation, lighting, vent, weather monitoring
        - Safety systems
        - Access: hatch, drivetrain trunk and vent
    - Internal equipment:
        - Cooling system
        - Paint
        - Grating
        - Lighting
        - Environmental: desiccant, fans
        - Protection: fire and water ingress

Triton-C Detailed Design Report: Reaction Ring

a. Reaction ring
b. Superstructure

Triton-C Detailed Design Report: SCADA System

a. Key controlled systems
b. Functional specification
c. I/O list: measurements and instrumentation
d. Wiring harnesses

Performance

The Triton C performance in its maximum design wave will provide approximately 50kW average power. The electrical systems within the Triton C are sized above this level due to a reliance on commercial off-the-shelf components. The device is ultimately intended for deployment in fully energetic wave environments with energies up to 40kW/m. In higher environments than WETS, the Triton-C will rely on a submerging survival strategy which is not implemented into this iteration of the device.

Power Matrix

The power matrix describes performance of the system across all possible wave conditions. This analysis starts by combining data inputs from two different simulation models to find the raw mechanical input power to the system (shaft power to drivetrain). In calculating this power, it is important to consider the realistic loss effects within the drivetrain. The core software that we use, Orcina Orcaflex, includes only a simple representation of the PTO and so somewhat underpredicts the losses to be expected. An alternative approach is to pass the Orcaflex numerical output through a full hydraulic simulation of the PTO in Matlab Simulink, however this tends to result in a slight over estimation of the losses due to the fact that the Simulink model is not directly coupled to the Orcaflex simulation of the WEC. By combining the two models, we attempt to improve the accuracy of the mechanical power estimation.

OrcaFlex Model

The OrcaFlex model is a mid-fidelity numerical model based on the utility scale Triton-C prototype. The code solves for the multibody dynamics of the coupled marine and Power Take Off (PTO) system, using the hydrodynamic coefficients derived from a frequency domain boundary element method (BEM) solver. For the surface float, the linearized excitation forces were computed using the BEM solver NEMOH and include forces due to frequency-dependent added-mass and damping. The PTO is modeled by simple non-linear spring-dampers with the force profiles being a bulk approximation of the hydraulics and the electrical generator. The main issue with this analysis is that it cannot include static friction of the hydraulics and does not represent stall correctly, resulting in somewhat of an over estimation of output power.

Hydraulic Model

The hydraulic model is implemented in MATLAB Simscape Fluids as a time series analysis that takes tendon force from the OFX model as an input, and calculates pressures, flow rates, and motions of the sheave and the generator. This model provides a realistic representation of the hydraulic system, and the speed versus torque profile of the generator. However, as it is not coupled to the Orcaflex model, this approach is expected to provide a conservative approximation.

Mechanical Input Power

Both approaches were used to calculate the mechanical power and the average value of the two was used. Instead of running all possible sea states, we selected twenty-two conditions that contributed most significantly to energy production over the course of a year. Each condition was run for 1000 seconds each. The remaining cells in the table were interpolated between the calculated values.

Combined Mechanical Power Matrix

This data has been generated from the Matlab and Orcaflex model. Weightings can be adjusted in the 'Final Power' Sheet.

Tz(s)	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5
Hs (m)												
0.25	0.00	0.00	0.00	0.00	0.00	0.00	0.09	0.01	0.00	0.00	0.00	0.00
0.75	4.48	1.80	0.56	0.39	0.13	0.15	0.14	0.02	0.00	0.01	0.00	0.00
1.25	11.33	7.84	5.18	3.42	1.83	1.16	0.74	0.43	0.24	0.12	0.03	0.00
1.75	21.39	16.13	12.10	8.27	5.44	3.46	2.13	1.30	0.80	0.43	0.11	0.00
2.25	34.71	28.03	21.53	15.40	10.63	6.96	4.39	2.78	1.82	0.97	0.22	0.00
2.75	50.13	42.16	33.64	24.34	17.17	11.55	7.57	5.01	3.33	1.96	0.68	0.00
3.25	66.27	57.16	47.76	35.90	25.43	17.26	11.89	8.38	5.84	3.72	1.71	0.00
3.75	82.30	71.44	60.03	47.49	35.13	24.44	17.93	13.26	9.58	6.43	3.49	0.59
4.25	97.68	85.22	72.49	59.41	46.40	34.90	26.20	19.67	14.52	10.13	6.10	2.18
4.75	112.41	98.82	85.27	71.85	58.32	46.05	35.68	27.29	20.47	14.71	9.55	4.60

Efficiency and Hotel Loads

Efficiency

The mechanical to electrical efficiency matrix is made from the Simulink electrical model and uses a lookup table to determine the generator efficiency (based on generator speed and the related controls logic). This matrix includes only the mechanical gearbox efficiency and generator efficiency, as hydraulic losses are effectively included in the mechanical power calculation. This is shown in Figure 4.

