MILESTONE DELIVERABLE

Task 1.0: Generator Specifications from System Aspects Including Wave Profiles, Wave Energy Converter (WEC) Characteristics, and Electrical PTO Requirements

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State of the art power take-off systems for flap-type wave energy converters use hydraulic PTO components. A direct-drive electrical generator and PTO system could offer significant advantages in terms of system simplicity and availability. However, the large generator size and cost for this extremely low and variable speed application is not currently available or competitive using conventional technology. The main challenge addressed by this project is the design of an electrical generator of a sufficiently reduced size and cost to be competitive with the hydraulic alternatives. One of the project goals addressed by the generator and system specifications is to determine roughly what is required from the generator and direct drive electrical PTO system in order to substitute for the hydraulic system.

1. SPECIFIED WAVE ENERGY CONVERTER MECHANICAL REQUIREMENTS:

This section discusses the specified mechanical requirements on the generator determined by the flap-type wave energy converter (WEC) device under the given wave profiles. Figure 1 illustrates the scale of the flap and generators, showing one possible configuration with the outer rotors of two separate generators joined to the base of the flap on either end of the common axis. Another alternative, depending on the generator length and final system bearing solution, could also use a single generator in the middle along the flap axis.

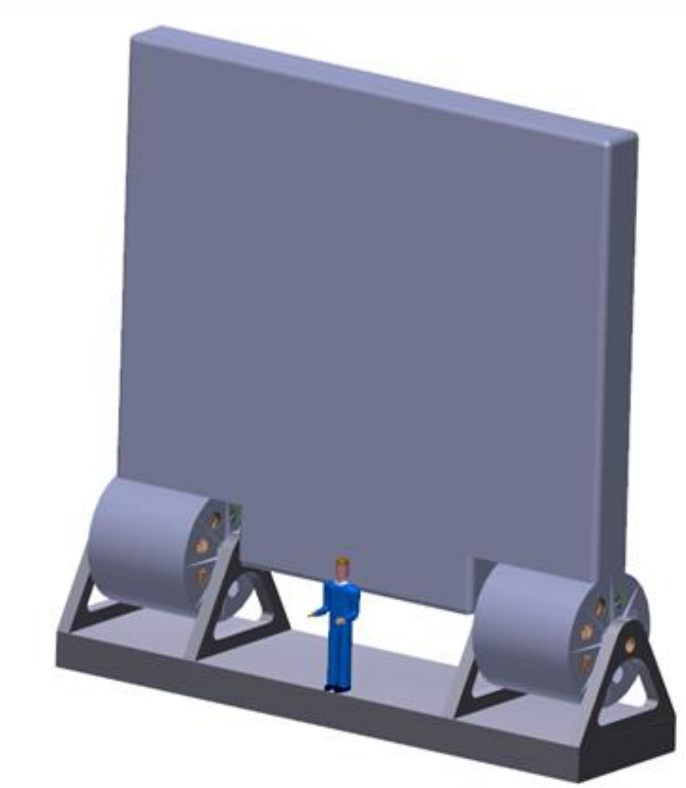

Figure 1. Concept illustration of flap integrated with two outer-rotor generators

A baseline flap and hydraulic PTO system have been defined for reference, target setting, and comparison to the proposed electrical PTO system. The reference system is rated for 30 kW electrical power output to the grid using a single 8 m wide by 7 m tall flap at rated sea conditions of 2.5 m wave height and 12 sec wave period. Both rated wave conditions as well as an annual distribution of wave conditions have been defined as input. Additionally, representative half-hour, data sets of simulated flap torque and speed for both rated sea conditions and a few reduced wave heights have been provided for partial load calculation and comparison.

The motion of the flap and directly coupled generator are unique for this application. Instead of the constant speed, continuous rotation typical for most electric motors and generators, the direct drive generator in this case will oscillate, rotating back and forth with the flap, stopping and changing direction twice every cycle. The average speed is low but the oscillations contribute highly variable peak values of speed and torque at irregular intervals. For the project Phase I and Phase II prototype development at reduced scale, the generators are designed and tested with an increased constant speed in order to make the prototypes more manageable. However, for the target application of the generator directly coupled with the flap in the sea bed, the actual motion is oscillating back and forth, as shown in Figure 2. The slow motion averages around 0.18 rad/sec and the rotation angle varies within ±70 degrees, usually much less. The peak to average speed ratio for this data set is nearly 4:1. The difference in generator performance between constant speed versus oscillatory rotation is discussed further in section 3.

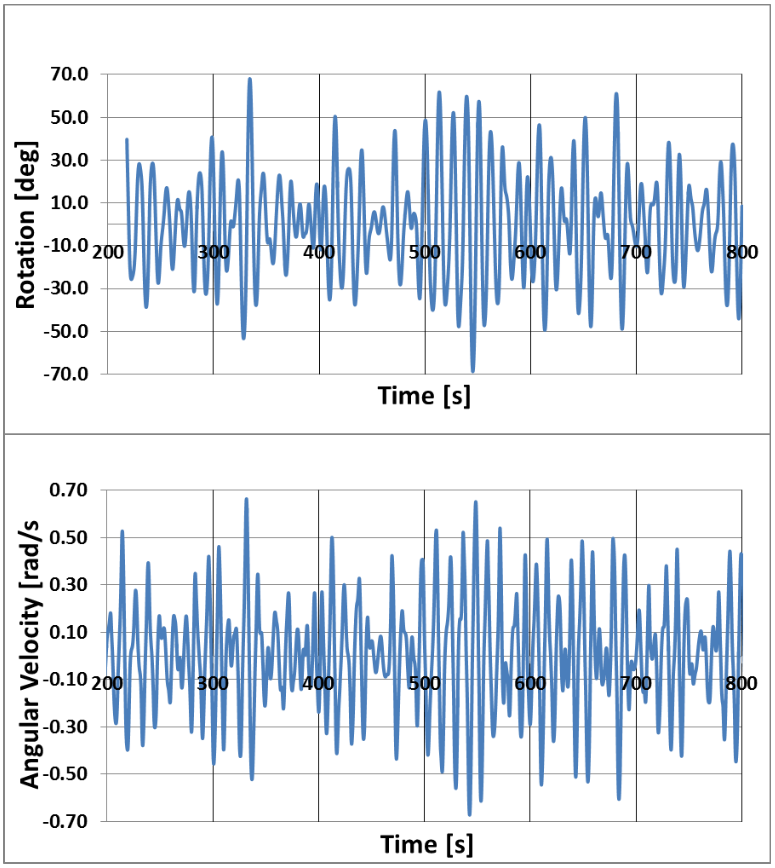

Figure 2. Example flap angle and velocity for 10 min interval with load torque limited to 320 kNm

The peak and average flap values under the rated wave conditions and with the load torque applied to the flap by the PTO system limited to no more than 320 kNm are provided below in Table 1. With no limit on the load torque applied to the flap, the peak torque can reach nearly four times the average value, and the peak power more than nine times the average.

