Hydrodynamic and Structural Performance of the Transverse Horizontal Axis Water Turbine

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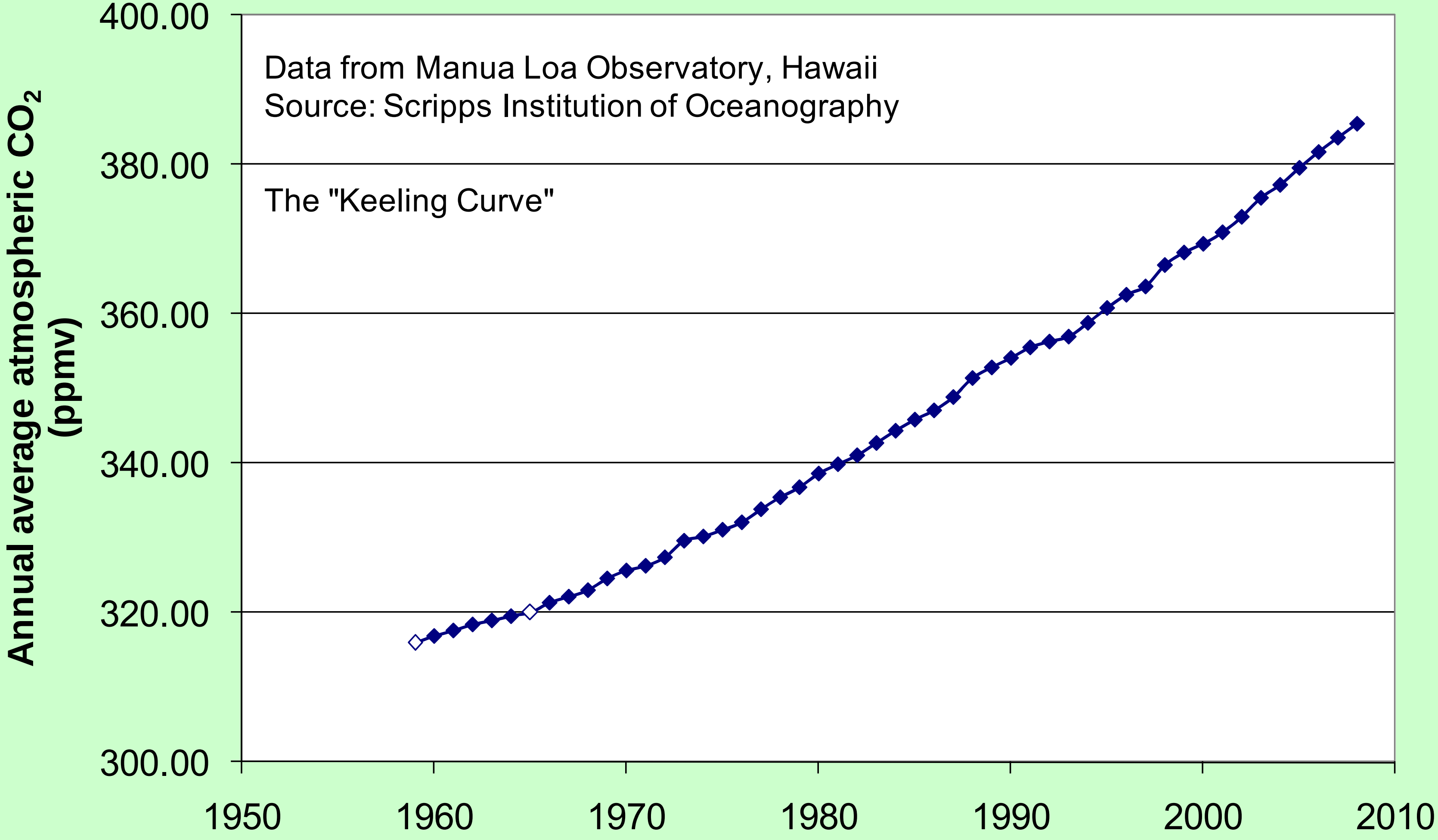
Research and Industry Workshop, University of Leicester
6th May 2011

