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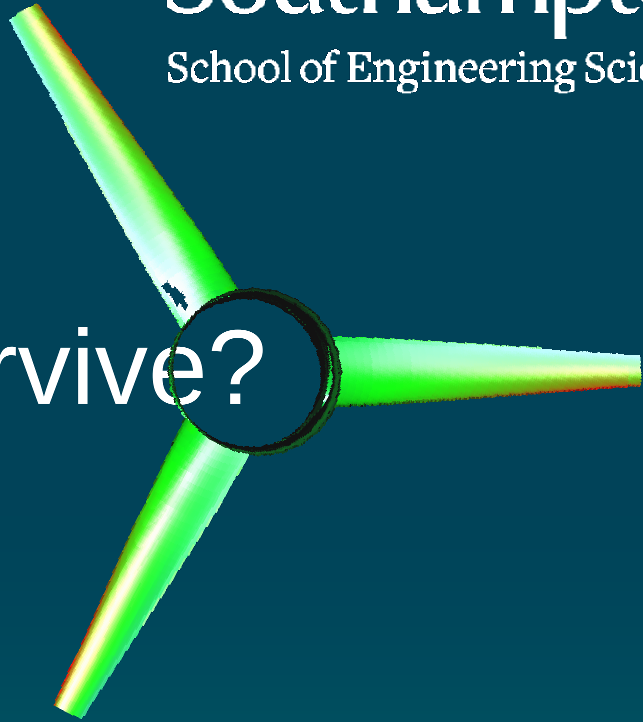
Tidal turbines that survive?



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Tidal Energy

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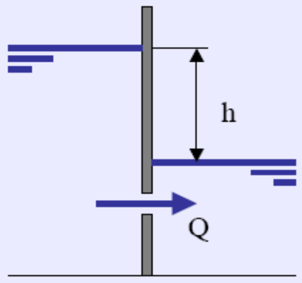
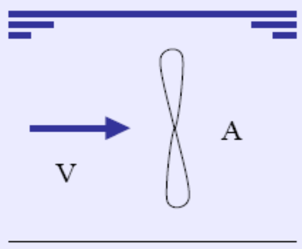
(predictable, sustainable, cost-effective?)



Tidal barrage, available power

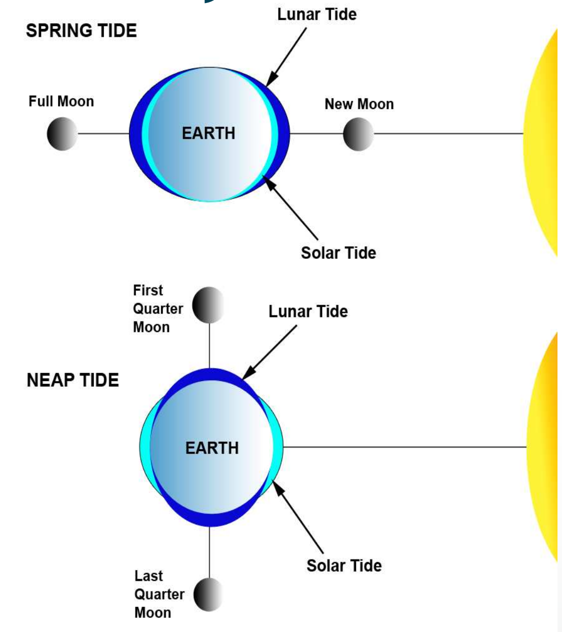
$$P = C_P \rho g Q h$$

Working on fill and empty cycle

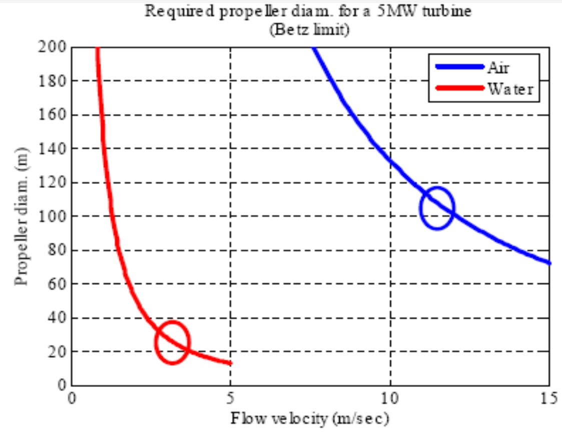


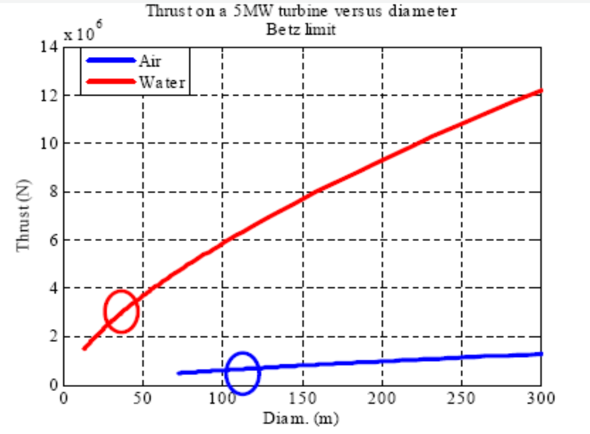
Kinetic energy of stream, available power

$$P = C_p \, \tfrac{1}{2} \rho A V^3$$



La Rance, Tidal Barrage
40years+, 240MW
Active cathodic protection





Marine Environment is

Unforgiving…

- Corrosion
- Extreme loads
- Inaccessible
- Marine Growth
- Salty
- Wind, waves and currents…
- Wet!

Electro-Mechanical design prefers

- Clean and dry
- Controlled temperature
- Easy to Access and Maintain

Challenge is to develop Cost-effective designs for Marine Renewable Systems

That can

1. Survive
2. Generate useful energy
3. Be profitable

Can available marine energy be harvested?

- Mount moving parts and electrical components away from sea

offshore wind turbine

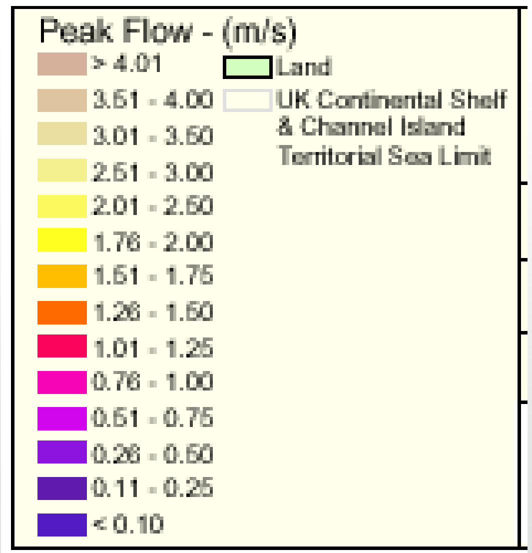
- Mount moving parts well below sea surface (reduce extreme loads)

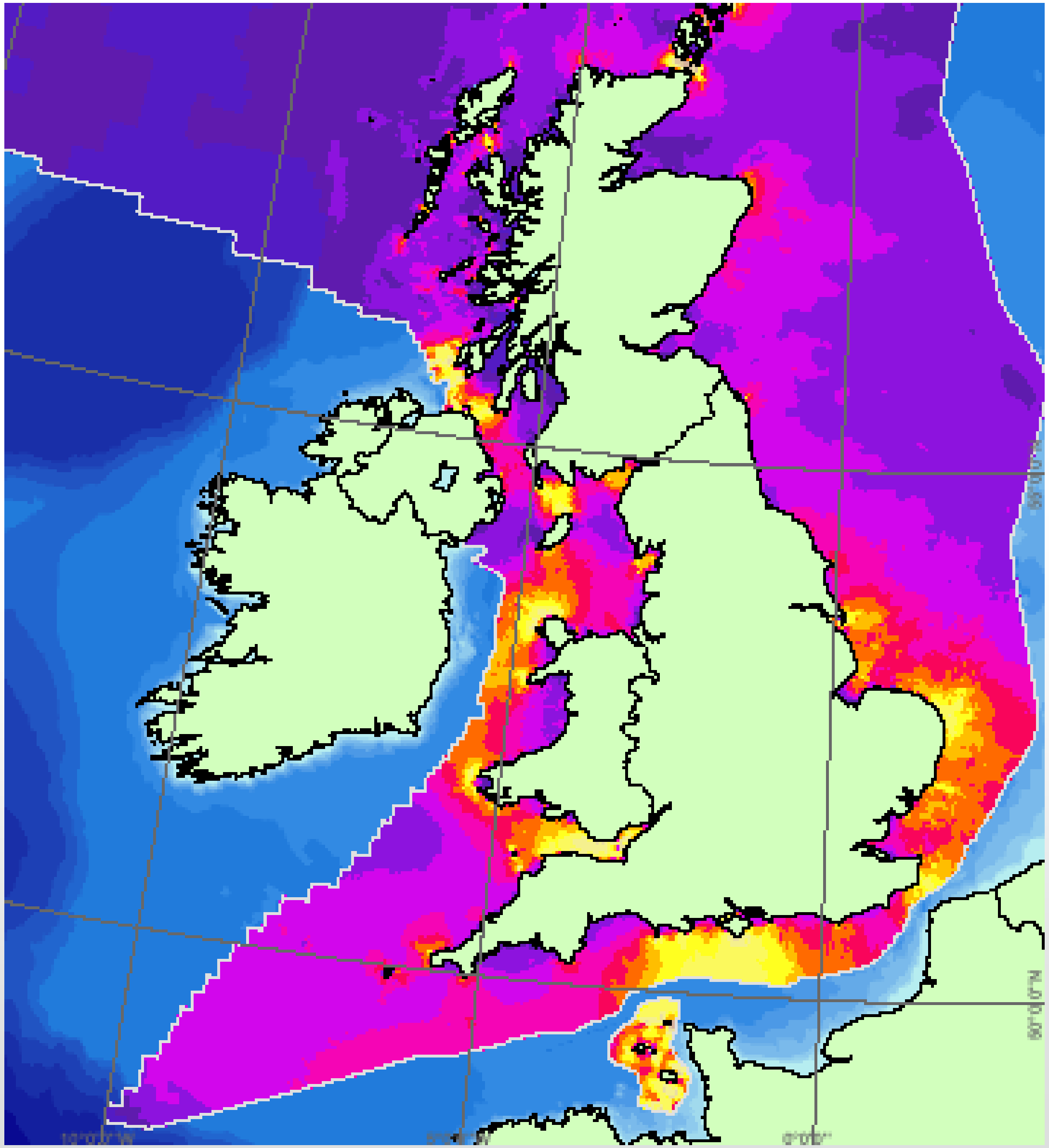
tidal turbines

- Mount on the sea surface

wave energy?