Electrical Efficiency

This data is from the Simulink electrical model/block and uses a lookup table for generator efficiency.
Input: speed from hydraulic model
Includes gearbox losses and motor controller losses
Ouptut: mean efficiency

Tz(s)	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5
Hs (m)												
0.25							0.910	0.910				
0.75	0.902	0.898	0.858	0.885			0.872	0.881				
1.25	0.903	0.902	0.900	0.899	0.898	0.895	0.892	0.889	0.887	0.889		
1.75	0.904	0.903	0.903	0.902	0.901	0.899	0.897	0.895	0.894	0.893	0.835	
2.25	0.905	0.905	0.904	0.904	0.902	0.901	0.900	0.898	0.898	0.894	0.782	
2.75	0.906	0.906	0.906	0.905	0.904	0.903	0.901	0.900	0.899	0.896	0.880	
3.25		0.907	0.906	0.906	0.905	0.904	0.903	0.902	0.901	0.899	0.894	
3.75		0.907	0.907	0.906	0.906	0.905	0.904	0.903	0.903	0.902	0.899	0.831
4.25		0.907	0.907	0.907	0.906	0.906	0.905	0.905	0.904	0.903	0.901	0.892
4.75			0.907	0.907	0.907	0.906	0.906	0.905	0.905	0.904	0.903	0.899

NOTE: Maximum efficiency can't be over 0.91, so calculation was capped.
Empty values indicates sea state does not exist

Figure 4: Gearbox and electrical efficiency matrix.

Hotel Loads

Electrical loads that enable the onboard systems of the Triton C system are termed 'Hotel loads'. These comprise systems such as cooling pumps, hydraulic pumps, SCADA and communications, lighting, etc. The makeup of the internal loads will be discussed later on, but they are incorporated into the AEP calculation as described in this section. For simplicity, these are categorized into three types based on the incident conditions which would dictate the typical systems that would be operational:

- **low waves (0-1m),**
  - No power generation. Minimum communications and monitoring systems enabled. No cooling or hydraulic systems.
- **operational waves (1m-4m);**

    - Normal operational power generation. Typical communications and SCADA operating. Typical hydraulic (loss compensation) and passive cooling pump loads. Average power of 4.88kW
- **extreme waves (>4m).**
    - Maximum power generation. Typical communications and SCADA operating. Maximum hydraulic losses and hydraulic pump operating. Maximum cooling pump operation with passive and active cooling pumps active and set to maximum.

It should be noted that the transition between low waves and operational waves, is defined by the balance of hotel loads to power generated. When the net power produced drops to zero, the system will enter the 'low wave' state. To better describe these systems states a curve depicting the mechanical power and electrical power loading at the different stages of generator startup is shown in Figure 5.