Outline

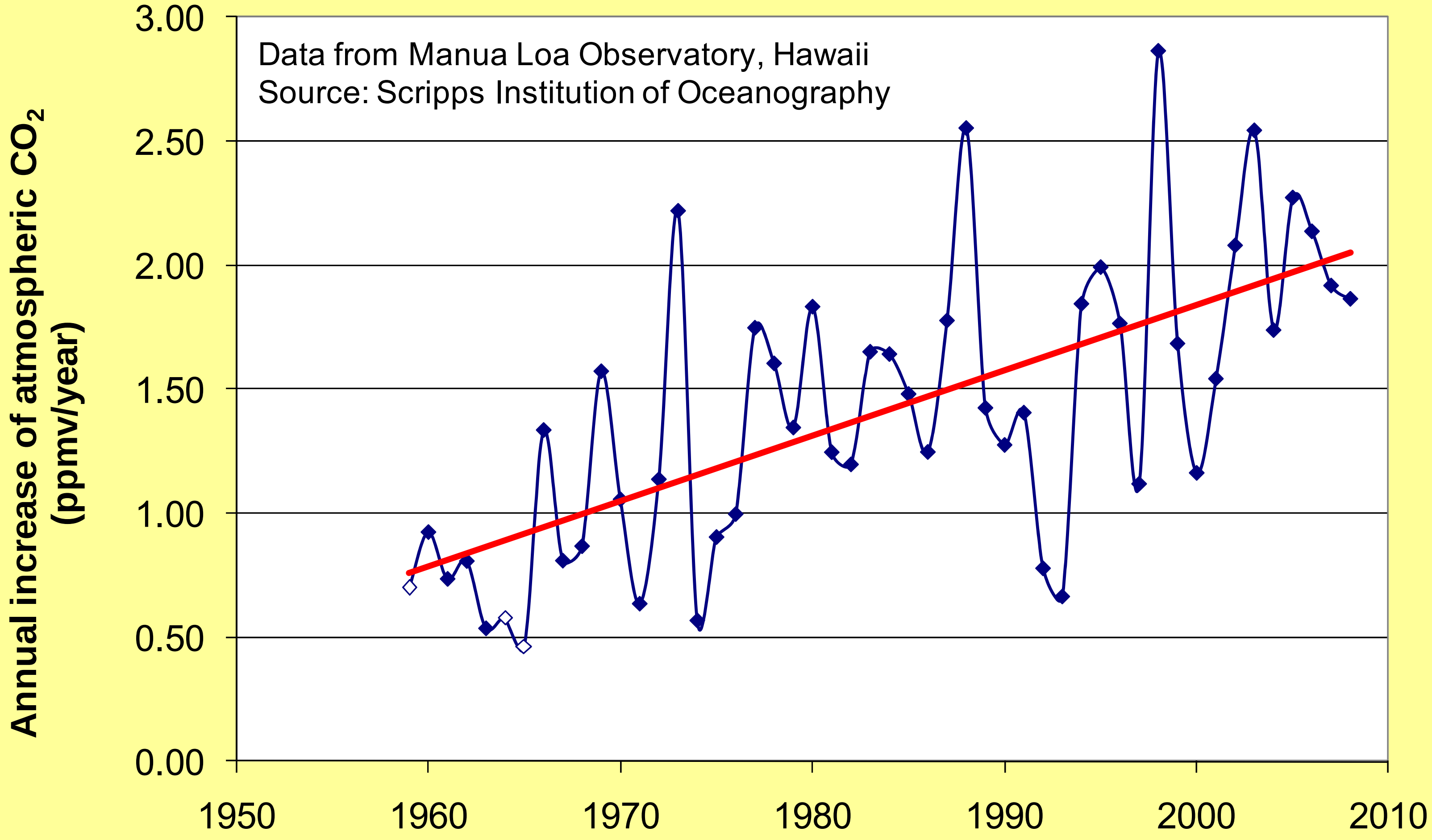
- Why renewable power?
- Why tidal stream?
- The THAWT concept
- Betz limit can be exceeded
- 1/20th Scale tests: hydrodynamics
- CFD adds understanding of flow
- Loads on blades