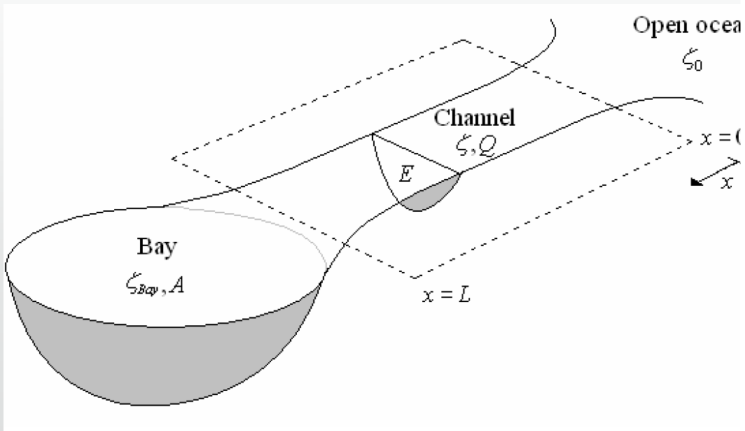
UK-Dti –Atlas Spring Mean Peak Flow

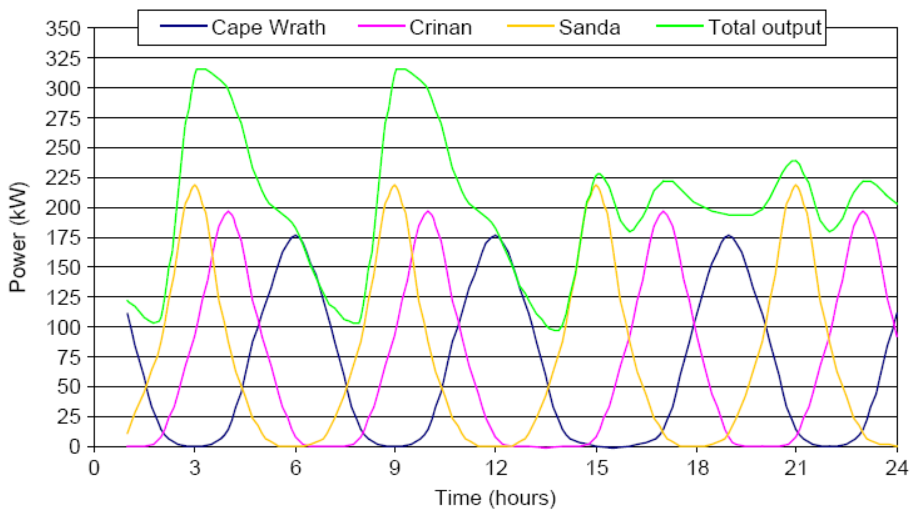




Resources and limits on energy extraction

- Require locations where tidal flow is constrained by bathymetry –near islands/estuaries/headlands/west facing
- Measurements of tidal race found on navigational charts can be used with knowledge of water depth to estimate tidal current energy resources
- For horizontal axis machine theoretical limit is 59% of kinetic energy of flow – a 20m diameter machine in 2.5m/s will give max. power of 1MW





Tidal Energy Systems in operation or under development

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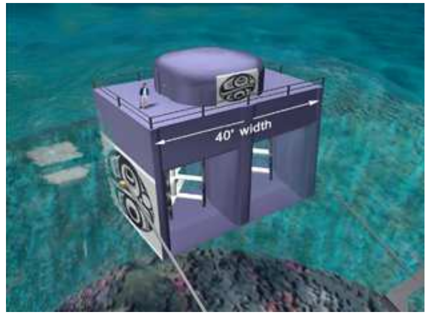


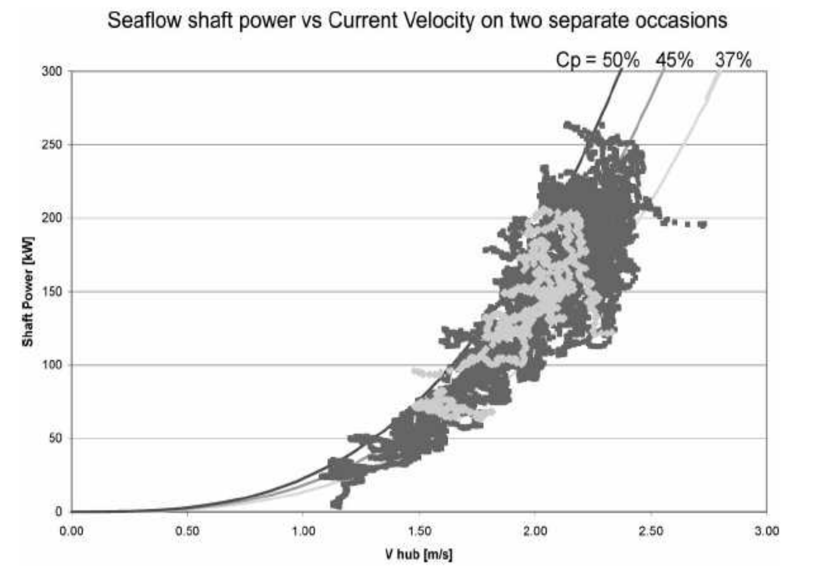
Limited number of development stage systems installed worldwide, 2003 Hammerfest, Norway, 2005 MCT Lynmouth, England.

Many developers, esp. in UK, actively exploring opportunities (also Korea, Japan, USA, Canada, New Zealand...)

On-line…

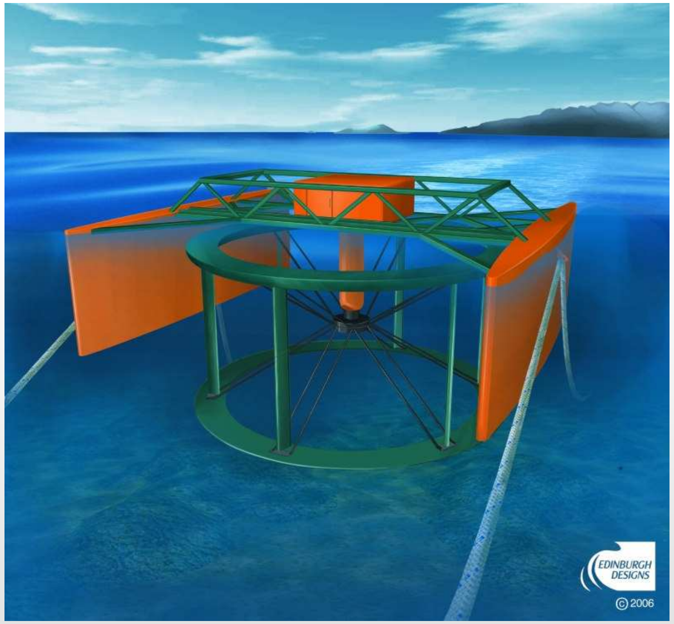
- Marine Current Turbines, Strangford Lough, 1.2MW twin HATT, rated power achieved in Dec 2008

- EMEC test site –Grid connected OpenHydro May 2008



New Designs of Tidal Energy Converters

- Horizontal Axis TT –contra-rotating
- Vertical Axis(!)



Environmental conditions and loadings

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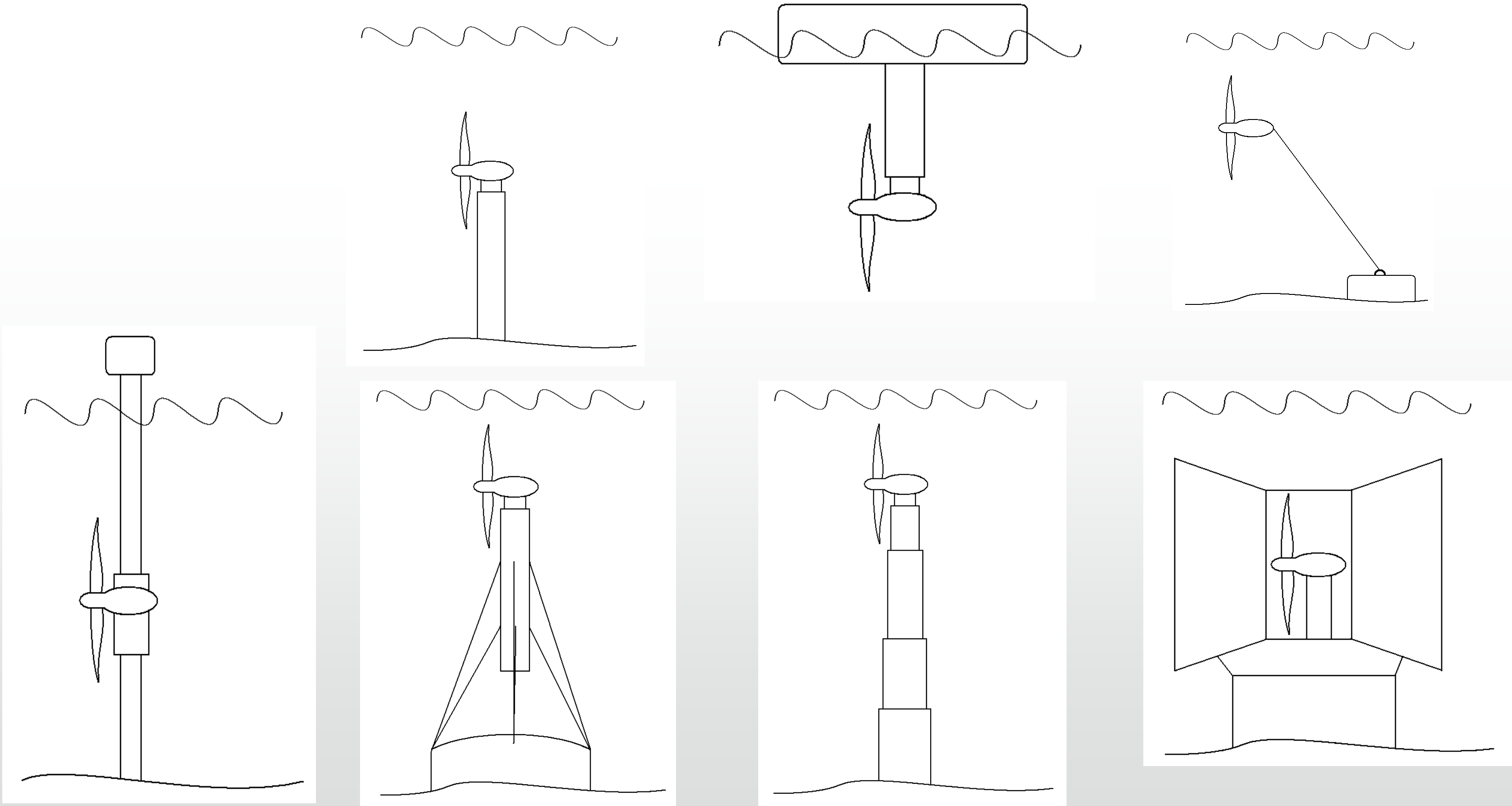
- Devices need to be secured to seabed –extraction of power from current flow results in large axial loads/moments.
- High currents give additional loadings on support structures –use of cylindrical structures will give rise to unsteady flows/vibrational response
- Wave loadings will cause variations in flow seen by blades and again on subsea support structure
- Any structure above sealevel will also be subject to wind/wave/ice loadings as for offshore wind turbines
- Scour regime can be severe – usually seabed hardened already

