

Green Cat Wave Turbine Information Sheet – Energy Capture

Introduction

The Green Cat Wave Turbine is designed to provide a simple mechanism for capturing power from the waves and converting it into electricity. Slow rotational motions of the sea are 'terminated' by the sympathetic motion of the cylindrical turbine to extract up to 100% of the waves' energy and convert it directly into electrical power, by use of a direct drive generator operating at low speed, without the need for a gearbox or hydraulic systems.

The expected annual energy production of one Green Cat Turbine is around 6.4GWh, enough electricity to power over 2000 homes.

Hydraulic Efficiency

A key attraction of the Green Cat Wave Turbine is that, in the presence of a small amplitude monochromatic wave with a wavelength to which the device is 'tuned' (i.e., its diameter corresponds with the wavelength, and its amplitude and frequency of rotation correspond to those of the wave, respectively), the energy capture from hydrodynamic theory is 100%¹. Assuming the device to be sized appropriately to the average wave climate of the North Atlantic and rotated at appropriate frequencies, its capture efficiency bandwidth can be expected to be high.

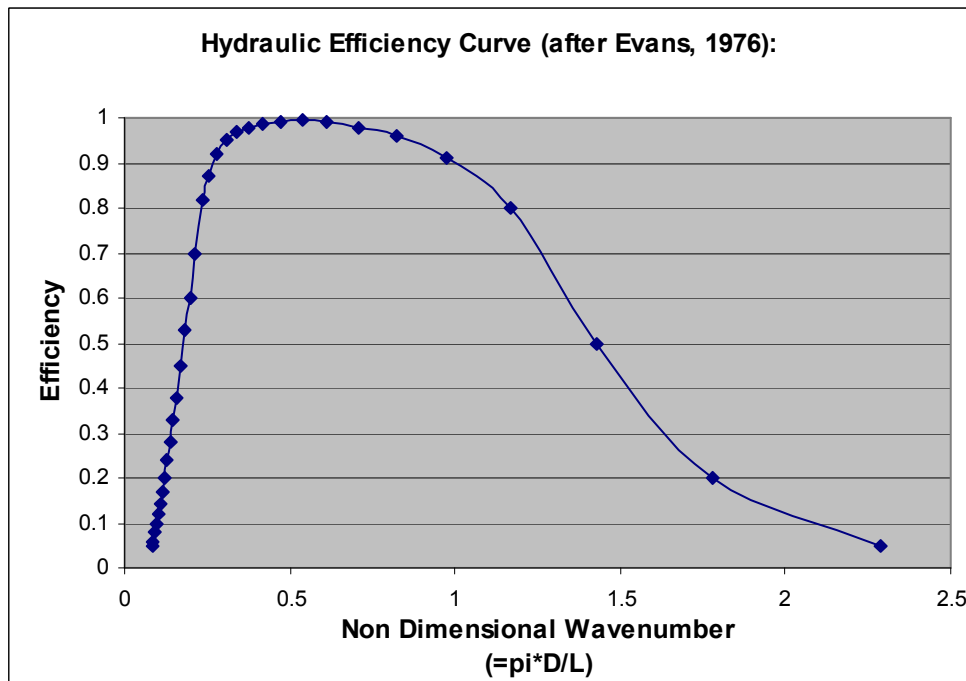


figure 1 – Hydraulic efficiency vs non dimensional wavenumber for an ideal submerged cylinder with tuned non dimensional wavenumber of 0.5 [after Evans, (1976)]²

For the Green Cat Turbine, appropriate values of the non dimensional wavenumber lie in the region 0.3-0.7, which corresponds to wavelengths of ~168 – 72m (~10.4 – 6.8s periods) for the

¹ Ogilvie, T.F., 'First and second order forces on a cylinder submerged under a free surface', J.Fluid Mech., **16**, (1963), p451

Evans, D.V., Jeffrey, D.C., Salter, S.H., Taylor, J.R.M., 'Submerged cylinder wave energy device: theory and experiment', Applied Ocean Research, **1**, no.1, p3

² Evans, D.V., ' ', J. Fluid Mech., **77**, (1976), p1

16m diameter turbine. As can be seen from the efficiency curve found by Evans, the device has a high capture efficiency over a large range of wavelengths.