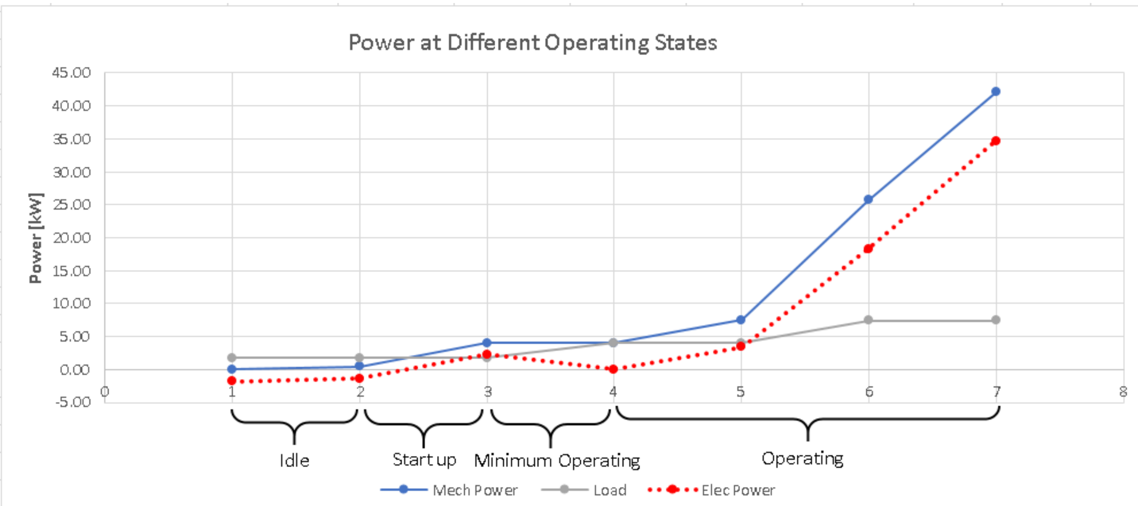

Figure 5: Curve illustrating hotel loads with increasing sea state. The x axis represents different 'states' of increasing incident energy.

Table 5. System operational state descriptions

State	Definition
idle	Device is not generating power, but is ready to, SCADA is on
start up	When wave height exceeds 1m, generator is turned on and starts producing power
minimum operating	Start up has finished, minimum systems are running (SCADA, min recharge, min pump)
operating	All systems on

Annual Energy Production

AEP is calculated as follows, using the electrical and mechanical efficiency terms described below.

$$AEP = 8766 \sum_{i=1}^{N} (P_{Mech,i} \cdot \eta_{Elec,i} - P_{Hotel,i}) \cdot F_i$$

In the above equation, the i^{th} bin represents one Hs, Te combination, 8766 is the average number of hours in a year and:

N = total number of bins
$P_{Elec,i}$ = Mean mechanical power for the i^{th} bin
$\eta_{Elec,i}$ = Electrical efficiency for the i^{th} bin
$P_{Hotel,i}$ = Hotel loads for the i^{th} bin
F_i = Probability of occurrence of the i^{th} bin

Electrical Output Power
This analysis produces the final matrix in Figure 6 below, showing an annual average power of about 7 kW with an AEP of about 61 MWh.

Final Developed Electrical Power Matrix

Tz(s)	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5
Hs (m)												
0.25	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.75	2.768	0.334	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1.25	8.842	5.706	3.349	1.794	0.356	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1.75	17.896	13.169	9.555	6.115	3.571	1.808	0.649	0.000	0.000	0.000	0.000	0.000
2.25	29.959	23.932	18.074	12.536	8.238	4.955	2.671	1.238	0.383	0.000	0.000	0.000
2.75	43.947	36.745	29.054	20.634	14.156	9.094	5.519	3.225	1.699	0.452	0.000	0.000
3.25		50.376	41.877	31.133	21.651	14.260	9.411	6.237	3.926	1.988	0.175	0.000
3.75		63.344	53.016	41.651	30.454	20.765	14.866	10.625	7.281	4.416	1.752	0.000
4.25		75.874	64.334	52.479	40.676	30.242	22.344	16.421	11.739	7.759	4.111	0.559
4.75			75.948	63.775	51.486	40.345	30.937	23.318	17.132	11.916	7.241	2.762

Annual average: 6.987851 kW
NOTE: Cells with blue border are energy values calculated in a non-existent sea state.

Annual Energy Production (AEP)	61.214	MWh
Average Power	6.988	kW
Capacity Factor		

Figure 6: Electrical output power matrix

Mass

Mass is an important factor in performance of the Triton-C. In order to maintain the design waterline on the float the overall mass of the system needs to remain the same. The mass distribution between the ring and float directly impacts the power production and drivetrain loads. As the float becomes lighter and the ring heavier, drivetrain loads increase and more power is produced. The detailed design at the highest level is broken into the ring and the float.

The mass of the surface float incorporates the various components and subsystems made by different manufacturers; the total mass has been calculated to around 40.32 tonnes from the detailed design package. This is somewhat heavier than FEED estimates. The breakdown of the mass within the surface float is seen in Figure 7. The mass of the ring must therefore be kept to a submerged weight of 38.6 tonnes (74.1 tonnes dry, for concrete) in order to maintain the correct float waterline.