Structural Response

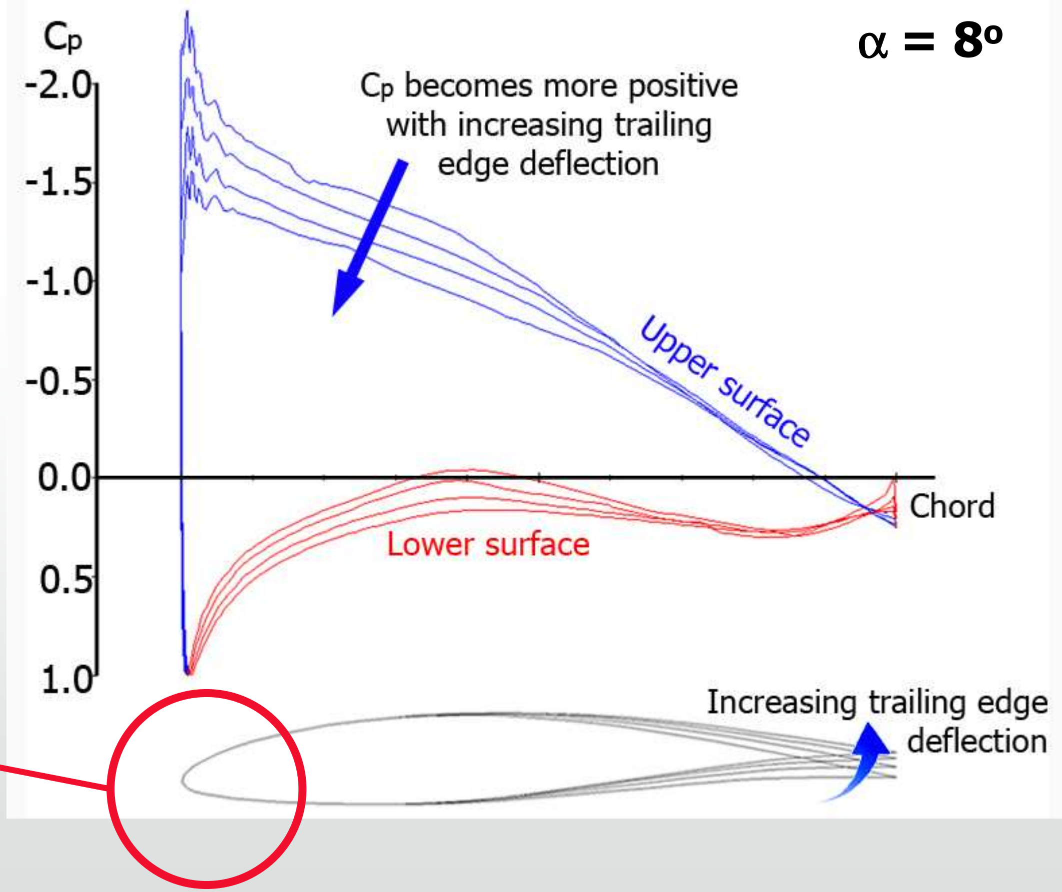
Types of structures : monopile, lattice/gantries, tripod, moored will all have individual responses to loadings

Seabed mounting/s need to be able to withstand applied vertical/horizontal forces and moments



Blade Element Momentum

- Code divides blade into 10 strips
- For each strip it ensures that there is a balance between the energy the strip extracts from the fluid flow and the drive force (torque) that causes the blade to rotate
- There will be for a given blade an optimum RPM for which maximum power can be extracted.



Marine growth degrades section performance
Eg Barnacles, Orme et al

Power Curve

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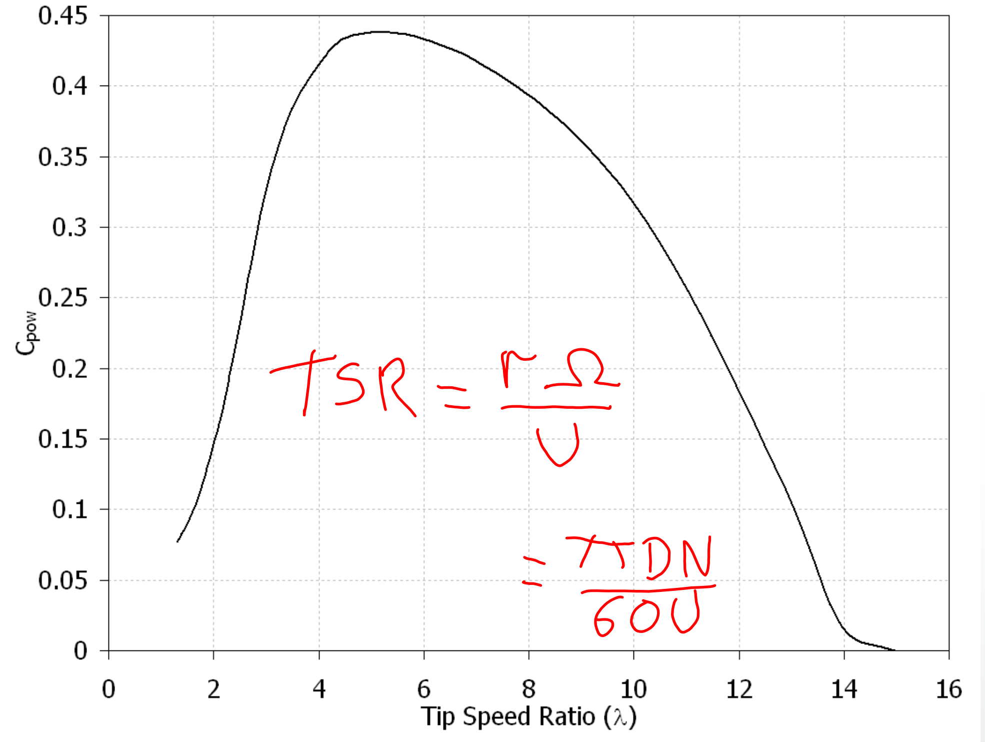
- Optimum operation occurs for a single value of 'tip-speed-ratio TSR'. This is the ratio of the blade tip speed (rΩ) divided by the local tidal current U, where r is the max radius and D=2r
- A power coefficient Cp represents the performance of a turbine at a given TSR
- It can be shown that Power is proportional to the square of turbine diameter and the cube of tidal speed.



Horizontal Axis TT Cp 0.4 -0.5?, Ct~0.8

Vertical Axis TT Cp 0.4?, Ct~0.8

$$\text{Power}=0.125\ \rho C_p\ \pi\ D^2U^3$$

$$\text{Thrust}=0.125\ \rho C_t\ \pi\ D^2U^2$$

Power Capture

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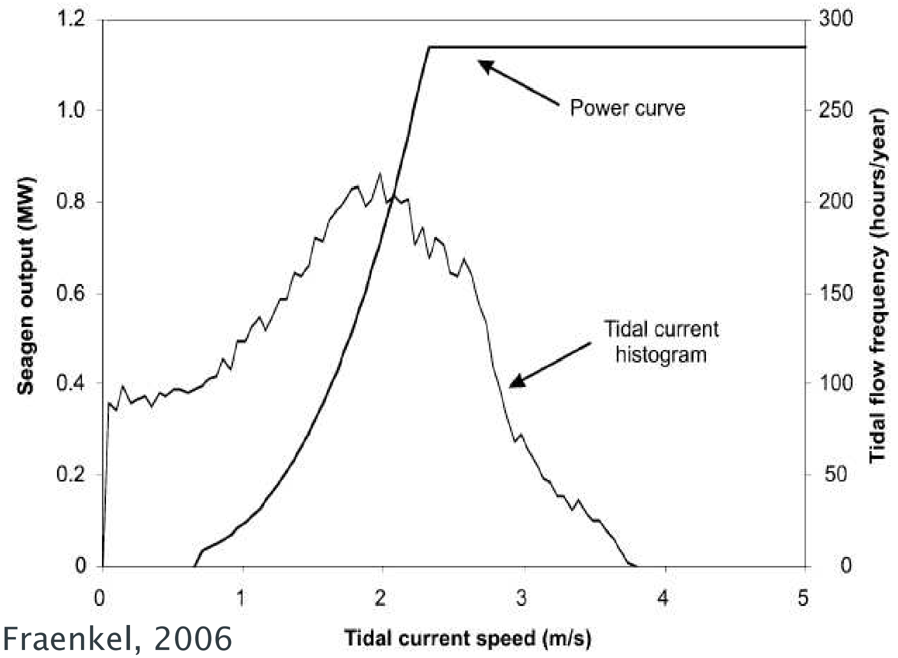
TSR ≥30.0 (slow current, <0.55m/s) it is stationary for 21.4% of lunar tidal cycle and generates no power

TSR ≥20.0 (modest current, <0.9m/s) it operates for 13.5% of time but generates 1.2% of power

TSR ≥10.0 (reasonable current, <1.78m/s) it operates for 44.2% of time and generates 36% of power

TSR<10.0 (high current, <2.5m/s) it operates for only 20.9% of time but generates 62.8% of total power.