Wave Climate Sensing & Active Generator Control

With ‘tuning’ being paramount, it is expected that an array of buoys will be situated around the device (or farm of devices). Each will sense the wave climate (wave amplitude, frequency and direction at the single point measured) and it is expected that a signal processing technique using a self learning algorithm will be used to combine all inputs, giving a picture of the wave climate upstream of the device(s).

With the wave climate estimated, active control of the generator torque will be used to change the angle of a hinged arm joining the device axis to its axis of rotation. This will result in control of the device’s orbital radius, ‘tuning’ it to the incident wave height.

It is expected that when heavy seas are sensed, vector control will initially limit energy capture by ‘de-tuning’ the device. This is analogous to active pitch control of a wind turbine. When seas reach storm levels, the device will be lowered towards the sea bed.

Optimum Device Positioning

The device will be positioned a little below the sea’s free surface for two reasons. It needs to be near the surface to capture the most energy, as wave particle orbits are greatest there, decreasing exponentially with depth. However, it is expected that a fully submerged device will experience fewer fatigue problems or efficiency losses due to waves breaking on it, and corrosion due to air and salt water will be reduced. Thus, for a small overall decrease in energy capture, the device’s longevity will be much increased.

Power Performance Curves

Electrical power curves (like the one below) can be derived for each value of period (T_e).

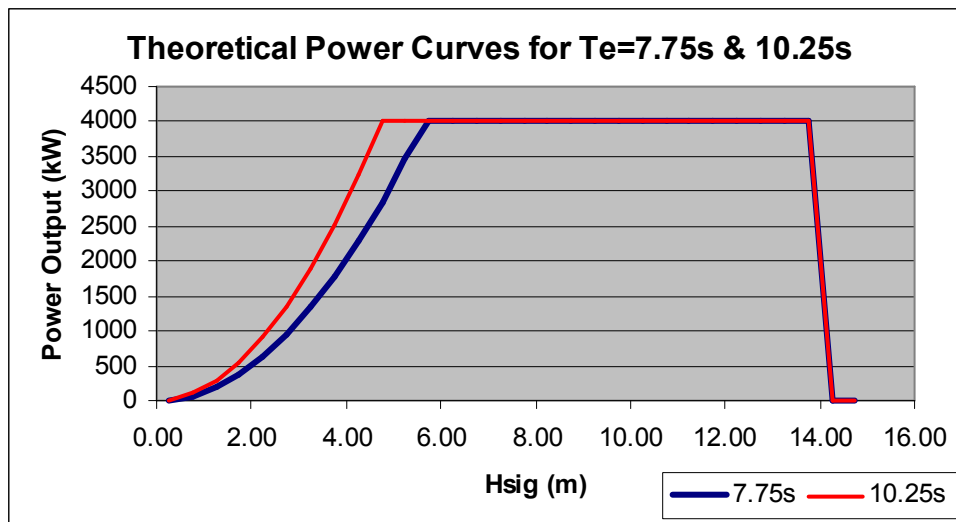


figure 2 – Theoretical power curves of a 4MW Green Cat Turbine of 50m length and 16m diameter for 2 sets of sea states

The curves show generation increasing steadily, in proportion to the power available in the sea state minus electrical losses within the generator. When the sea state (defined via the period or

wavelength) reaches a certain wave height, the power available minus the electrical losses equals the rated power and if the swell continues to increase in height, the device is de-tuned to ensure that only the rated power is extracted. If these heavy seas continue to develop into a storm, the device will be completely detuned and sunk towards the sea bed, at which point no power will be extracted.

When curves for each wave period are collated, a power production matrix can be produced which shows the electrical output power level for a full range of possible sea states, including those in which no power is generated either because the machine has been shut down to avoid storms or because there is not sufficient wave resource to generate useful energy.