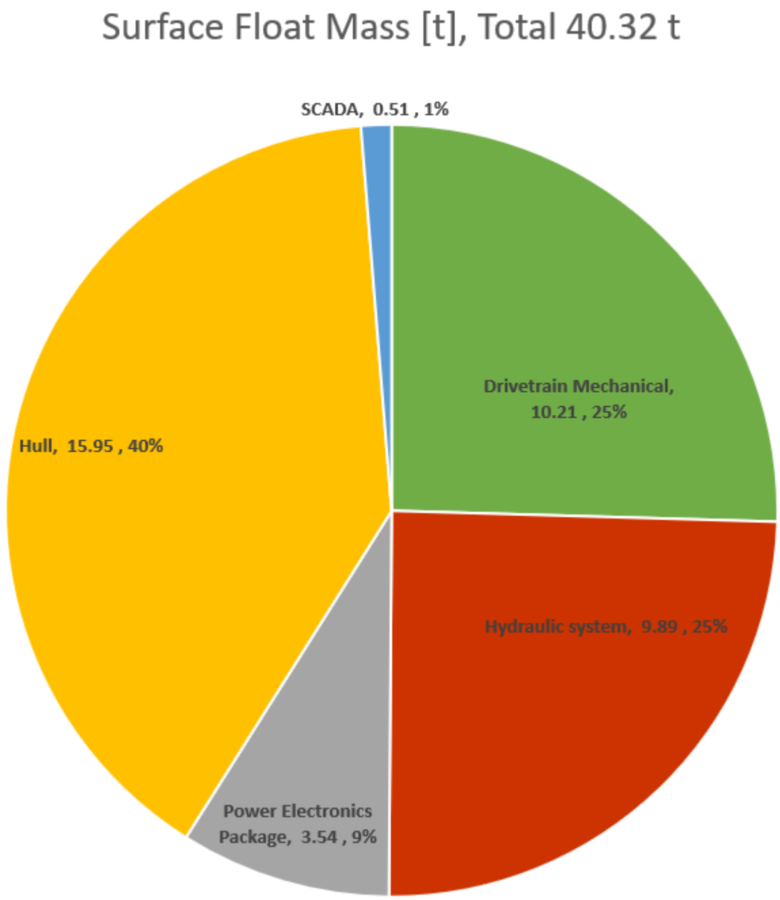

Figure 7: Overall Surface Float Mass (in tonnes)

A mass breakdown of the sub-systems and components within the surface float can be seen in Figure *7*. The Hull, SCADA system, mechanical drivetrain, power electronics package, and hydraulic system are broken out.