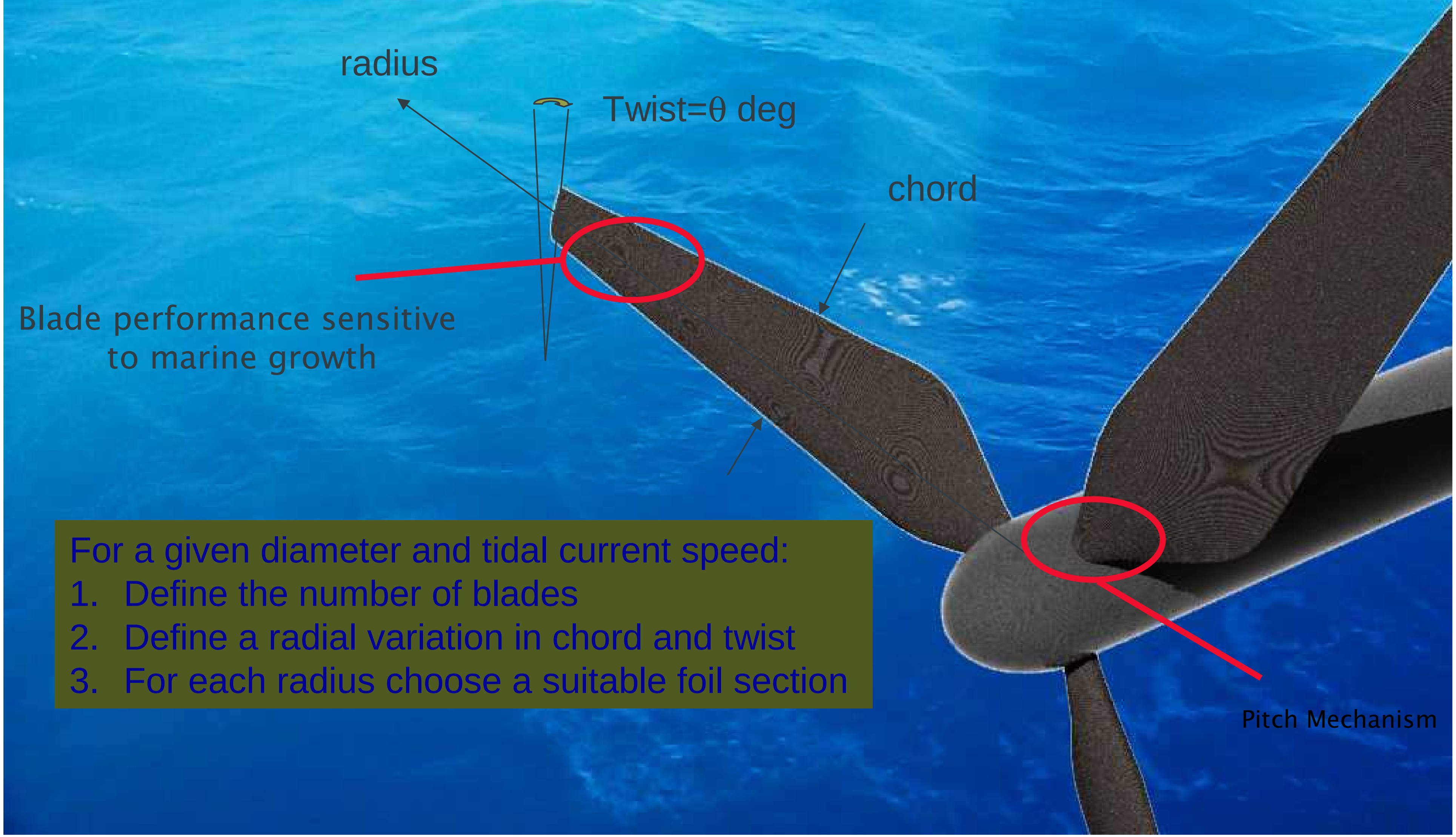


Fraenkel, 2006

Is it better to turn turbine over all the time to reduce marine growth or to start at high cut-in speed to reduce mechanical wear on drive train?

How to design a blade?

[O(7) cycles for fatigue]



For a given diameter and tidal current speed:

1. Define the number of blades
2. Define a radial variation in chord and twist
3. For each radius choose a suitable foil section

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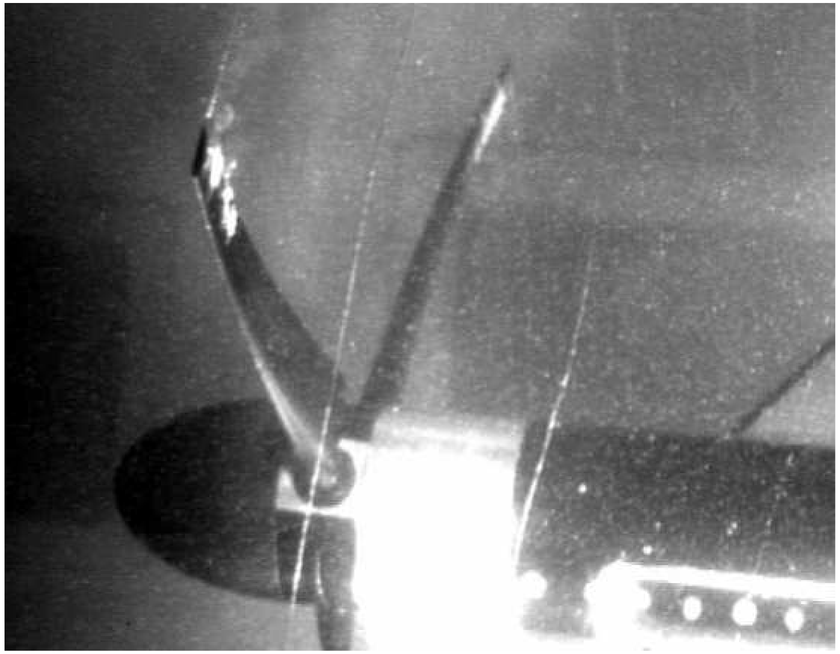
Cavitation limits tip speed



Bahaj et al 2007

$$\sigma = \frac{P_0 - P_V}{0.5\rho V^2} = \frac{P_{AT} + \rho g h - P_V}{0.5\rho V^2} = -C_P$$

For typical tip speed limit of 17-20ms/,

Blade chord Reynolds Number of O(6), Cf~4x10^{-3}

Shear Stress >O(2) N/m^2

Materials in Marine Energy

“ Wave / tidal power are areas in which increased investment is likely to lead to step change breakthroughs ’’ [UK Gov. Energy White Paper 2003]

Current materials status:

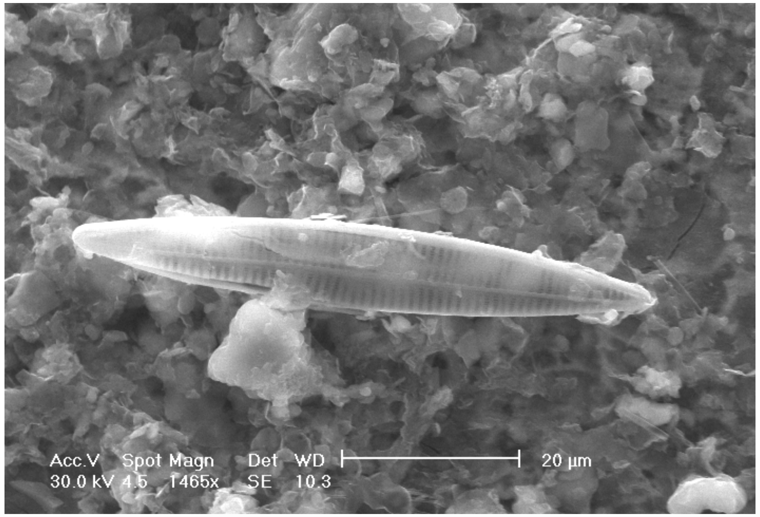
- Materials currently exist for water turbines and wave power. However, due to seawater corrosion and heavy seas, designers tend to over engineer resulting performance penalties. Corrosion, erosion and cavitation issues still remain technical challenges.

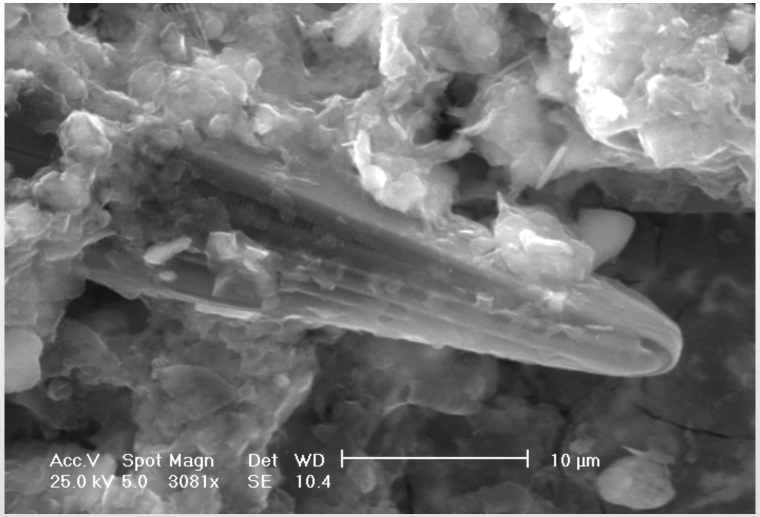
Key advances in material performance:

- Existing materials need optimising, with robust design criteria and improved life prediction methods.
- Composite materials offer higher corrosion resistance and condition monitoring. Materials knowledge maybe transferable from existing marine technology.
- Relevant materials technology is already available.

Biofouling

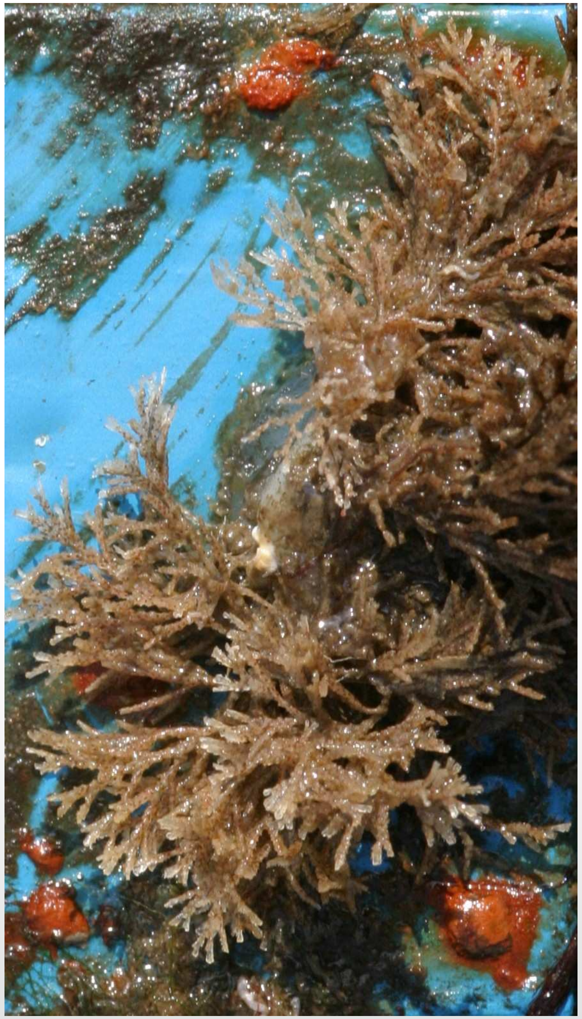
- **Physicochemical interactions – microorganisms and solid surfaces**
  - Control of these interactions leads to management of cell attachment, survival and biofilm formation.
  - Free energy of surfaces (wettability) are believed to be important – max. attachment is reported to occur for surface energies between 20 – 27 mN.m^{-1}.
  - Interfacial van der Waals forces, electrostatic and hydrogen-bonding will influence attachment mechanisms.
  - Practically all surfaces are colonised with a biofilm sooner or later.