Power (kW)	Te (s)	0.25	0.75	1.25	1.75	2.25	2.75	3.25	3.75	4.25	4.75	5.25	5.75	6.25	6.75	7.25	7.75	8.25	8.75	9.25	9.75	10.25	10.75	11.25	11.75	12.25	12.75	13.25	13.75	14.25	14.75	15.25	15.75			
Hs (m)	0.25	UNP	UNP	IDLE	IDLE	IDLE	IDLE	IDLE	IDLE	IDLE	2	3	4	5	6	7	8	9	9	10	11	11	12	12	11	10	9	9	8	7	6	5	5			
	0.75	UNP	UNP	UNP	IDLE	IDLE	IDLE	IDLE	IDLE	4	14	28	39	48	56	64	71	78	84	90	96	101	104	104	103	93	83	77	68	60	54	48	43			
	1.25	UNP	UNP	UNP	UNP	IDLE	IDLE	IDLE	2	12	39	78	108	133	156	177	197	216	234	251	267	280	288	288	287	258	232	214	190	167	151	133	119			
	1.75	UNP	UNP	UNP	UNP	UNP	IDLE	IDLE	4	23	76	154	211	261	305	347	387	423	458	493	524	548	564	565	562	505	455	420	373	328	297	261	232			
	2.25	UNP	UNP	UNP	UNP	UNP	IDLE	IDLE	6	38	126	254	349	431	504	573	640	699	757	814	866	906	933	935	930	835	751	695	616	542	490	432	384			
	2.75	UNP	UNP	UNP	UNP	UNP	UNP	1	10	56	188	379	521	644	753	856	955	1044	1131	1217	1293	1353	1394	1396	1389	1248	1122	1038	921	810	732	645	574			
	3.25	UNP	UNP	UNP	UNP	UNP	UNP	UNP	14	79	263	530	728	899	1051	1196	1335	1459	1580	1699	1806	1890	1947	1950	1940	1743	1568	1450	1286	1132	1023	901	801			
	3.75	UNP	UNP	UNP	UNP	UNP	UNP	UNP	18	105	351	706	969	1197	1400	1592	1777	1942	2104	2262	2405	2516	2592	2596	2583	2320	2087	1930	1712	1507	1362	1200	1067			
	4.25	UNP	UNP	UNP	UNP	UNP	UNP	UNP	135	450	906	1244	1537	1798	2044	2282	2494	2702	2906	3089	3232	3329	3335	3318	2980	2681	2479	2199	1935	1749	1542	1371				
	4.75	UNP	UNP	UNP	UNP	UNP	UNP	UNP	168	562	1132	1554	1920	2245	2554	2851	3116	3376	3630	3859	4000	4000	4000	4000	4000	3723	3349	3097	2746	2418	2185	1926	1712			
	5.25	UNP	UNP	UNP	UNP	UNP	UNP	UNP	UNP	687	1383	1898	2346	2743	3120	3482	3806	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	3783	3355	2953	2669	2352	2091		
	5.75	UNP	UNP	UNP	UNP	UNP	UNP	UNP	UNP	824	1659	2277	2814	3290	3742	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	3543	3201	2822	2509	
	6.25	UNP	UNP	UNP	UNP	UNP	UNP	UNP	UNP	UNP	1960	2691	3325	3888	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	3782	3334	2964	
	6.75	UNP	UNP	UNP	UNP	UNP	UNP	UNP	UNP	UNP	2286	3138	3878	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	3889	3457	
	7.25	UNP	UNP	UNP	UNP	UNP	UNP	UNP	UNP	UNP	2637	3620	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	3989	
	7.75	UNP	UNP	UNP	UNP	UNP	UNP	UNP	UNP	UNP	UNP	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000
	8.25	UNP	UNP	UNP	UNP	UNP	UNP	UNP	UNP	UNP	UNP	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000
	8.75	UNP	UNP	UNP	UNP	UNP	UNP	UNP	UNP	UNP	UNP	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000
	9.25	UNP	UNP	UNP	UNP	UNP	UNP	UNP	UNP	UNP	UNP	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000
	9.75	UNP	UNP	UNP	UNP	UNP	UNP	UNP	UNP	UNP	UNP	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000
	10.25	UNP	UNP	UNP	UNP	UNP	UNP	UNP	UNP	UNP	UNP	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000
	10.75	UNP	UNP	UNP	UNP	UNP	UNP	UNP	UNP	UNP	UNP	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000
	11.25	UNP	UNP	UNP	UNP	UNP	UNP	UNP	UNP	UNP	UNP	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000
	11.75	UNP	UNP	UNP	UNP	UNP	UNP	UNP	UNP	UNP	UNP	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000
	12.25	UNP	UNP	UNP	UNP	UNP	UNP	UNP	UNP	UNP	UNP	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000
	12.75	UNP	UNP	UNP	UNP	UNP	UNP	UNP	UNP	UNP	UNP	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000
	13.25	UNP	UNP	UNP	UNP	UNP	UNP	UNP	UNP	UNP	UNP	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000
	13.75	UNP	UNP	UNP	UNP	UNP	UNP	UNP	UNP	UNP	UNP	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000
	14.25	UNP	UNP	UNP	UNP	UNP	UNP	UNP	UNP	UNP	UNP	UNP	UNP	UNP	UNP	UNP	UNP	STA	STA	STA	STA	STA	STA	STA	STA	STA	STA	STA	STA	STA	STA	STA	STA	STA	STA	
	14.75	UNP	UNP	UNP	UNP	UNP	UNP	UNP	UNP	UNP	UNP	UNP	UNP	UNP	UNP	UNP	UNP	STA	STA	STA	STA	STA	STA	STA	STA	STA	STA	STA	STA	STA	STA	STA	STA	STA	STA	