Table 1. Wave energy converter flap characteristics with PTO torque limiting

Mechanical PTO Load Torque				**Rotaional Angle**				
Ave PTO Torque	240	kNm		Ave Rotation Angle	18.4	deg		
Peak PTO Torque	320	kNm		Peak Rotation Angle	68.7	deg		
Peak/Ave Torque Ratio	1.3	pu		Peak/Ave Angle Ratio	3.7	pu		
Flap Mechanical Output Power				**Angular Velocity**				
Ave Mech Flap Power	53	kW		Ave Angular Velocity	0.18	rad/sec	= 1.7	rpm
Peak Mech Flap Power	215	kW		Peak Angular Velocity	0.67	rad/sec	= 6.4	rpm
Peak/Ave Power Ratio	4.1	pu		Peak/Ave Velocity Ratio	3.83	pu		

Limiting the torque applied to the flap by the PTO system can significantly reduce the generator peak torque and peak power output with a comparatively small reduction in average torque and power. For example with the same flap, limiting the peak generator torque from about 1,180 kNm to no more than 320 kNm reduces the average torque only from 320 to 240 kNm. Similarly, the peak mechanical power output reduces from 564 kW to 215 kW while the average mechanical output drops only from about 64 kW to 53 kW. With the limited generator torque, since the wave input does not change, the average angular flap speed also increases from about 0.13 rad/sec to 0.18 rad/sec (1.2 to 1.7 rpm), helping to reduce the generator size and cost.

The load torque can be limited by bypassing the pumps in the hydraulic case. In the electrical PTO case there are a number of possible strategies to limit the torque including reducing the field current in field wound synchronous machines, reducing the generator phase winding current by controlling the conduction time of the solid state switches used to rectify the generator output power for permanent magnet machines, or slipping poles in a magnetic gear. This topic will be discussed in more detail as part of the comparison between generator alternatives.

2. <u>ELECTRICAL PTO SYSTEM REQUIREMENTS</u>:

This section describes the target values for the electrical PTO system including power output, efficiency, and cost. The baseline hydraulic PTO system is the starting point for the electrical PTO system requirements. The overall specifications of the electrical PTO system are defined in order to provide at least equal electrical power output to the grid, using the same flap under the same wave conditions (rated for 30 kW output in this case for a single 8x7m flap).

a. Baseline Hydraulic PTO System Overview

The descriptions here do not include the flap prime-mover and its foundation or the interface to the utility grid or anything that is common to both cases since the goal is a comparison between the hydraulic and electrical systems.

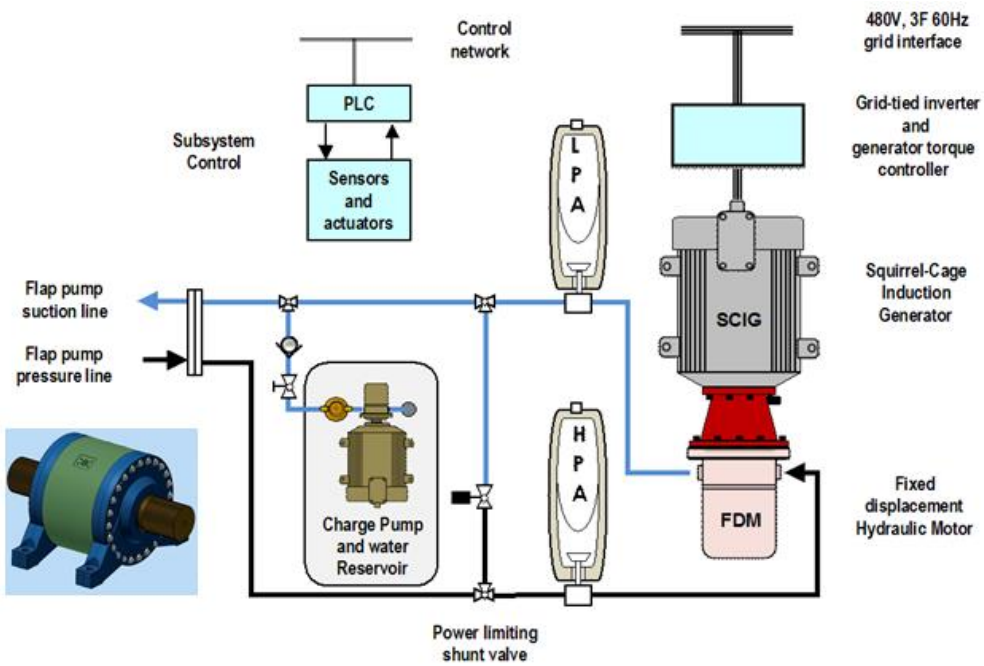

Figure 3. Reference hydraulic PTO system solution

For operation of the hydraulic PTO system, the flap drives a pair of rotary hydraulic pumps delivering pressurized water to a fixed displacement hydraulic motor via a "pressure" pipe line to shore and return "suction" line. Since the pumps operate in an oscillatory manner, the pump ports are interfaced to the pressure and suction lines via one-way valves configured as a “hydraulic rectifier” so that pipe line flows are unidirectional. Fluctuations in hydraulic power during and between each wave oscillation cycle are suppressed from reaching the hydraulic motor by the high pressure accumulator (HPA), acting as the energy storage component in the hydraulic solution. The fluid extraction rate from the HPA is determined by the PI controller monitoring the speed of the Fixed Displacement Motor and coupled generator that is in turn determined by the generator reaction torque. The generator torque is controlled by the matrix converter regenerative motor drive and links the generator to the grid. The charge pump and Low Pressure Accumulator (LPA) maintain a small positive pressure on the fluid returning to the pump to prevent cavitation damage. The principal components with estimated costs are included in Table 2.