Increase of atmospheric CO_2

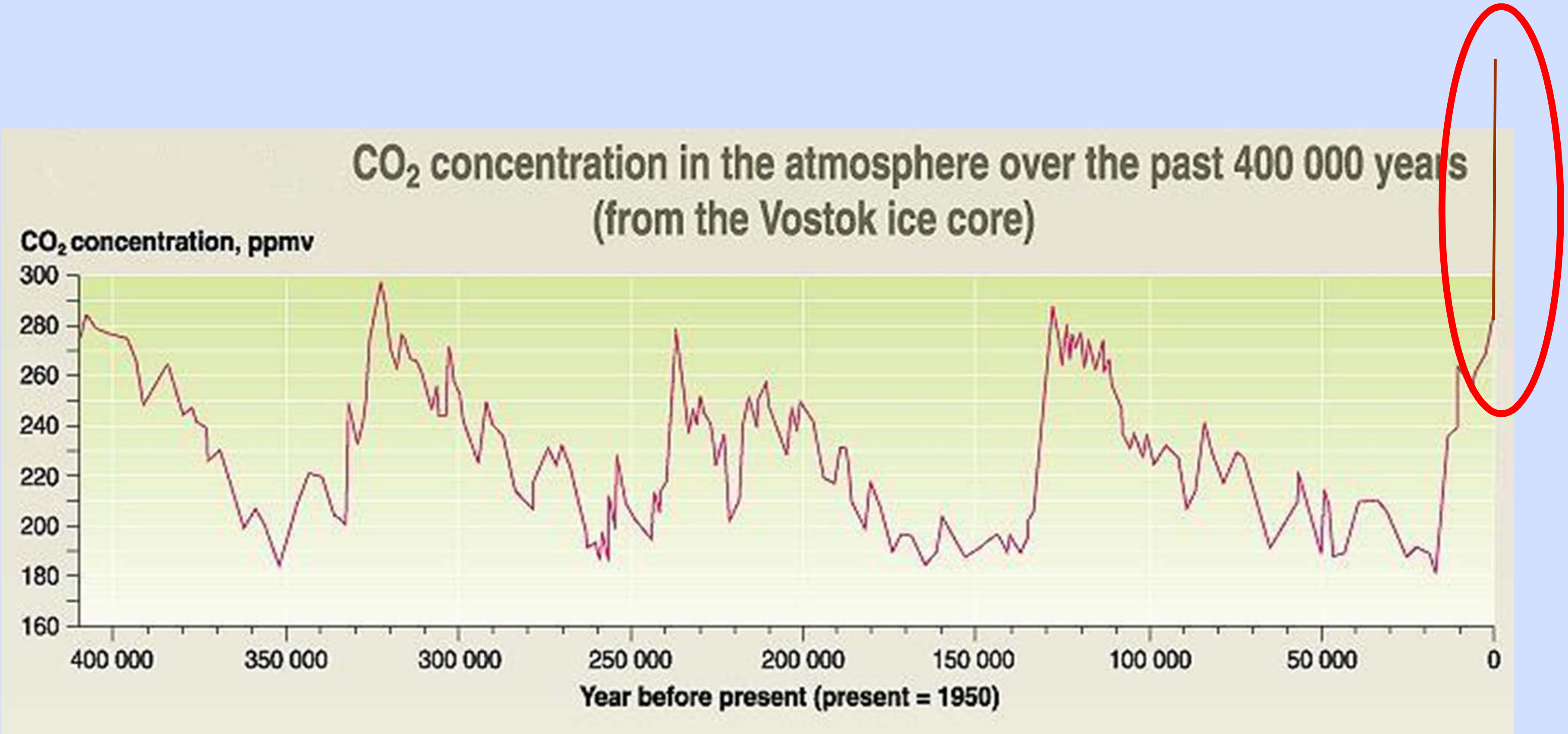


May 2009 – first monthly average over 390 ppmv

Increase of atmospheric CO_2