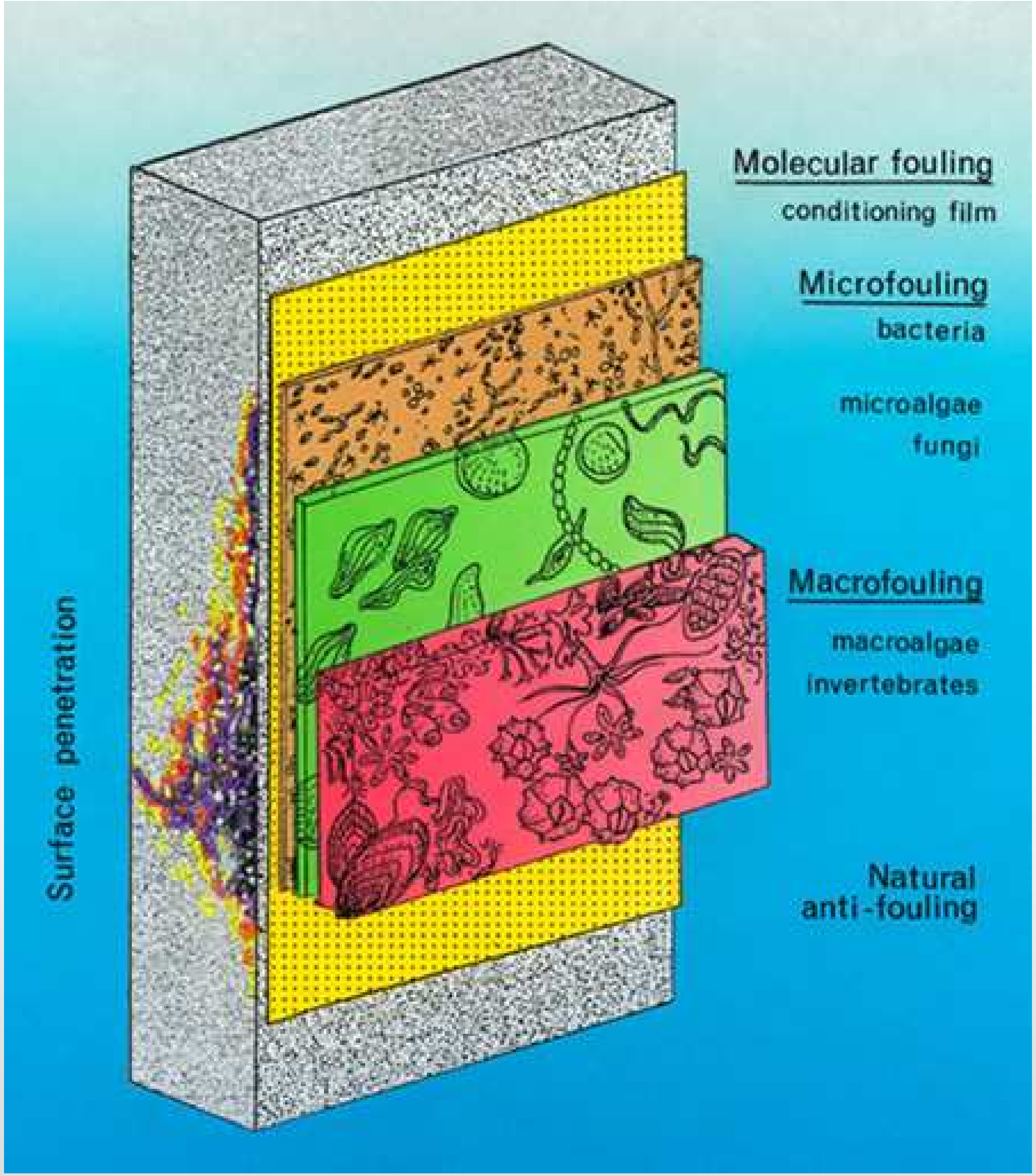


Marine Growth

- The extent of marine growth depends on a number of different factors such as the geographic location, season of the year, water chemistry, temperature, substratum type, sunlight, distance from the shoreline and conditions of turbulence.
- Microbial biofilm attachment has been observed at wall shear stresses in the order of 100 to 300 N m^{-2} [Duddridge, Finlay].
- Biofilms formed under high fluid velocities are thinner and denser in structure or consist of cell clusters which exhibit a greater resistance to detachment than single cells [Finlay, Melo, Wijeyekoon].



Will growth inhibit sensors, degrade blade performance, impair seals, damage mechanisms?



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- Challenges for coatings are durability and their own response to high shear regime
- What is replacement period?

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Material properties

- **Metals**
  - Biofilm formation occurs on all metals – copper-based alloys have a degree of inherent antifouling capability (natural toxicity to marine organisms).
  - Anticorrosion and antifouling coatings.
- **Composites**
  - Polymers contain additives, pigments, stabilisers to improve physical and chemical properties – these may leach out and become nutrients.
  - Often biofouling is reported to be as much as four times greater than for stainless steels.
  - Antifouling agent incorporated into composites.

Materials used for Seagen (Douglas et al) Life Cycle Assessment

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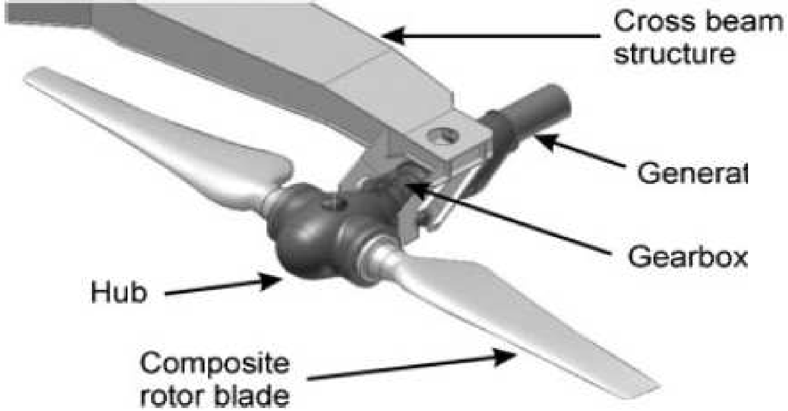


Fig. 5 Seagen power train

Table 1 Technical specifications of Seagen Marine Current Turbine

Parameter	Value
Rated power	1.2 MW
Capacity factor	48%
Rotor diameter	16 m
Design life	20 years
Reliability	$>$90%
Overall efficiency	89%
Design rotor power coefficient	0.45
Cut-in speed	0.7 m/s
Rated speed	2.25 m/s

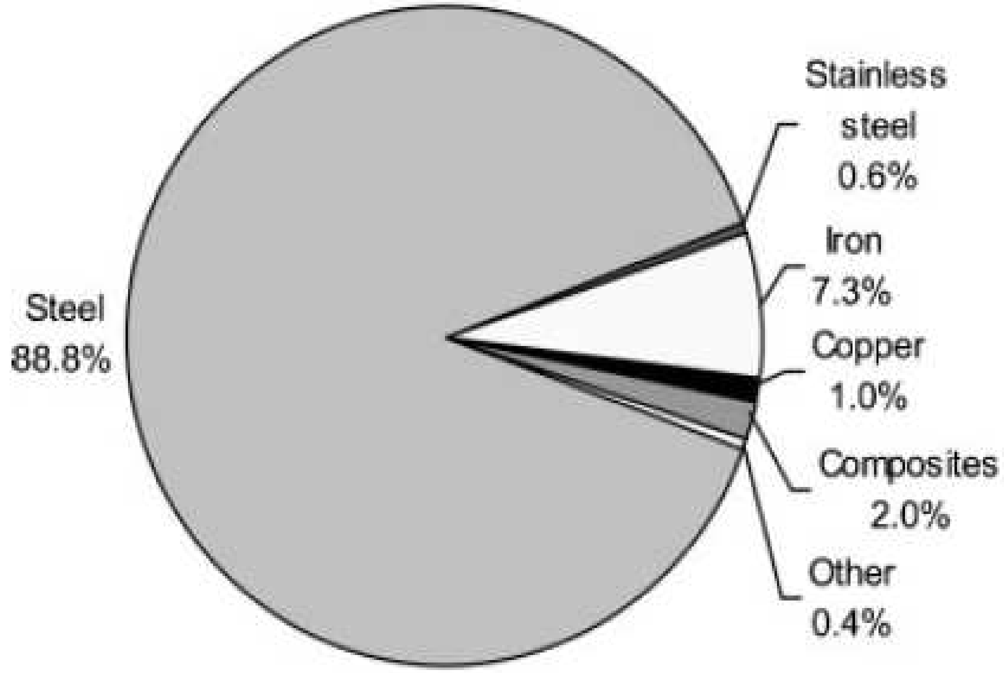


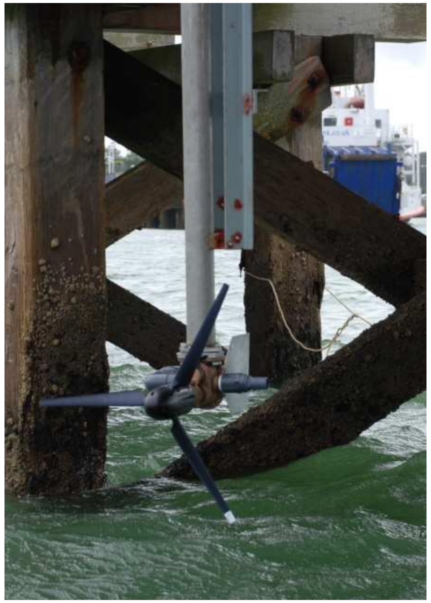
Fig. 4 Mass breakdown of Seagen turbine

dti

ECONOMIC VIABILITY OF A SIMPLE TIDAL STREAM ENERGY CAPTURE DEVICE

CONTRACT NUMBER: TP/3/ERG/6/1/15527/REP

URN NUMBER: 07/575



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- Aim was to examined economic viability of alternative HATT designs based on simplifying mechanical design:
  - Remove ability to follow current direction
  - Remove ability to pitch blades

- Is trade-off in reduced capital cost and O&M paid-back from greater availability compensating for loss of energy capture?