Table 2. Hydraulic reference PTO system cost breakdown estimation

Description	Unit Cost	Qty	Ext Cost	Source
Flap pump	263,000	2	526,000	MicroMatic
Pressure pipe	50/m	765m	38,250	Fiberspar
Suction pipe	50/m	765m	38,250	Fiberspar
Flanged pipe connector	1,100	4	4,400	Fiberspar
Pump rectifier assembly	10,000	2	20,000	TBD
HPA assembly	33,000	1	33,000	Parker Hannifin
LPA assembly	33,000	1	33,000	Parker Hannifin
Hydraulic motor (FDM)	52,000	1	52,000	Parker Hannifin
Induction generator	15,000	1	15,000	Marathon
Generator shaft encoder	1,500	1	1,500	Marathon
Generator control & protection	10,000	1	10,000	TBD
Hydraulic system sensors	10,000	1	10,000	TBD
PLC and accessories	10,000	1	10,000	Allen Bradley
Generator inverter-torque control	10,000	1	10,000	Yaskawa
		TOTAL	**$801,400**	
		Cost/kW	**$ 26,713**	

a. Electrical PTO System Initial Overview

The variable current and voltage waveforms produced by the direct-drive generator with the periodic and bidirectional waves require customized power conversion technology. The wave energy variability must be supplemented with an energy storage system in order to maintain a constant output voltage and limited output power ramp rate. The energy storage system acts as an energy buffer, smoothing the power output at the grid-tie. Figure 8 shows the potential direct-drive system interconnected with the grid.

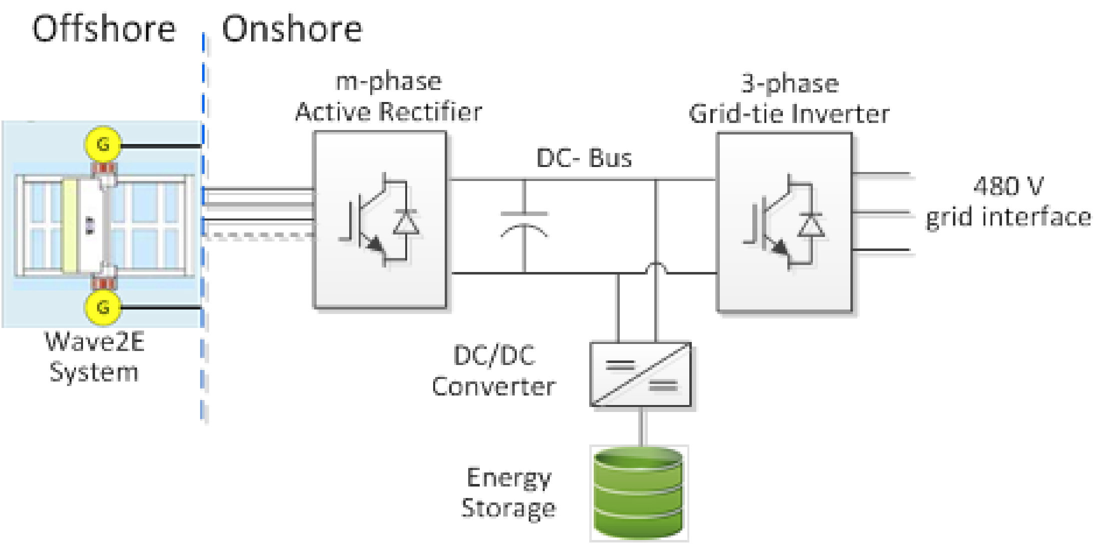

Figure 4 . Electrical PTO system configuration

In this configuration the dc-link is an essential intermediary between the low and variable frequency generator and the 60 Hz grid. The energy storage is a requirement of the power conversion and needs to be sized only large enough to maintain the output voltage level and minimum power ramp rates required by the grid. Additional energy storage could be included for both hydraulic and electrical PTO systems to provide power during extended periods of no or light waves, but this is not included at this stage.

One of the typical challenges in integrating such a variable output power to the grid is in controlling the dc-link voltage stability within the power conversion system. The stability of the dc voltage can be ensured by having a fast dynamic energy storage system connected directly to the dc-link [1]. The energy storage system improves dc bus voltage regulation by using a bidirectional dc/dc buck-boost converter to dynamically control the charging/discharging of the super-capacitors proportionally to any variation in the generator output.

The principal components and estimated costs are provided in Table 3. Estimates are based on commercial products from various vendors for the given rating. In this case the estimated material cost of the direct-drive generator has been doubled to roughly account for manufacturing costs.

Table 3. Estimated cost of electrical PTO system components

Description	Est Rating	Unit Cost	Qty	Ext Cost	Source
Direct Drive Generator	40 kW	400,000	1	400,000	ABB
AC-DC Rectifier	125 kW	60,000	1	60,000	ABB, ZBB
Cable	3-core 775 meters	7,175	2	14,350	Mercury Wire
Capacitors - DC Bank	350 - 450 V, 220uF	130	30	3,900	AVX
Bidirectional DC -DC Converter	125 kW	60,000	1	60,000	ABB, ZBB
Grid side DC - AC Converter	80 kW	60,000	1	60,000	ABB, ZBB
Super Capacitor Module	125 V, 144Whr	6,500	16	104,000	Maxwell Technologies
System Controller	-	20,000	1	20,000	ABB, ZBB
Aux - System Protection	-	50,000	-	50,000	TBD
			TOTAL	$772,250.00	
			Cost/kW	$25,700	

These values suggest a reasonable, direct-drive electrical PTO system can be cost competitive with the baseline hydraulic PTO system. The final electrical PTO system design will be reviewed and updated with the Phase II prototype testing and delivered at the end of Task 6.

The following calculations are based on data for the sea state frequency of occurrence and hours per year at Yzerfontein South Africa site at 7m depth, and the power capture matrix of the power output for each wave condition for the RME 8x7x0.75m flap with linear damping.

Table 4. Initial input for LCOE Calculation

Flap and Electrical PTO System Installed Cost, Power, and Energy Estimates		
52.9	kW	Ave Flap Mechanical Power at rated sea conditions w/ 320kNm torque limiting
64.2	kW	Ave Flap Mechanical Power (at rated sea conditions w.o. torque limiting)
0.824	-	Power output ratio for scaling estimated yearly energy production due to torque limiting
363,031	kWh/yr	Annual Flap Mechanical Energy production for given flap and sea, w.o. torque limiting
299,133	kWh/yr	Annual Flap Mechanical Energy estimation for given flap and sea, w/ 320kNm torque limiting
8,766	h/yr	365.25 days/yr * 24 h/day = 8,766 h/yr
34	kW	Estimated Flap annual average power rating (Annual Energy/h/yr)
20	yr	Estimated system life
772,250	USD	Estimated electrical PTO ***SYSTEM*** installed cost
0.60	-	Estimated minimum electrical PTO system efficiency
0.96	-	Target Availability
172,300	kWh/yr	Estimated electrical annual average power output to grid with torque limiting (Annual Energy/h/yr)
3,446,010	kWh	Estimated energy production over 20 year life
0.22	USD/kWh	Estimated energy cost from installed costs (neglecting service, maintenance, or other operating expenses)

In addition to equal or lower cost, the electrical PTO system must also provide equal or greater electrical output power to the grid as the rated 30 kW hydraulic solution under similar wave conditions. Since the input mechanical power from the flap is also the same for both systems, this requires equal or higher power conversion efficiency for the electrical PTO system. In order to meet this goal, each major component of the electrical PTO system requires at least the minimum efficiency values as given in Table 5.