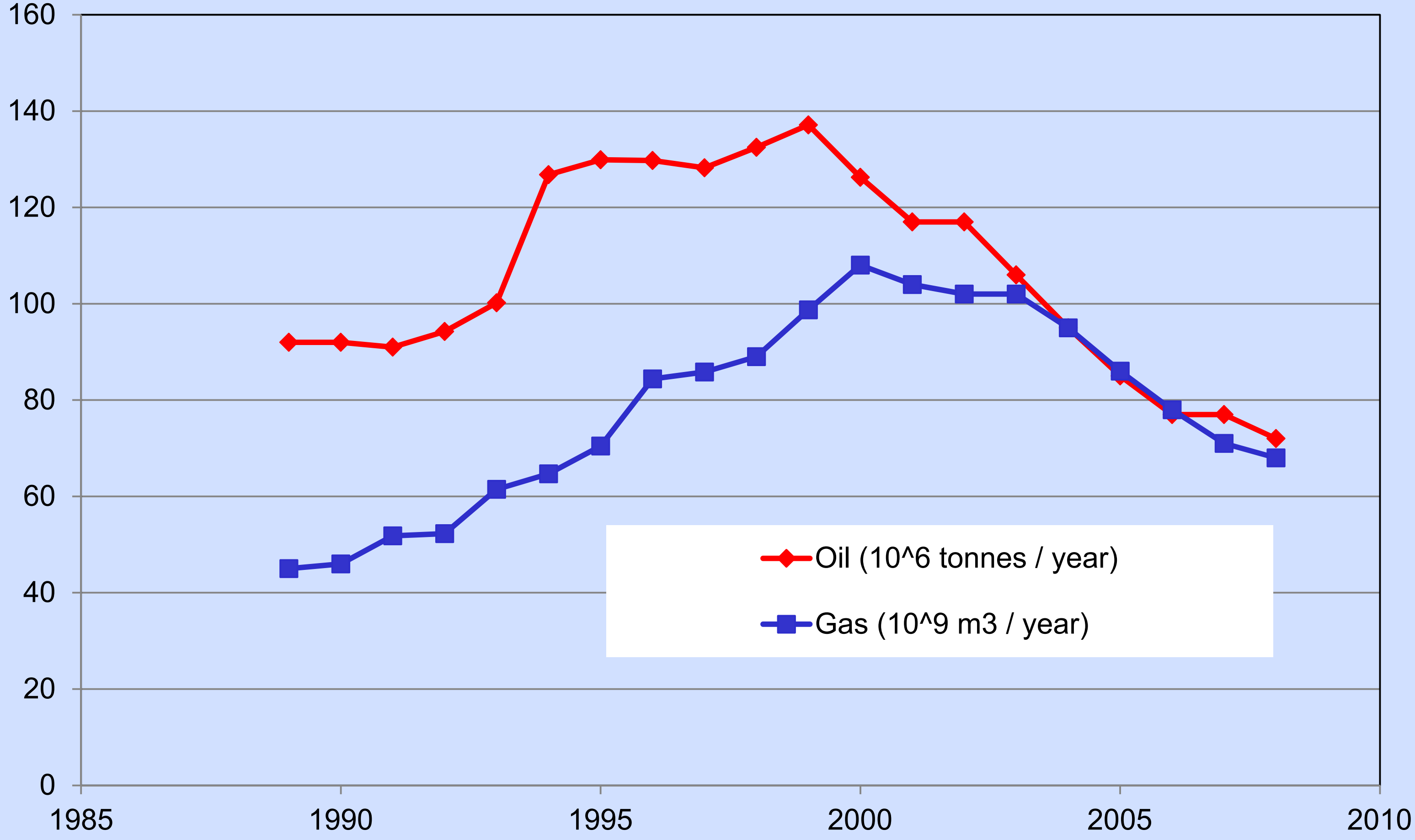


Historical records of atmospheric CO_2



Source: GRID-Arendal (United Nations Environment Programme)