- Log+1 et al, 2007

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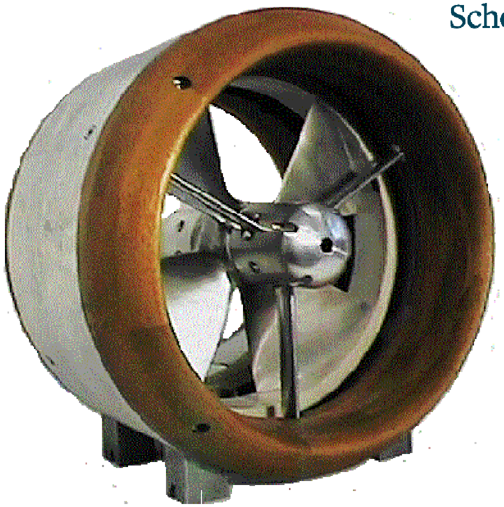
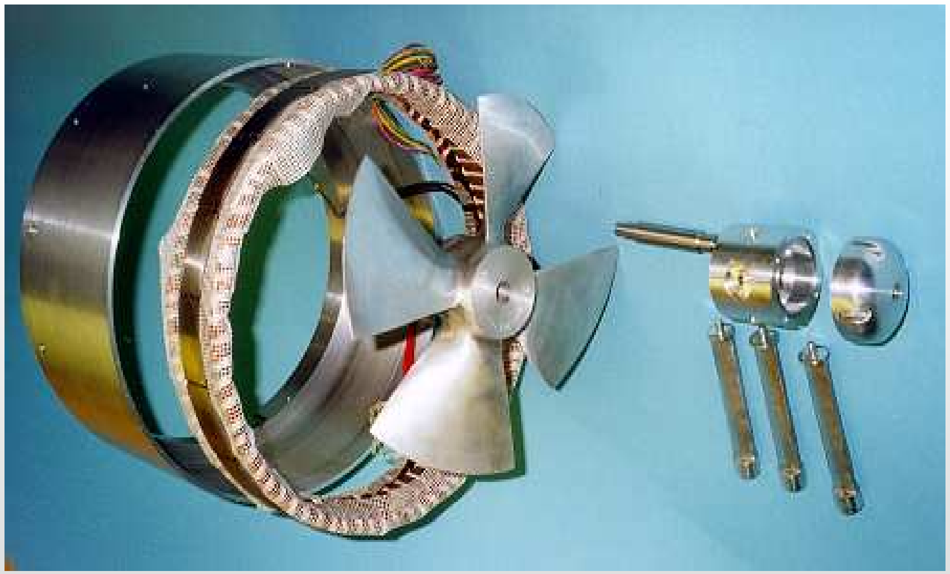
Effect of Yaw?

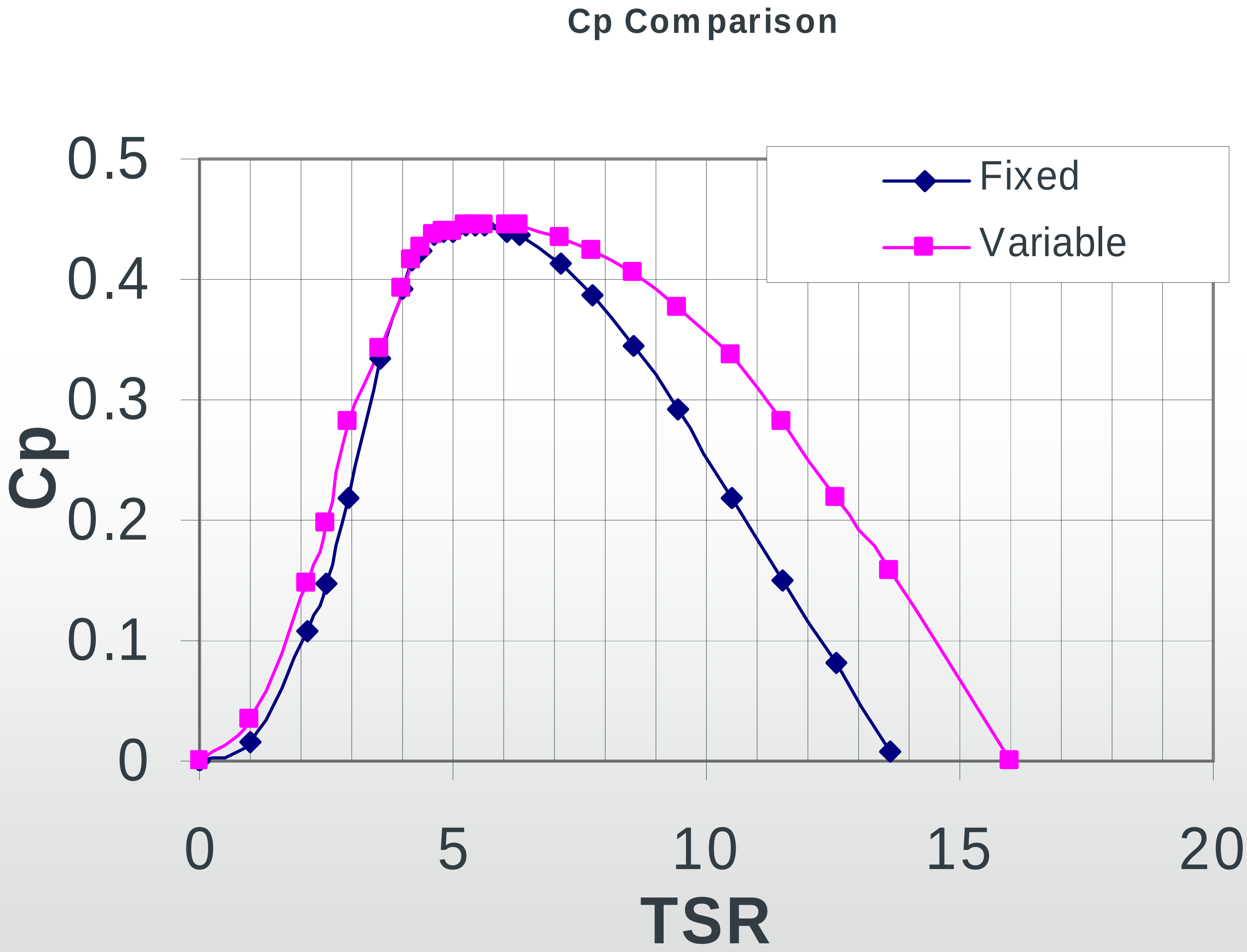
Fixed Orientation

- Well represented for off-axis flow by $\cos^3\phi$
- More important is bi-directional nature of flow
- Is it better to use section designed to operate in one direction and accept poorer performance in other, Or
- Design section to work well in both directions…
- Abu-sharkh et al 2002





Horizontal Axis Tidal Turbines



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HATT Basis

- What was common?
  - Same (monopile) support structure with single turbine
  - Assumed 40m depth, 20m diameter, max tide 2.5m/s
  - Effect of local yaw negligible

Power Capture Control
– power electronics vs mechanical complexity

- Fixed Pitch blade, Fixed RPM generator
- Fixed Pitch blade, Variable RPM generator
- Variable Pitch Blade, Fixed RPM
- Variable Pitch Blade, Variable RPM

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Basis of Study

Parameter	Value	Unit
Generator rated power	1	MW
Maximum tidal current – spring tide	2.5	m/s
Ratio of peak spring tidal current speed : peak neap tidal current speed	2.0	-
Rotor diameter	20	m
Maximum nacelle diameter	4	m
Maximum nacelle length	10	m
Water depth	40	m
Number of blades	3	
Transmission voltage	33	kV
Cable distance from device to shore	5	km
Number of devices per farm	30	

Effect of pitch system/rated generator

Energy per lunar month -MWh

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Diameter	Rated Power +10%	BI-DIRECTIONAL DESIGN		VARIABLE PITCH DESIGN			
m, [hub/D =0.2]	MW	Fixed RPM (14.0)	Variable RPM	Fixed RPM (17.0) Variable Pitch	Variable RPM, Variable Pitch	Fixed RPM (17.0) Constant Pitch	Variable RPM Constant Pitch
20	1.1	114	160	169	177	166	177
20	0.75	90	151	158	163	156	163
20	1.25	114	161	169	178	167	177

Note: *The total capacity is taken to be the rated power over 29.4 x 24 hours. For the three rated generators of 1.14, 1.0 and 0.68 MW the energy they could have absorbed would be 0.802, 0.704, 0.481 GWh respectively.*

For the purposes of the economic assessment hydrodynamic capacity factors of ***23%(****bi-directional) and* ***25****%(variable pitch) based on a rated* ***1MW*** *generator capacity*