Table 5. Electrical PTO system component minimum efficiency requirements

PTO System Component	Min Efficiency
Generator	80%
AC/DC Rectifier	93%
Cabling & Connections	94%
DC-DC Converter	96%
Energy Storage	92%
Grid Inverter	97.5%
Electrical PTO System:	**60%**

Efficiency values can also be traded between components as long as the system total remains at or above the 60% target, ensuring at least 30 kW of the roughly 50 kW (The average flap mechanical power from Table 1 is actually 53 kW, so 50 kW is a conservative and convenient value to use for clearer calculations.) of mechanical power available from the flap is delivered to the electrical grid. With roughly 50 kW of input mechanical power from the flap, an 80% minimum generator requires at least a 40 kW electrical output from the generator. With the minimum 40 kW input from the generator, an electrical PTO power conversion system with an efficiency of at least 75% will ensure that the required 30 kW is delivered to the grid. The next section narrows the focus down to the generator, as the source behind the electrical power output as well as the main new and enabling component of the electrical PTO system solution.

3. DIRECT DRIVE ELECTRICAL GENERATOR REQUIREMENTS:

The previous section included a minimum generator efficiency requirement of at least 80%, determined by the available flap input power and required PTO system electrical output power. This is a rather low efficiency value for a typical 40 kW electrical machine, and is not expected to be a challenge or limiting factor for a permanent magnet generator. A higher generator efficiency would increase the electrical power output, but the goal of the minimum efficiency is to minimize generator size and cost while still meeting the electrical PTO system requirements. The 80% generator efficiency requirement can be reexamined for the final generator and system design in Task 6, in case of unexpectedly low efficiency anywhere else in the system. These are net, total values, and depending on the aspect ratio and supporting structure requirements, the 40 kW could be from a single generator mounted in the center of the flap or two separate generators symmetrically attached to the flap as illustrated in Figure 1 and Figure 8.

Also from the previous section, the cost for the total 40 kW direct drive electrical generator material should be less than about $200,000. From the first section, the rated generator speed dictated by the torque-limited flap averages about 1.7 rpm with the generator average torque 240 kNm with the peak torque limited to 320 kNm.

One starting point for the generator design is to first consider a generator with constant rotating speed equal to the average speed of the actual flap. The low but constant rotational speed case is simpler to model and compare to machines rated for other values of speed and power output. In particular, the torque, size, weight, and cost of the Phase I and Phase II prototype generators are significantly reduced by increasing the rated speed and running the machines continuously rotating. This enables multiple prototypes to be built and tested within a limited time and budget. Still, it is critical to also consider how the constant speed, rotational case relates to the motion of the actual application. Initial examination during the second quarter found a 15% reduction in average torque when using a sinusoidal speed waveform with a 1 rpm average value compared to a constant 1 rpm speed.

A more detailed comparison of the generator performance under constant speed and oscillations using a 40 kW design is included below as shown in Figure 3. Values are selected from the baseline flap for a 12 second cycle time and a 1.7 rpm average speed for both cases. For this calculation, a simplified sinusoidal waveform is used instead of the more complicated actual flap torque waveforms. Besides simplifying the process, the sinusoidal oscillation, with a peak to average ratio of only about 1.6 provides a conservative estimation of the impact on the power output. An increased peak to average ratio will only increase the average power output for the oscillation case. The generator and power conversion equipment must be designed to handle the peak current values. If the peak torque is limited, the generator power output can increase with the increased flap speed during the intervals of maximum applied torque. Comparison of the generator current, torque and power are shown in Figure 4, Figure 7, and Figure 8.