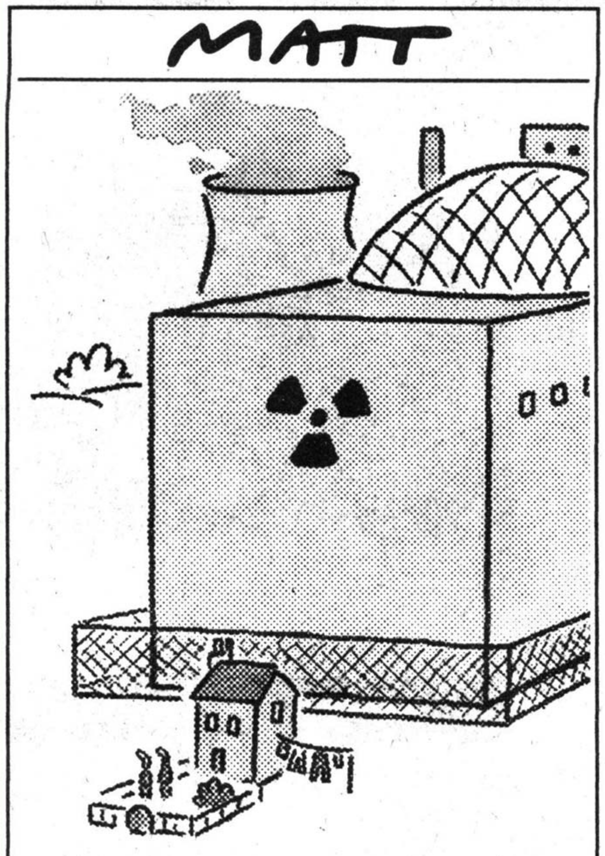
UK oil and gas production



Source: Office for National Statistics

Problem:

- Climate change due to fossil fuel use
- Diminishing supply of hydrocarbons



'Thank goodness you stopped that wind farm being built'