figure 3 – Power production matrix for the 4MW machine showing unphysical wave regimes (UNP), storm avoidance (STA) conditions and system idling (IDLE)

Energy Loss Mechanisms

As the device uses the minimum number of steps to convert sea wave motions into electricity, a high level of overall energy capture can be expected. However, there are a number of energy loss mechanisms which will affect the hydraulic performance of the device:

- Uncertainties in wave measurements – The wave buoys used to monitor the sea state surrounding the device (or farm of devices) will measure the properties of each wave at one instant in time and at one geographical position. In real seas, waves do not progress uniformly in one direction or maintain their height and frequency uniformly. Thus, there will always be a level of uncertainty in the sea climate interacting with the device, which will prevent it being perfectly tuned to each wave state it encounters.
- Real sea states – Even if the wave climate is perfectly known, it typically consists of multiple wave frequencies and amplitudes, with some waves travelling in slightly different directions. The device will be tuned to the underlying wave frequency for a particular wave state and will lose energy in the other components comprising the wave front – this is an unavoidable energy loss mechanism. The key to minimising this is to size the rotor correctly for the local wave climate.
- Cylinder size – The cylinder size has to be optimised for the wave climate. Previous work has suggested that a 16m diameter cylinder would be the best for a North West Atlantic climate. This will be tested by CFD modelling, as well as looking at other rotor shapes, such as cylindrical ovals.
- Directional losses – these result from reduced energy capture efficiencies when waves arrive at an angle to the device. We are currently working to the assumption that the energy capture will drop off in a cosinusoidal fashion from the optimum orientation. Using directional data published by the Carbon Trust, we have estimated these losses to be $\sim 22\%$ ³.

In addition, the energy delivered to shore by the device is limited by losses comprising:

- Generator losses – the direct drive generator will have an efficiency of around 85%, which is quite low for a generator of its size, reflecting the very low speeds it will be required to operate at.
- Transmission losses – the fraction of electrical energy lost (predominantly through transmission cables) between the device and connection to the national grid $\sim 5\%$
- Availability – the percentage of time that the device is able to generate. All electrical generators require periodic maintenance which limits how often they can generate. In this case, the harsh operating environment means that the device will have to be towed to a dry dock for maintenance and if there is a malfunction, sea conditions may prevent repairs being undertaken quickly. Based on a Monte Carlo simulation of the Green Cat Turbine (detailed in the conceptual design report) we estimate an availability of around 81% for early commercial machines, rising to over 90% as the technology is refined.