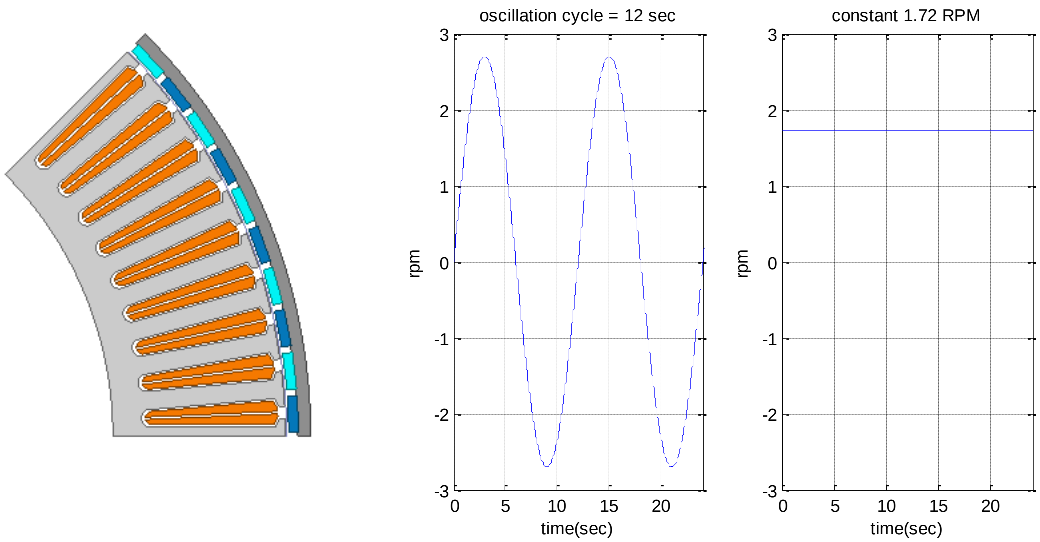

Figure 5. Geometry and speed for constant vs oscillation calculations

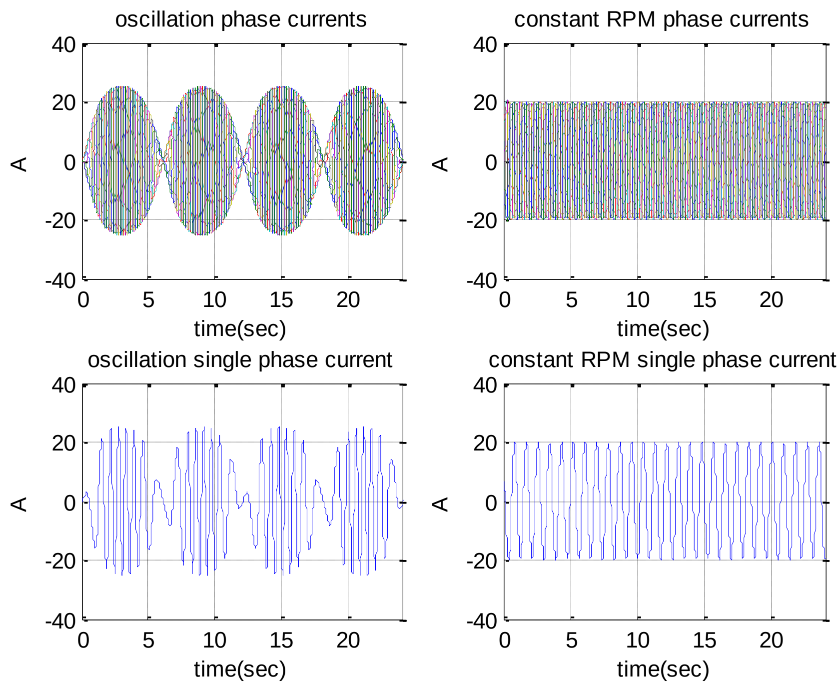

Figure 6. Generator phase current for sinusoidal oscillation (left) and constant speed (right)

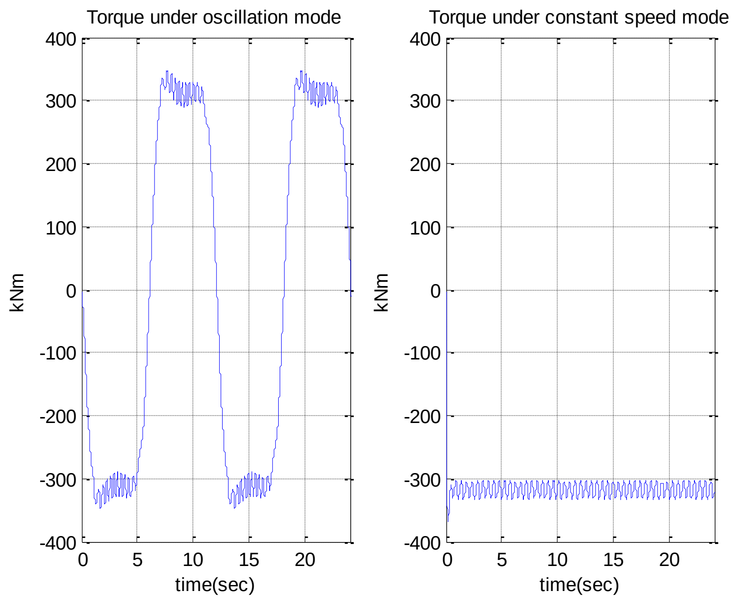

Figure 7. Generator torque for sinusoidal oscillation (left) and constant speed (right)

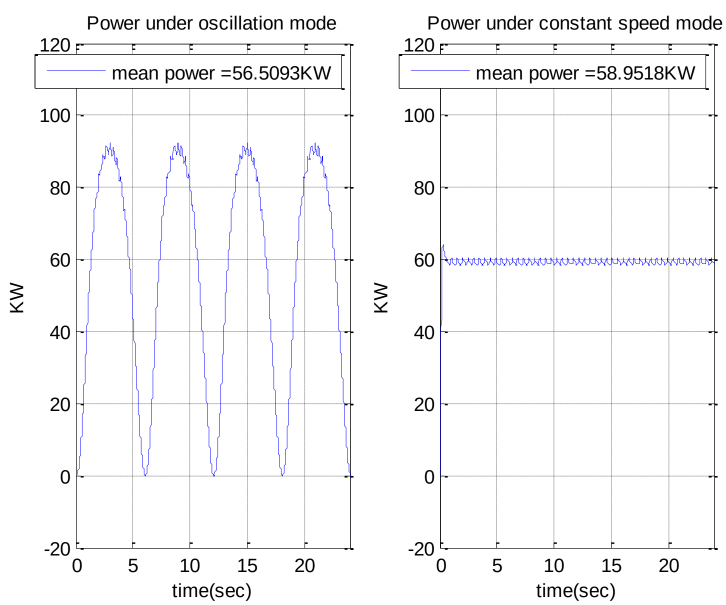

Figure 8. Generator output power for sinusoidal oscillation (left) and constant speed (right)

The average torque values in this case are about 270 kNm and 320 kNm for the sinusoidal and constant speed cases. The average torque in the sinusoidal case is about 18.5% lower, similar to the 15% calculation in the Quarter 2 Report. The power output, as a function of both the torque and the speed, is a better value for comparison. The average power here only reduces by 4% in the sinusoidal oscillation case, and higher power output will result from the actual flap torque and speed waveforms, with the increased peak values. We have also already run simulations using sections of the flap torque and speed waveforms when evaluating a field wound alternative rotor with no surprises. The same performance trends and design tradeoffs apply for either the constant or highly variable generator speed, provided the generator and power converter components are correctly sized for the increased peak, periodic currents. The simulated torque and speed flap waveforms as in Figure 2 will also be used to estimate the power production of the final generator design in Task 6.

Specific, initial torque density requirements for the full scale and prototype generators have been defined for this project based on doubling the mass and volume torque density values of state-of-the-art direct drive industrial motors with ratings as similar as possible. This goal has not changed, but the target values given in the original proposal and later SOPO have varied slightly, depending on how the values were calculated. The active volume calculation used for the rest of the project will be a function of the outer (OD) and inner (ID) diameters of active material and the core length (L_{core}) plus any axial extension of the end windings past the core (L_{end}).

$$Active\ Volume = \pi(OD^2 - ID^2)/4 * (L_{core} + 2L_{end}) \qquad (1)$$

This calculation applies equally well for both prototype and full scale designs. Moving forward, the greatest of the torque density values previously given will be used as the torque density targets. These values all at least double the baseline motor values according to this calculation and in some cases set an even more aggressive target.

Table 6. Baseline motor and target torque density values

BASELINE MACHINE DESCRIPTION					
	Output Power	Speed	Torque	Active Mass	Volume (OD-ID, L+Ends)
	[Watts]	[rad/sec]	[N.m]	[kg]	[m^3]
Full Scale Reference	186,500	13.09	14,248	2,600	0.430
Prototype Reference	5,222	31.42	166	91	0.020
TORQUE DENSITY VALUES					
	Output Power	Speed	Torque	Active Mass Density	Volume Density
	[Watts]	[rad/sec]	[N.m]	[N.m/kg]	[kN.m/m^3]
Full Scale Reference	186,500	13.09	14,248	5.5	33
Prototype Reference	5,222	31.42	166	1.8	8
TORQUE DENSITY TARGETS (USING GREATEST OF PROPOSAL, SOPO, OR DOUBLE BASELINE VALUES)					
	Output Power	Speed	Torque	Active Mass Density	Volume Density
	[Watts]	[rad/sec]	[N.m]	[N.m/kg]	[kN.m/m^3]
Full Scale Reference	40,000	0.18	224,689	**14**	**84**
Prototype Reference	1,000	31.42	32	**4**	**16**

All else being equal, the higher the torque density and the smaller the generator the better. However, the cost for the required power output at the given torque and speed is an important factor. There is a rough, general correlation between machine size and weight and material cost, but making a smaller and lighter generator with increased power density (for example with increased permanent magnet material) is not beneficial if the total cost is not still competitive. The cost for the required average power output and speed is a critical requirement for enabling the direct drive generator and electrical PTO system.