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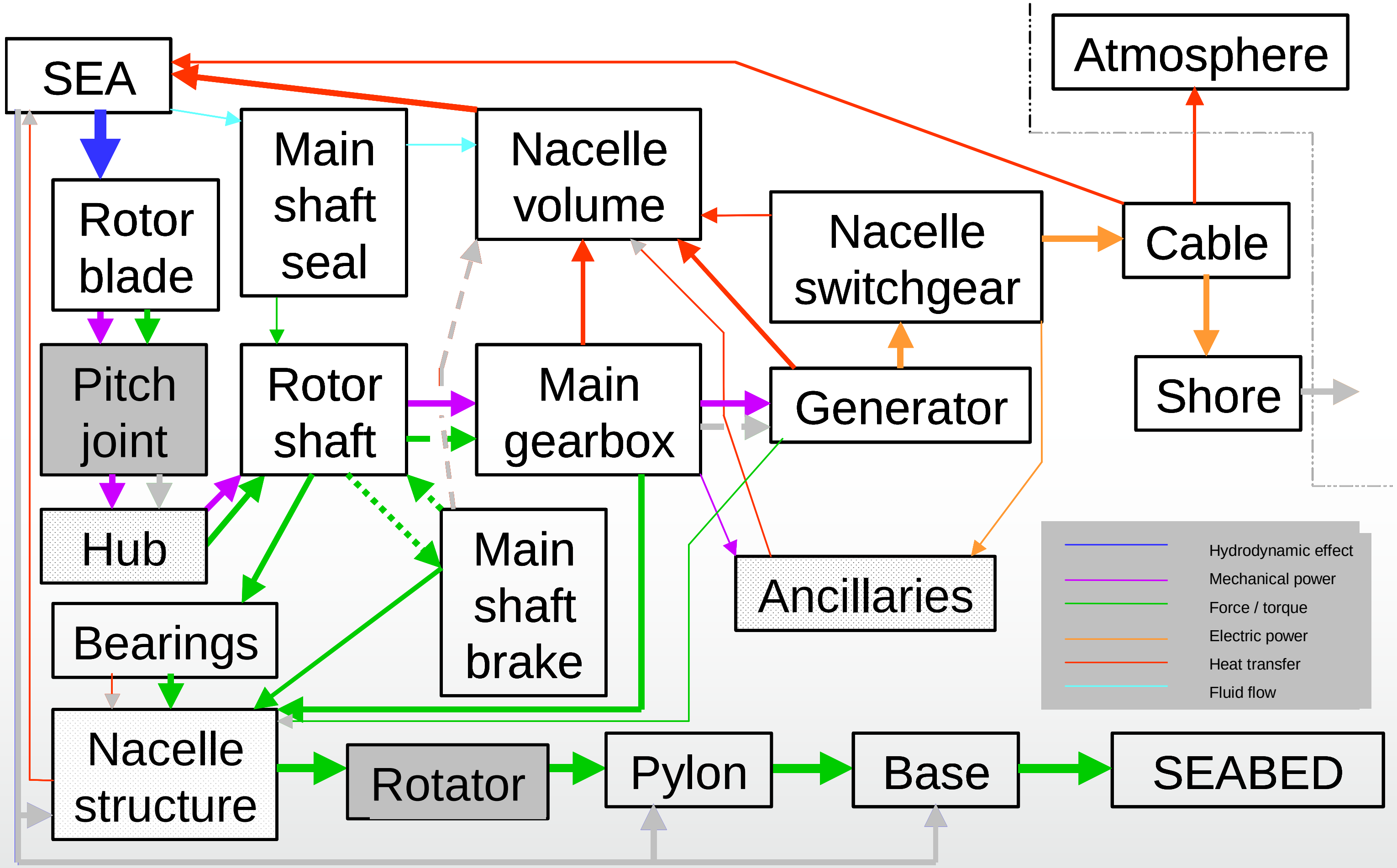

Components specific to variable pitch device

Components differing between fixed- and variable –pitch devices

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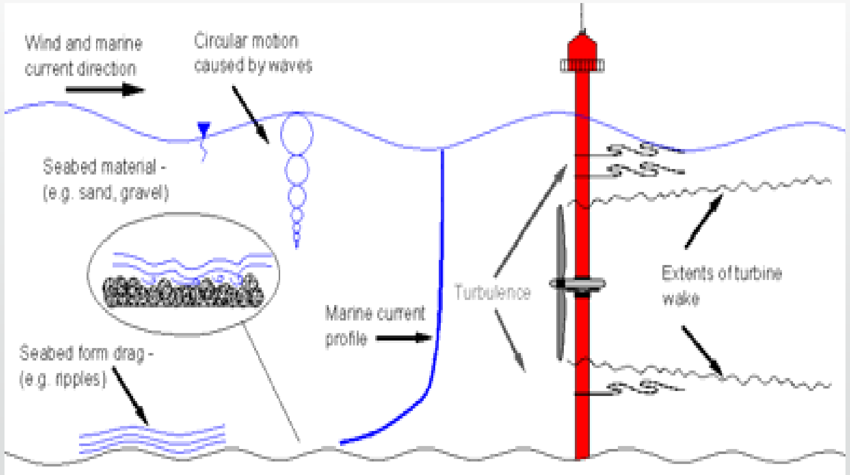
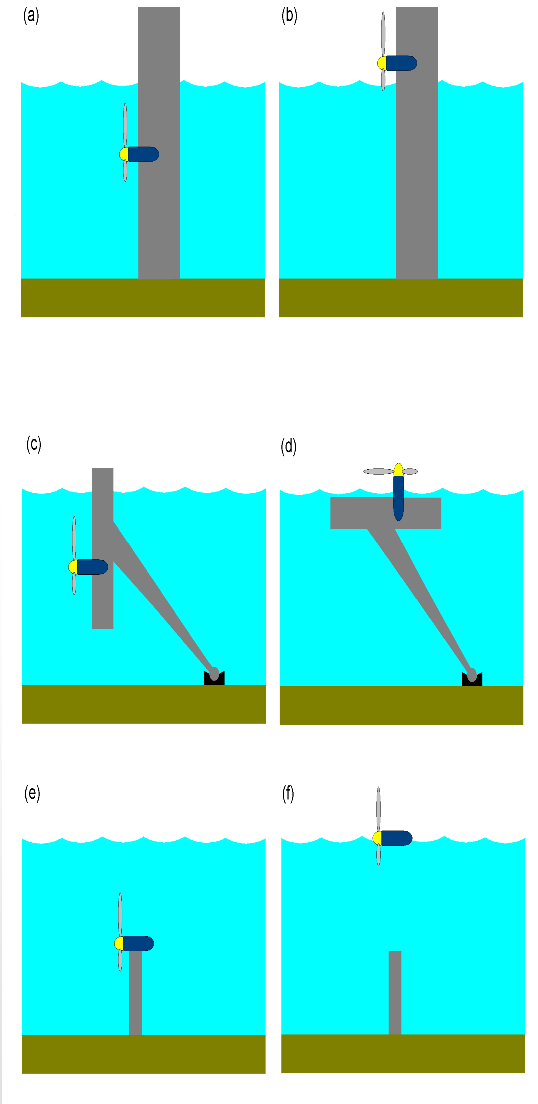
Assumptions…

- Farm scale architectures
- For farm of 30 can connect to 33kVA grid
- Remote control
- Major components in nacelle along with rotor blades all are considered as a single replacable unit





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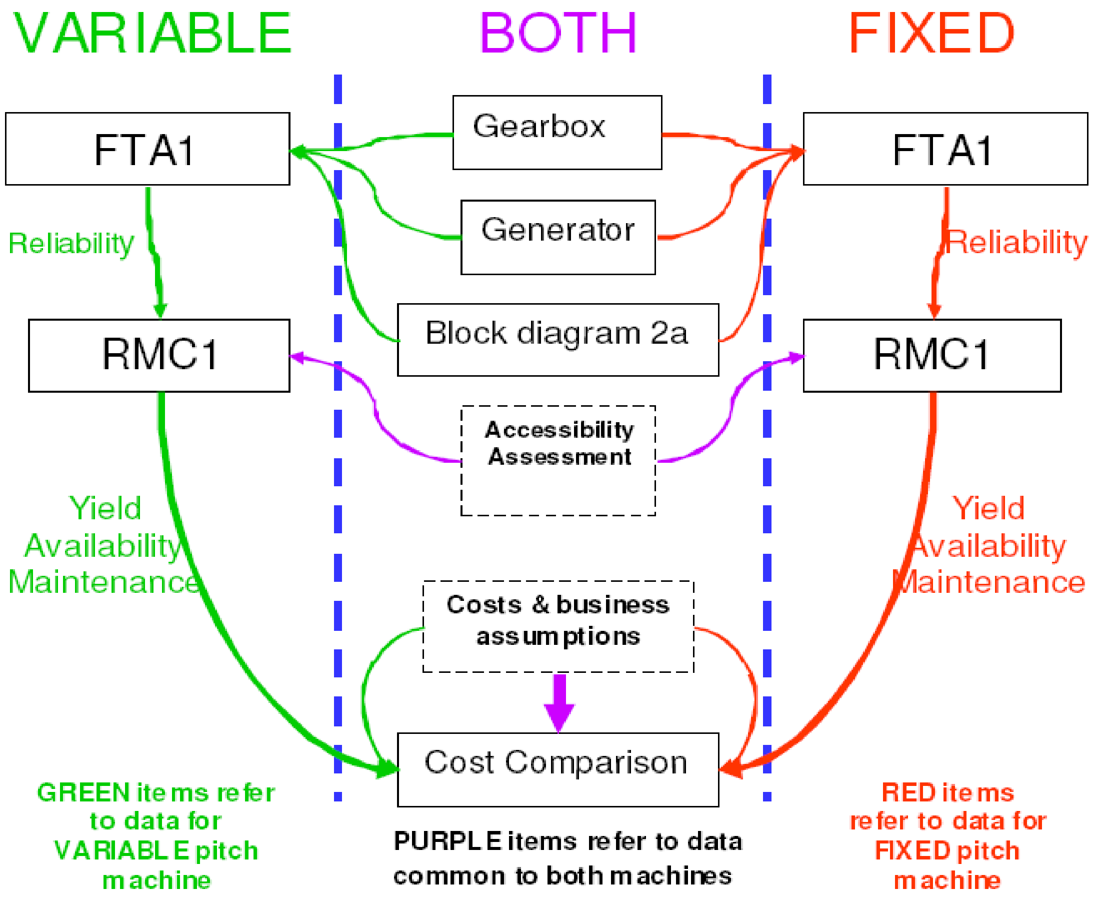
FTA