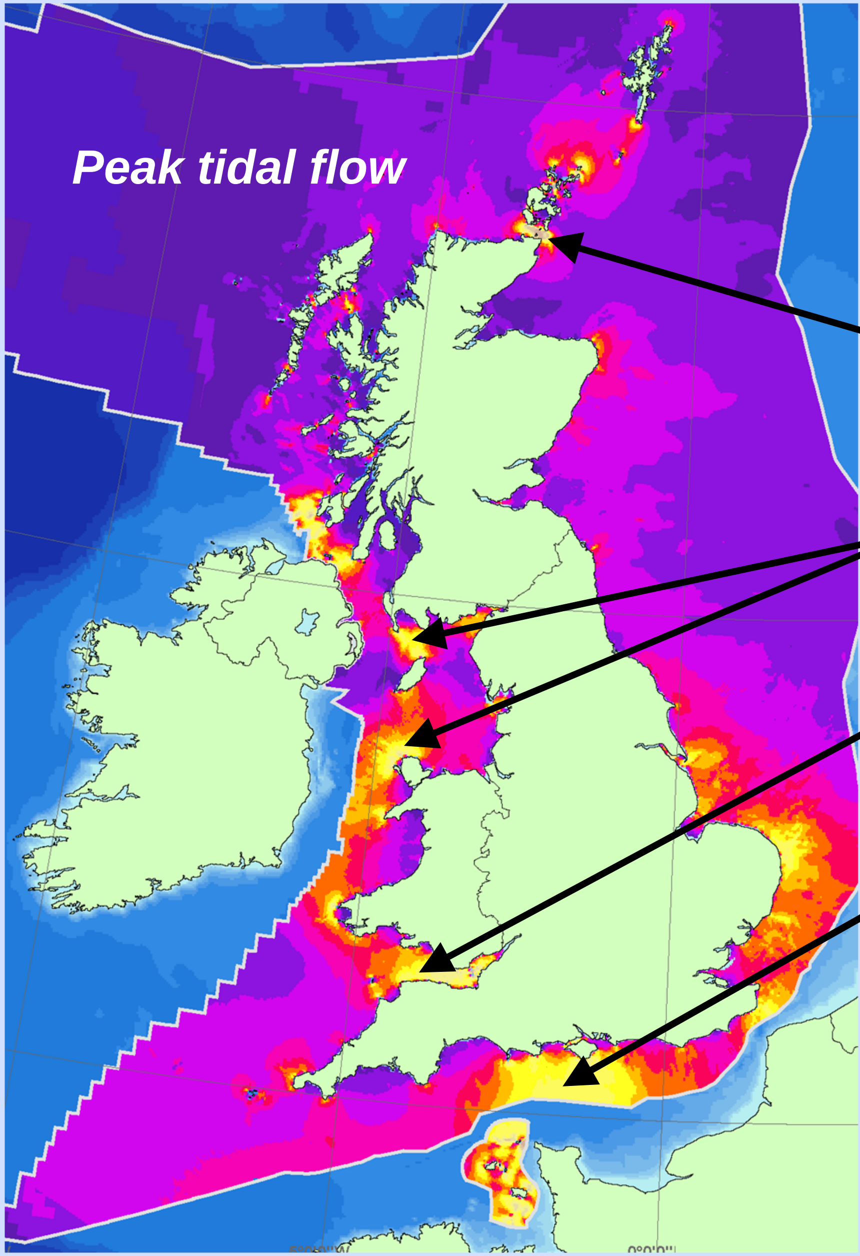
Solution:

- Nuclear
- Renewables

Why Tidal Stream Energy?

- Potential to supply at least 18TWh/yr (6%) of UK electricity requirements (source: Black & Veatch/Carbon Trust)
  - Minimal environmental impact - unlike a barrage
  - Power is highly predictable - unlike wind
- Resident UK-based expertise in marine engineering
- Export potential