Table 7. Direct drive generator targets

Parameter	Final Generator Design	Phase II Prototype	Phase I Prototype
Min Rated Ave Power [W]	40,000	10,000	1,000
Min Rated Ave Speed [rpm]	1.7	30	300
Min Rated Ave Torque [Nm]	240,000	3,180	32
Min Rated Ave Efficiency [%]	80	80	80
Max Generator Material Cost [$]	200,000	2,750	100
Torque Density [kN.m/m^3]	84	84	16
Torque Density [N.m/kg]	14	14	4

The same minimum efficiency limit is simply maintained constant across the board for lack of a better way to scale it. Motor efficiency typically increases with increasing power output, but in this case, there is no need to reduce the already low 80% full scale efficiency target for the smaller scale prototypes. Only the active mass is used for the torque density calculation, and the effective volume is calculated using (1). The Phase II and Phase I prototype requirements are determined using the scaling procedure described in the next section. The estimated material costs are calculated from nine separate finite element designs at 1, 10, and 40 kW output each at 300, 30, and 1.7 rpm.

4. GENERAL SCALING PROCEDURE:

This scaling procedure is intended to help set additional target requirements for the Phase I and II prototypes consistent with the full scale design requirements, in order to better gauge progress towards the final project goals. Requirements for the full scale system and generator are determined by comparison to the full scale hydraulic PTO baseline. This procedure combines approximate analytical equations and estimated finite element machine calculations at different power and speed to translate the full scale targets roughly to the Phase I and Phase II prototype levels. Because of the complexity in scaling between different power and speed values, designs are independently developed for the Phase I, Phase II, and Full Scale generators, and the prototypes at different power and speed levels are intended to help validate these initial scaling predictions

It is a challenging task and there is no single, clear, and simple method to consistently compare and rescale machines of different power ratings, different rated speeds, or different design topologies. One common metric of comparison is the volume ($D_g^2L_e$) sizing equation [1], which compares the machine power on the basis of the air gap volume, where D_g is the diameter at the machine air gap and L_e is the effective stack length of the electrical steel core. However, the machine outer diameter D_o is more directly coupled with the volume and thus to the cost and size of the machine. The general-purpose sizing and power density equations based on the main machine dimensions $D_o^2L_e$ instead of air gap dimension $D_g^2L_e$ have been developed for machine evaluations and previously validated by comparison with a wide range of machines [2], [2].

From the work presented in [4], the electromagnetic torque in a machine can be approximated by:

$$T_e \approx \left(\pi r_{ag}^2 l\right)\left(\hat{A}_s B_{rg}\right) = \lambda_0^2 v_m \left(\hat{A}_s B_{rg}\right) \qquad (2)$$

Where

$$\lambda_0 = r_{ro} / r_{ag} \qquad (3)$$

is a conversion ratio to get from air gap radius and volume to outer radius and total machine volume, v_m, with

$$v_m = \pi r_{ro}^2 l \qquad (4)$$

In these equations r_{ag} is the center of the air-gap radius, r_{ro} is the machine outer radius (rotor outer radius for our outer rotor machines), l is the stack length, $\hat{A}_s$ is the peak stator current loading, and B_{rg} is the flux density in the air-gap due to the rotor magnets.

The equation for power is obtained from the torque as

$$P_e = \omega_{rm} T_e = \omega_{rm} \lambda_0^2 v_m \left(\hat{A}_s B_{rg} \right) \qquad (4)$$

where ω_{rm} is the angular velocity of the rotor. Or equivalently expressing the torque as in (5) shows the dependence of the torque on both the rated power and speed.

$$T_e^* = P_e^* / \omega_{rm}^* \qquad (5)$$

Since the torque accounts for changes in both power and speed, it is a convenient parameter for scaling machine dimensions. The machine torque and generator output power are a result of the interaction between the stator current (represented as $\hat{A}_s$) and the rotor magnets (contributing B_{rg}).

From **Error! Reference source not found.** and (4), the volumetric torque and power density are directly proportional to the energization quantities $\hat{A}_s$ and B_{rg}. As a first order estimate, the air gap flux density from the magnets will be assumed roughly constant for our low speed range of interest, limited by the electrical steel magnetic saturation, total effective air gap length, and magnets. The current is limited by the maximum current density, losses, and cooling strategy. In general, the current loading can increase with increasing size if, for a constant current density and slot fill factor, the slot area increases faster than the air gap circumference.

However, the integrated magnetic gear machine designs offer the highest potential torque density values at the Phase II and Full Scale sizes. The overall sizing for these machines is dominated by the lower speed magnetic gear components, where the torque is a result of the interaction of the magnets on both the low and high speed rotors. The stator winding and electric loading of the higher speed, and correspondingly smaller sized, generator components of the integrated machine have little impact on the overall sizing of these machines.

We had previously also claimed that the torque is a function of the radius cubed, but this statement had skipped an important step and point to emphasize about the generator aspect ratio. As a first order approximation, with constant electric and magnetic loading, the torque is roughly linearly proportional to machine volume. If a coefficient, K_L, shown in (6), is added to account for variations in aspect ratio, *then* the torque can be approximated as in (7).

$$K_L = \frac{l}{r_{ag}} \qquad (6)$$

$$T_e \approx (\lambda_0^3 \pi r_{ro}^3 K_L)(\hat{A}_s B_{rg}) \quad (7)$$

This highlights the importance and impact of the aspect ratio on the machine design. Figure 9 and Figure 10 show material costs increasing by 50%, from around $2k to around $3k, for designs using different combinations of diameter and length in this case all for the same 10 kW and 30 rpm output power and speed. In Figure 9, the solid lines are analytical calculation and the “*” points are individual finite element designs calculations. Similar plots have also been shown for the 40 kW, 1.7 rpm, full scale generator and could be developed for a given machine of any target speed and output power.

Now from (7), *for a given aspect ratio*, the outer radius can be roughly scaled as the cube root of the ratio of the torques. This provides a scaled generator outer diameter requirement, which can then be used to derive a machine design, analytically or using FEA, and approximate active material mass and cost.