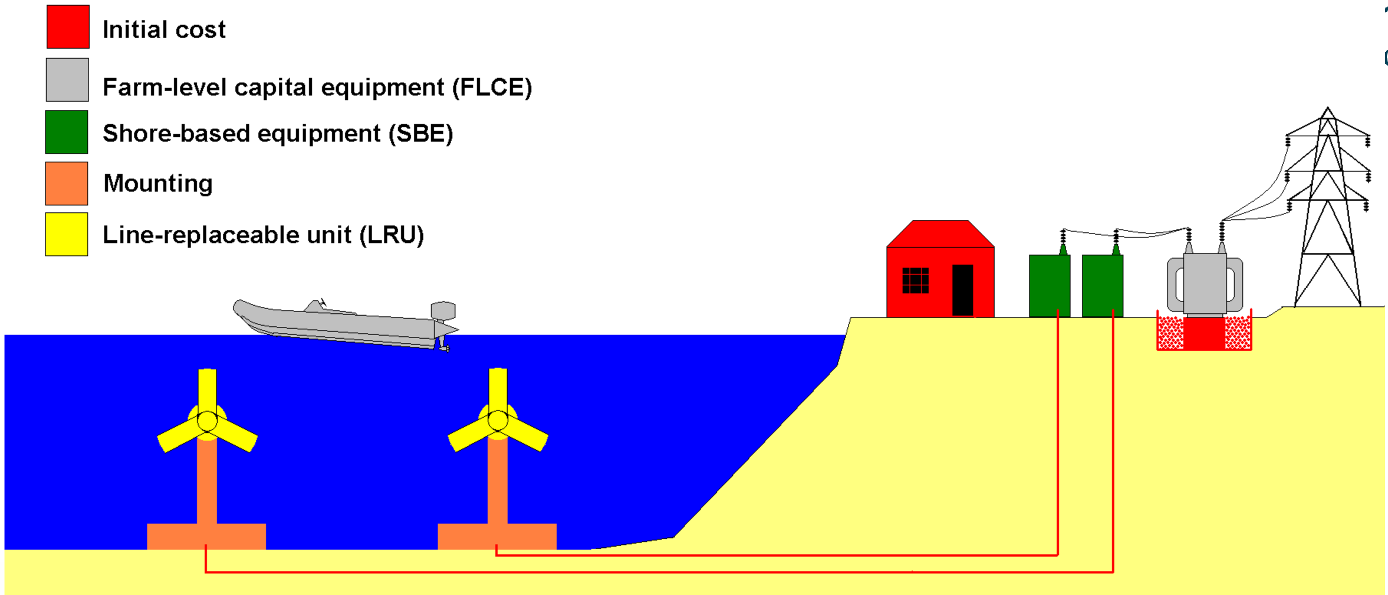
Fault Tree Analysis

RMC1

Monte carlo analysis



OREDA Data	No of failures *		Unplanned Availability	
	Fixed	Variable	Fixed	Variable
Mean	52	71	92.6%	90.1%
Max	143	194	81.1%	74.5%
Min	3	5	99.6%	99.4%



Assumptions	Units	Fixed Pitch Farm	Variable Pitch Farm
Rated Plant capacity	MW	30	30
Capacity factor	%	23	25
Plant life	Years	15*	15*
Year cost base		2006 £	2006 £
NPV discount rate		10%	10%

15 years for principal LRU life, other elements have longer assumed lives.

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Cost Estimates

Cost Item		Number per farm		Farm cost	
	Cost	Fixed	Variable	Fixed	Variable
Initial set-up cost	£ 3,750,000	1	1	£ 3,750,000	£ 3,750,000
Farm Level Capital Equip,	£ 4,500,000	1	1	£ 4,500,000	£ 4,500,000
Shore Based Equip.	£ 150,000	15	15	£ 2,250,000	£ 2,250,000
Mounting - Fixed	£ 300,000	15		£ 4,500,000	
Mounting - Variable	£ 322,500		15		£ 4,837,500
Line Replacement Unit - Fixed	£ 750,000	30		£ 22,500,000	
Line Replacement Unit - Variable	£ 806,250		30		£ 24,187,500
			Total	£ 37,500,000	£ 39,525,000
			Cost/MW	£ 1,250,000	£ 1,317,500

Table 8.3 Cost estimates

Fixed pitch machine used as basis
– variable pitch estimated as 5.4% more expensive

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Operation and Maintenance

Operation and Maintenance	Intervals	Fixed Pitch Total Cost (2006 £)	Variable Pitch Total Cost (2006 £)
Routine O&M (per MW/year)	p.a.	£37,500	£40,300
Major servicing	5 yrs	included in above	included in above
	as required	£24,000	£25,700
Fixed annual farm running cost	p.a.	£320,000	£320,000
Rates	p.a	included in above	included in above
De-commissioning costs, per mounting	At yr 25 after mounting commissioning	£25,000	£25,000

Table 8.4 Operation & maintenance assumptions and estimates

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Cost of electricity

- Used unscheduled availabilities, hydrodynamic capacity factor, and scheduled availability of 15 years
- Mean failure rates gives 53Gwh(fixed) 55Gwh(variable). For max failure rates energy production drops by 12% and minimum increases by 8%
- Base case gives

	10 year	15 year	Range(15 years)
fixed	£119/MWh	£94/MWh	£55-150/MWh
variable	£129/MWh	£104/MWh	£55-188/MWh

Outcomes

- Variable pitch machine (10% better) produces more energy in a given period unless reliability is very low
- Fixed pitch always offers lower initial capital cost and unplanned maintenance costs
- Fixed pitch always offers lower cost per unit except if very high reliability
- Fixed pitch offers more robust design concept (within limitations of study)
- However, assumptions as to actual time between maintenance and what is actually required strongly influence cost model.

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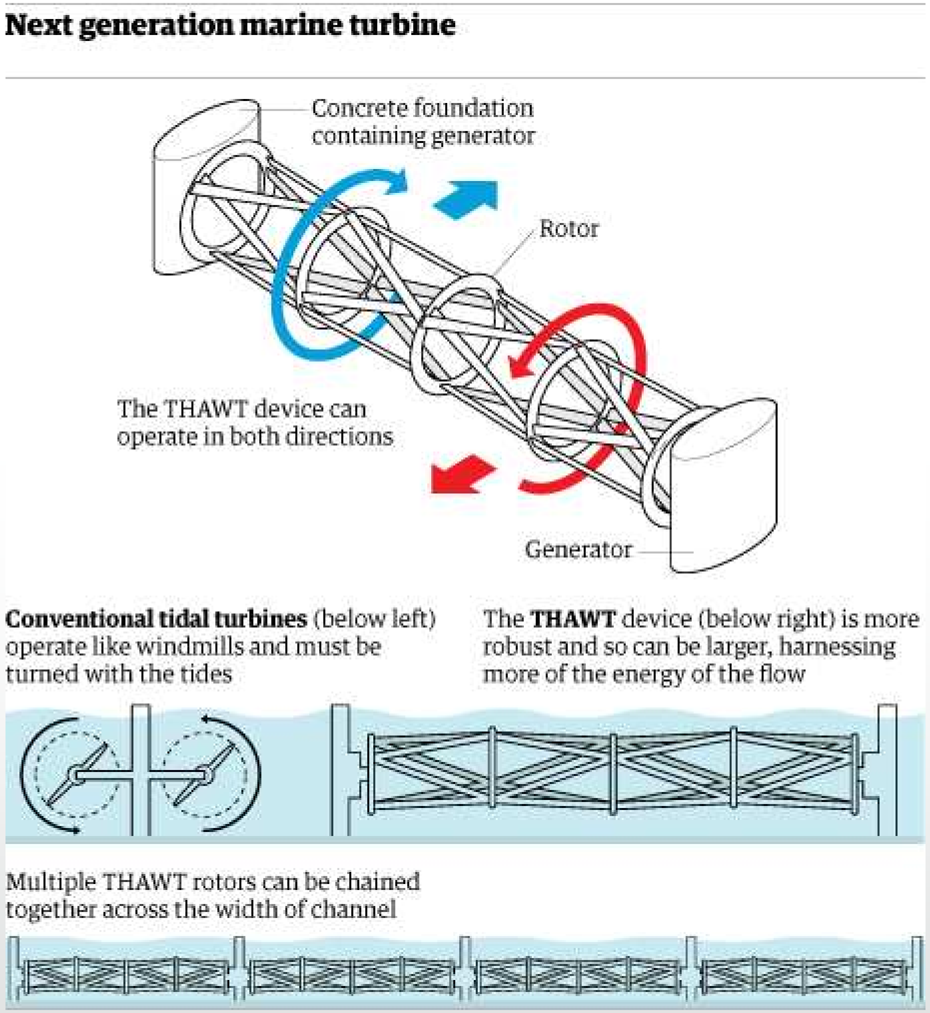
Future Designs?

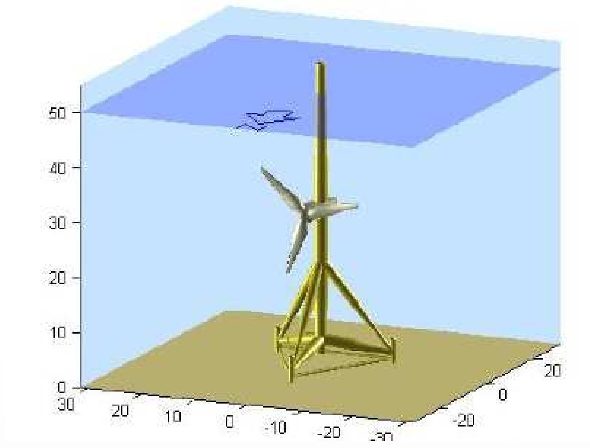
- Structure still has to withstand thrust loading (Ct~0.8?)
- Is capital/installation cost of end structures cheaper than multiple monopiles
- Most uncertainties due to lack of in-water experience

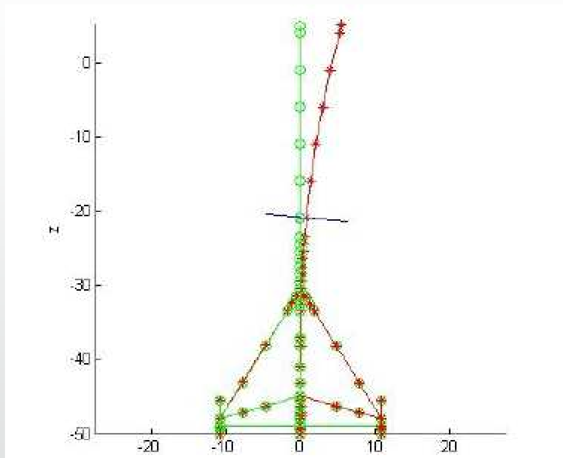


Oxford University press release, 2009

Concluding Remarks

- Tidal turbines offer an exciting opportunity to exploit ocean current flows to generate sustainable energy.
- However, a key to their success is the ability to operate with minimal intervention in the ocean over extended periods (15-20 years).
- This talk explored the likely design and operational issues that will influence satisfactory performance associated with material corrosion and biofouling.
- Main difficulty is that turbine economic viability is capital driven so whole system, including operation and maintenance needs to be as cheap as possible
- Although can use approach from ship design and offshore industry need to appreciate cost-drivers are different. 'Gold plated' technology approach from oil and gas industry may not deliver cost-effective solutions





McCann et al

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- Figures used from public websites and information from references quoted or directly from publications listed below. The main sources are

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