Tidal Resource – UK Target Areas



Pentland Firth, 4m/s

Irish Sea, 2m/s

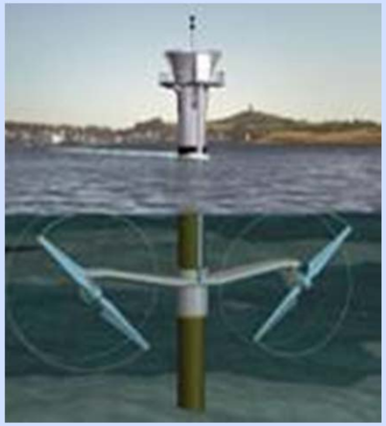
Bristol Channel, 2m/s

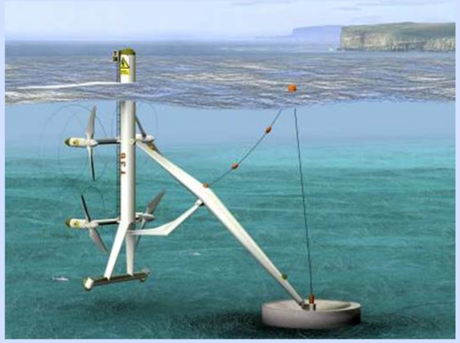
English Channel, 2m/s

NB: Tides are cyclic but totally predictable

Source: DTI Atlas of UK Marine Renewable Energy Resources

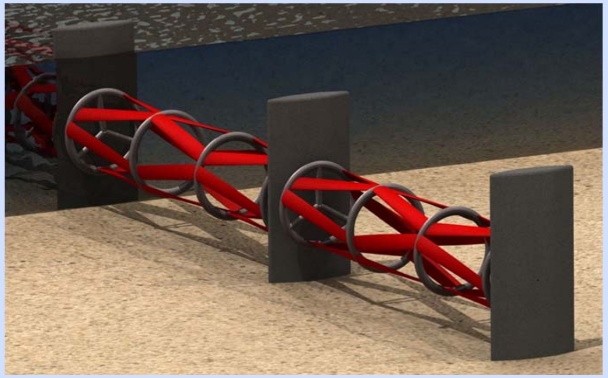
Options for tidal stream power (1)



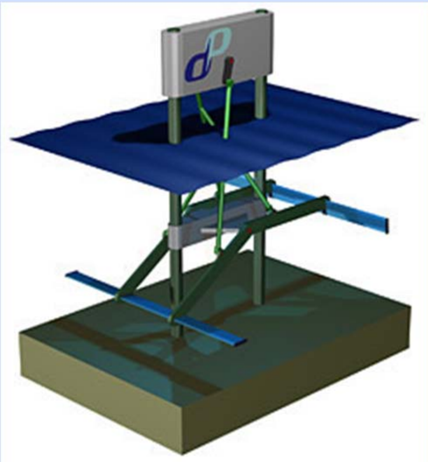


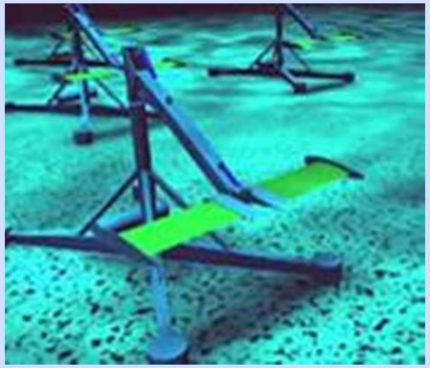
- Axial flow turbines ("underwater windmills")
  - "Unducted"
    - » MCT (most developed)
    - » TidalStream
    - » Tidel
    - » … at least 8 others
  - "Ducted"
    - » Lunar Energy
    - » Open Hydro
    - » … at least 8 others
  - Fixing options:
    - Fixed foundation
    - Pivoted
    - Anchored

Options for tidal stream power (2)

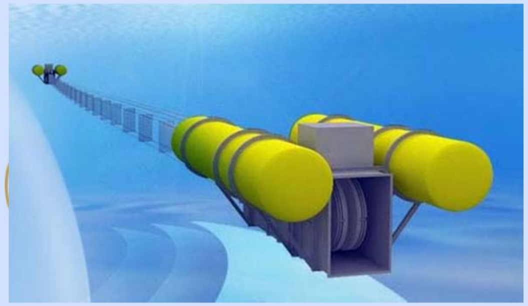


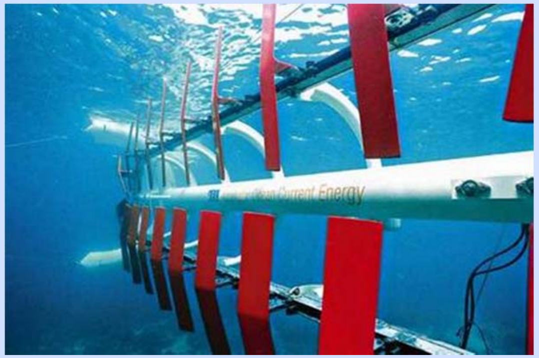
- Vertical axis turbines
  - Blue Energy
  - Polo
  - … 4 other vertical axis devices
- Horizontal axis turbine
  - THAWT (Oxford development)
  - … one or two others?