At the full scale, the single air gap generator is not expected to be able to meet the target torque density requirements. This will be discussed in more detail during the Phase II prototype design selection. An integrated radial-flux magnetic gear and generator is expected to meet all of the full scale targets. Still, as a first estimate, we can use the same calculations for approximate overall dimensions. For example, Table 8 below gives an example for the scaling in torque, radius, and length for the three defined machine size and speed levels used in this project. The aspect ratio is held constant, with the diameter being twice the length for all three theoretical machines. All three cases have a volumetric torque density around 71 kNm/m^3, estimated using only the radius and length.

For a consistent, 2:1 ratio of outer diameter to stack length, the dimensions given in Table 8 are roughly consistent with the full scale torque density target of 84 kN/m^2 and therefor good rough targets for the Phase II and Final designs. The dimensions for the 1kW, 300 rpm machine are less realistic for an air-cooled machine.

Table 8. Scaling example for estimated overall dimensions

Rated Power, P, [kW]	Rated Speed, N, [rpm]	Rotational Speed, ω, [rad/sec]	"Torque*" P/ω [N.m]	Torque Scaling Factor, K_T, (T_1/T_2)^(1/3)	Radius, r, [m]	Length, l, [m]
40	1.72	0.18	222,077	-	1.000	1.000
10	30	3.14	3,183	4.1	0.243	0.243
1	300	31.42	32	19.1	0.052	0.052

The 1kW dimensions in Table 8 may not be realistically achievable, but the scaling is still roughly consistent with our Phase 1 prototypes. The torque density in the table is about 71 kNm/m^3, estimated using only the radius and length, roughly 4 times the prototype values. However, the actual Phase 1 prototypes had similar length but roughly three times the radius, four times the power and torque at 4 kW, and roughly double the volume in the torque density calculation when the winding end turn length was also included. Using a factor of 8 instead of 9 from the square of the factor of 3 in radius (This is justifiable since subtracting out the inner diameter reduced the prototype active volume by ~10%.), and dividing by 4 for the increased power and torque, gives a factor of 2. Multiplying this factor of 2 times the additional factor of 2 for increased volume including the end winding explains the approximate factor of four difference in torque density between the Phase I prototypes and the theoretical 1 kW example from Table 8.

Assuming a 2 m outer diameter for the full scale generator design, Table 9 below shows the resulting values for the Phase II prototype. In this case the cube root of the ratio of torque is almost ¼, about 0.24, for a roughly 0.5 m outer diameter. Active material mass and cost have also been estimated from a number of the finite element models as shown in Figure 9 and Figure 10.

Table 9. Generator scaling example

	Power [kW]	Speed [rpm]	Torque [kNm]	Air gap [mm]	Outer Diamter [m]	Cost [$]
Full Scale Design	40	1.7	225	5	2	200,000
Phase II Prototype	10	30	3.2	2.5	0.5	2,750

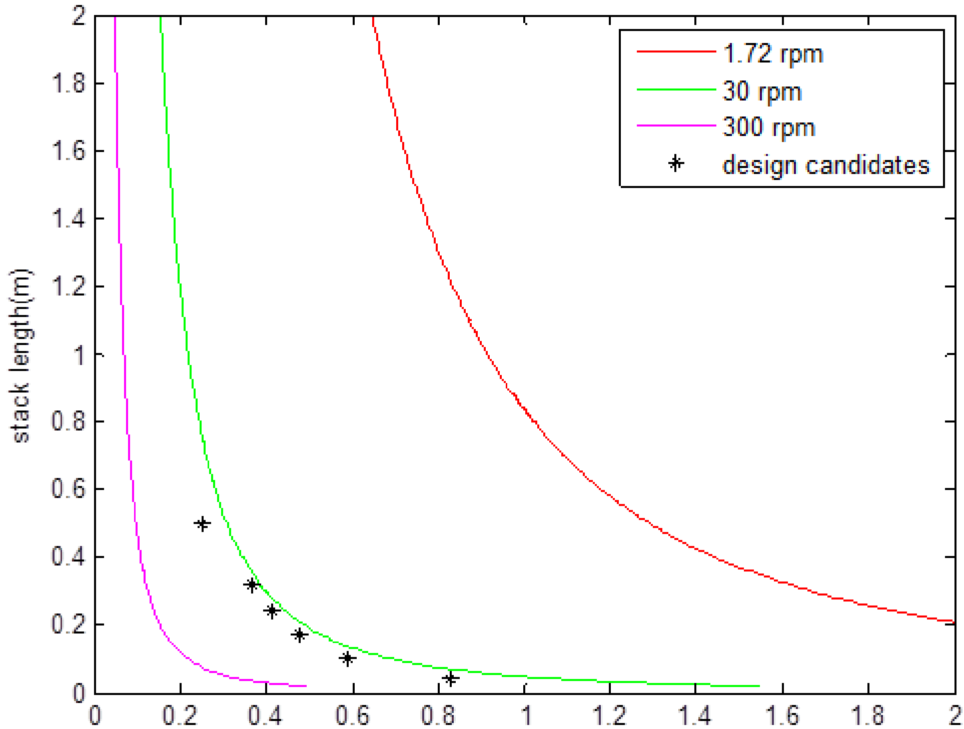

Figure 9. 10kW generator sizing with different aspect ratio

In Figure 9, the solid lines are analytical sizing equations and the *'s represent particular finite element models with different active material aspect ratio. The active material costs for these same designs are estimated below in Figure 10.