³ Directional data taken from Carbon Trust report: ‘Variability of UK Marine Resources’, Environmental Change Institute, Oxford, 2005. This can be found on their website at <http://www.thecarbontrust.co.uk/ctmarine3/res/Variabilityofwaveandtidalstream.pdf>

Annual Energy Capture

These considerations allow an estimate of annual energy capture for the device to be produced. The following gives an indicative annual energy capture based on sea states measured off the coast of South Uist:

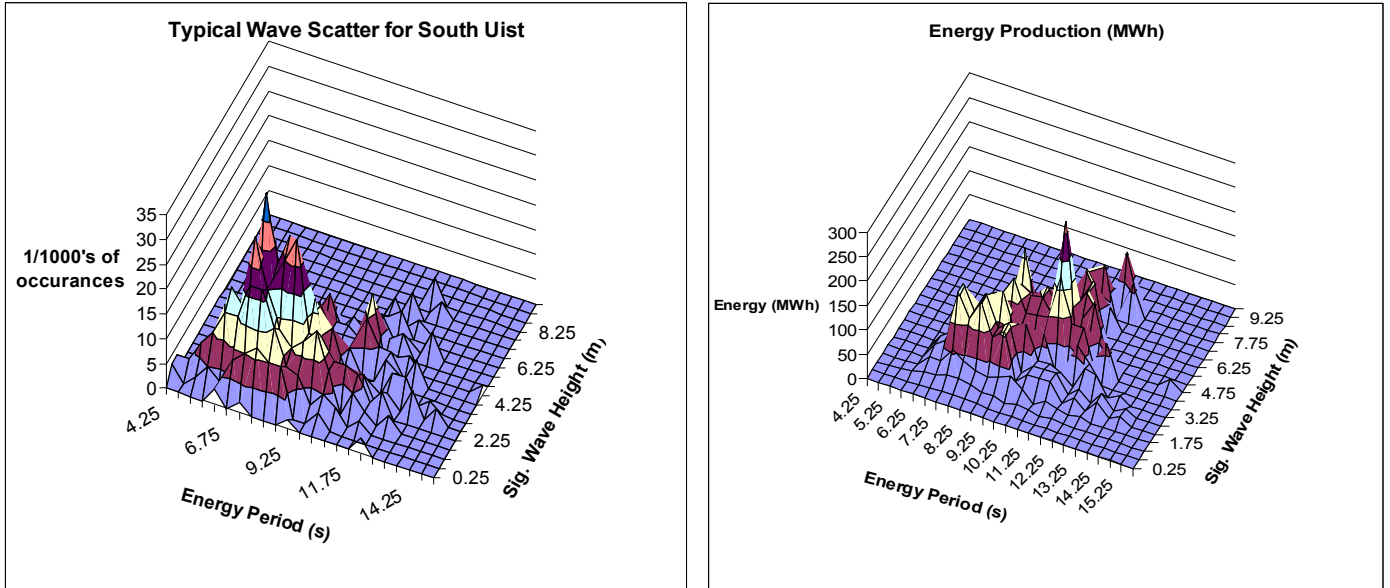


figure 4 – a) Typical South Uist wave climate; b) Energy production matrix in 40m depth of water off South Uist

Care should be taken when interpreting this figure: From figure 4 a) it can be seen that the most commonly occurring sea states are in the approximate range: period of 4-10s, and significant wave height of 1-5m. Looking at b), however, makes clear that the energy available increases with increased T_e and H_{sig} , hence much of the energy capture takes place in ‘big’ seas.

The expected annual energy production of one 50m long, 16m diameter, cylindrical Green Cat Turbine is around 6.4GWh. However, it is anticipated that further optimisation of the device size and shape, utilising the power of CFD modelling, will improve this figure.