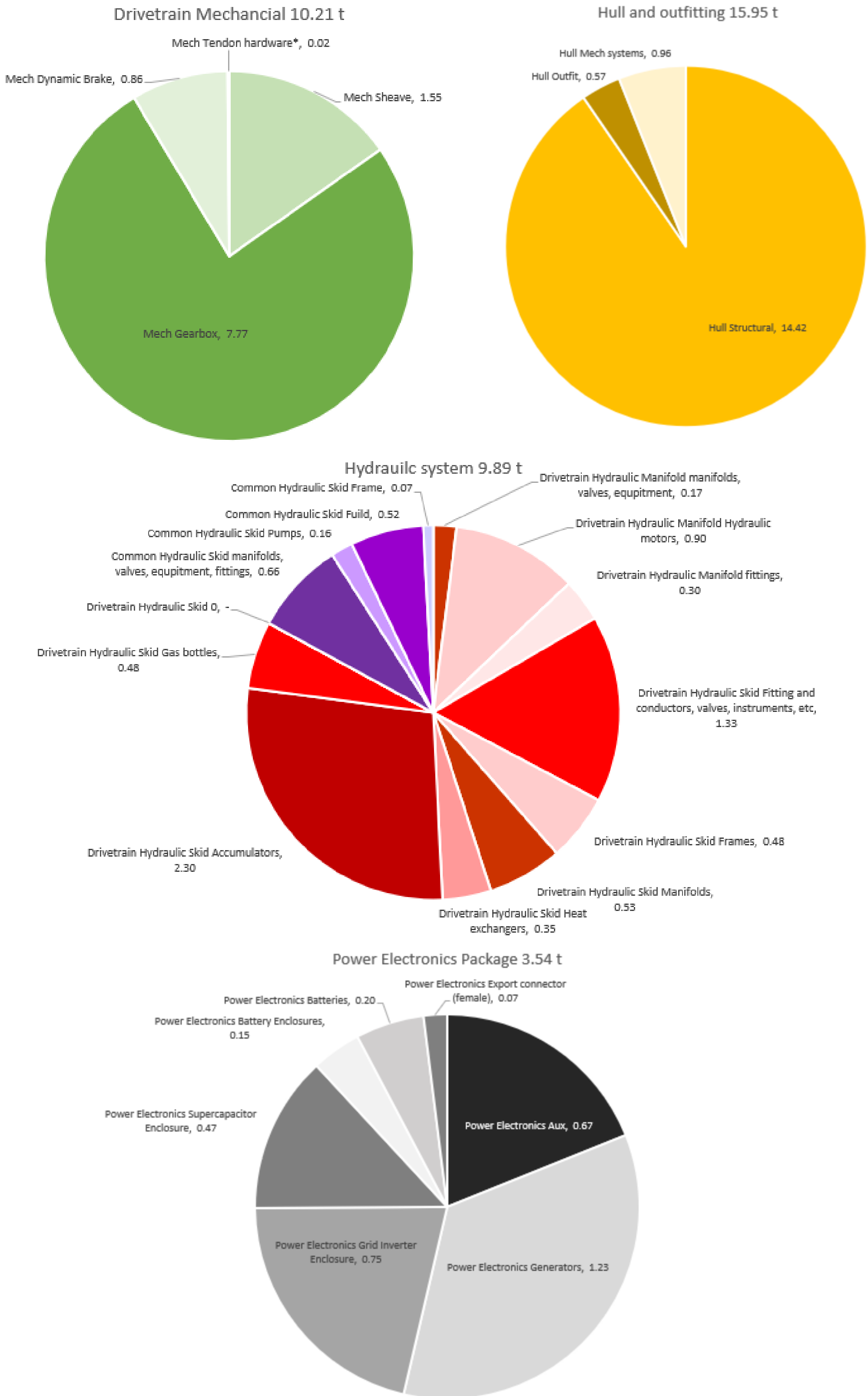

Figure 8: Detailed mass breakdown

Figure 8 shows detailed pie charts breaking down the major sources of mass: the structural hull containing all system parts within the float; the drivetrain mechanical gearbox which houses the mechanical drum, gears and shafts; and the drivetrain hydraulic skid components including skids, manifolds, valves, frames.

The hydraulic system mass is higher than anticipated. We have attempted to mitigate this as much as possible through the use of composite accumulators and custom components. The lighter weight components are at least partly responsible for the cost overrun on the hydraulic system.

It should further be noted that this is a prototype system and as such is not exactly comparable to a future commercial system. Variations in mass can be accounted for in our numerical performance models. Future systems are expected to see significant mass reductions in a number of areas, from composite hull construction, more refined component designs and smaller engineering margins, once the loads and operating conditions are accurately known as a result of these tests.

Costs

A high-level breakdown of system costs is provided in Figure 9. This is substantially correct with quotations received based on the final engineering drawings provided. Some long lead items, such as the Hull and mechanical systems, have already been ordered and these costs are identified as actuals.
Installation costs are still primarily estimates until the detailed operations installation and maintenance plan (Task 8.1) has been developed.

CAPEX		Cost for prototype System to be deployed at WETS - Not indicative of a production system **Single unit costs**		**Cost Assumptions**
Triton - C System			**$ 3,214,269.00**	
Hull		$549,520.00		Actuals
Tendon		$83,061.00		Quotation from SWOS/Whitehill
Reaction Ring		$489,000.00		Quoation - Umaine
Mooring & Maring Systems		$33,215.00		Quotes
Control		$120,000.00		Quotation. Includes software development
Instrumentation		$172,574.00		Quotations - Extensive Suite
Drivetrain & Electrical Systems		$1,628,052.00		
Electrical Systems	$389,931.00			Quotation
Hydraulic Systems	$541,872.00			Quotation (preliminary)
Mechanical	$651,249.00			Actuals
Fairleads	$45,000.00			Quotations for Duplex asymetric fairleads (ballard machine works)
Onshore Electrical equipment		$42,500.00		Estimate
Umbilical		$96,347.00		JDR/Ditrel Quotations
Installation Costs			**$ 217,750.00**	
Anchor Installation		$0.00		Anchors in Place
Export Cable		$0.00		In place
Insurance		$153,000.00		Estimates
Reaction Ring assembly		$25,000.00		Sea Engineering Estimate
Hull floatover and mating		$13,500.00		Sea Engineering Estimate
Tow to site / install		$26,250.00		Sea Engineering Estimate
		Prototype system CAPEX	**$ 3,432,019.00**	

Figure 9: High level cost summary

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