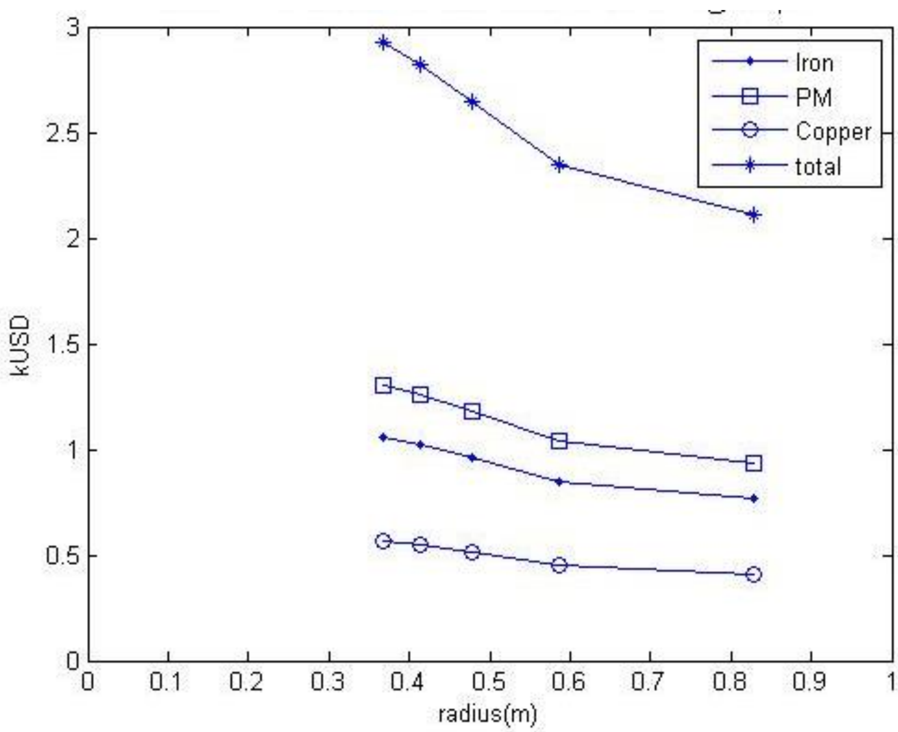

Figure 10. Active material cost estimation of 10 kW, 30 rpm FEA models

5. <u>ESTIMATED SYSTEM RELIABILITY</u>:

Assuming the direct drive electrical PTO system can deliver similar power output and performance at a similar system cost, then the main advantage claimed over the hydraulic PTO system is increased reliability and availability. This claim is consistent with conventional wisdom and general trends in the automotive and aerospace industry, where safety and reliability are critical, but this section provides more specific data and justification. The information below provides an initial indication of what to expect in terms of a reliability comparison between hydraulic and electrical system components. This first look will be expanded during Phase II for data, estimations, and justification for wave energy conversion devices or other subsea components.

The initial reliability data is gathered from recent papers covering topics on power electronics in renewables (wind, wave, etc.), a comprehensive survey on reliability performed by the Army Corp of Engineers, and ABB internal documents and citations. The numbers are presented in the form of Mean Time Between Failures (MTBFs) and Mean Time to Repair (MTTR) statistics from literature and communications with vendors and experts in their respective fields, for components similar to those planned for the electrical PTO system.

The IEEE 493 Standard for the Design of Reliable Industrial and Commercial Power Systems published in 2007 cites a comprehensive review of hydraulic and electric component reliability and downtime produced by the US Army Corps of Engineers and Reliability Analysis Center. The study, referred to as Annex Q in gathered over 6,000 records of O&M data from commercial and industrial facilities, manufacturing utilities, universities, and others for a variety of equipment in service during a span of 30 years.. The study concluded in 1997 and consists of dated data for certain parts of the electrical system; hydraulics, in contrast, have been well established and changed less since the study started. Therefore, MTBF and MTTR have been updated to replace outdated values for the converter and inverter MTTR and a field for supercapacitors has been added, which were not widely available at the time of publication. The results for MTBF and MTTR are presented in Table 10 and Table 11 below.

Table 10. Estimated hydraulic PTO system component reliability data

Category	MTBF [hrs]	MTTR [hrs]	Reliability for a period of 20 Yrs
Accumulator	1336648	8.22	88%
Induction Motor < 600V	791448	1	80%
Piping, Water, >2<=4 inch	426692	14.08	66%
Positive Displacement Pump	1066720	8	85%
Valve, Check	33963360	1	99%
Valve, Pressure Relief	6587760	2	97%

Table 11. Estimated electrical PTO system component reliability data

Category	MTBF	MTTR	Reliability for a period of 20 Yrs
Cable Connection	23624073	0.75	99%
DC-DC Converter	6500894	1	97%
Rectifier	1960032	0.5	91%
Inverter	1817016	0.5	90%
Cable-Below Ground, 1000 ft	1512727	6.77	89%
Super Capacitor Bank	1.33E+10	0.5	99%
Capacitor Bank	5022133	0.5	96%

These tables quantitatively describe the advantage of an electrical PTO system in terms of MTBF and MTTR of components versus a similar hydraulic system. The column titled "Reliability for a period of 20 Yrs" uses the well-known formula for comparing likelihood a component will successfully run for 20 years according to the formula below:

$$Reliability = e^{\frac{-20*8760}{MTBF}}$$

Based on the reliability numbers, the average likelihood that a hydraulic component and system will meet a 20-year lifespan is reduced compared to the same measure for a comparable electrical system. To improve the hydraulic PTO system reliability requires more frequent scheduled maintenance, but at the same time, this will increase the downtime and decrease the availability. Based on the MTTR, maintenance and repair of the hydraulic system also requires nearly four times longer on overall average. The complete system projected downtime and availability are summarized in Table 12 below. Since the actual availability of the electrical direct drive generator is still unknown, for this calculation it is assumed equivalent to the "Induction Motor" included in Table 10 of the hydraulic system components.

The system availability is calculated mathematically as:

$$p(0) = 1 - p(x_1) - p(x_2) - \cdots ..$$

where, $p(0)$ is the probability that all components are in service (total availability of the system), it is equal to the 1 minus the sum of the unavailability of the other components in the list and $p(x_j)$ $p(x_j)$ is the unavailability of component x_j. The unavailability of component x_j is equal to 1 minus its availability, and the component x_j operational availability is given as:

$$p'(x_j) = \frac{MTBF}{MTBF + MTTR} - SEU$$

where, SEU is scheduled unavailability. The scheduled unavailability is assumed to be one day a year for the electrical PTO system and four times this for the hydraulic PTO system from a combination of increased frequency and duration of required maintenance. The resulting availability values are presented in Table 12. These initial estimated values provide a quantifiable indication of the expected comparative difference in availability between hydraulic and electrical systems. The comparison is useful, but the exact values are overestimated since the given availability data is for typical, dry conditions and many of the PTO system components will operate in subsea or near shore environments

Table 12. Estimated hydraulic vs electrical yearly PTO system availability

PTO type	Typical availability over a year
Hydraulic	96.70%
Electrical	99.10%

As argued in the original proposal, if maintenance costs make up 18% of the levelized cost of energy (LCOE) for a wave energy farm as estimated by the UK Carbon Trust in 2012 [5], then a 60% reduction in downtime and maintenance results in a 10% decrease in LCOE. The relative increase in availability for the electrical PTO system in this calculation shows roughly a 75% reduction in downtime and maintenance, consistent with a more than 10% reduction in LCOE. This argument also requires equivalent electrical power output from the interchangeable hydraulic and electrical PTO systems.

The reliability reference data and calculated availability estimates for both hydraulic and electrical PTO systems will become more realistic as the technology becomes more established. However, even in the near-term, the relative comparison still provides justifiable support for the potential improvement in availability and reduction in LCOE for the direct drive electrical PTO system compared to the hydraulic baseline.

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