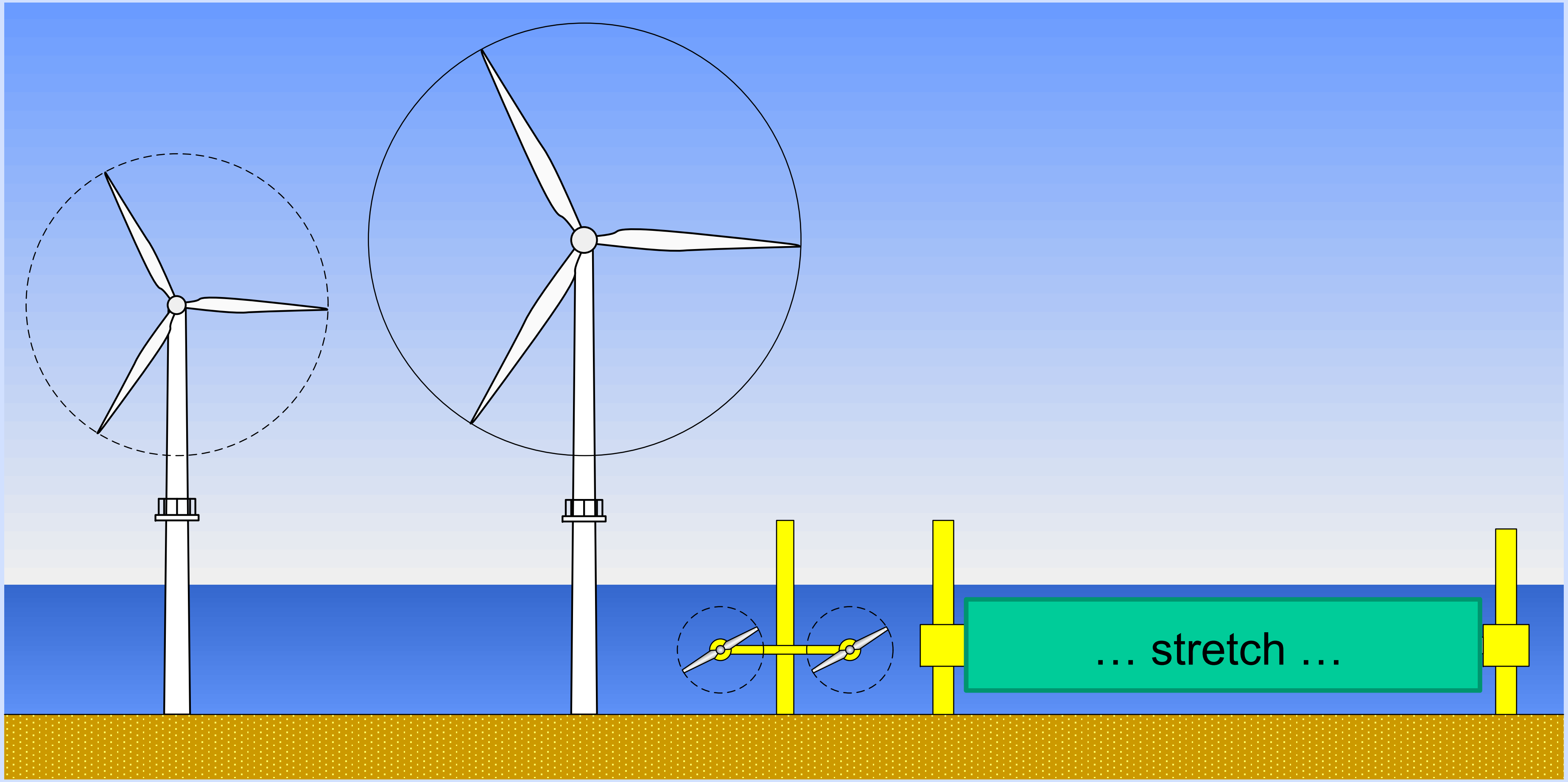
- Oscillating devices
  - Stingray
  - Pulse Tidal
  - … other oscillating devices



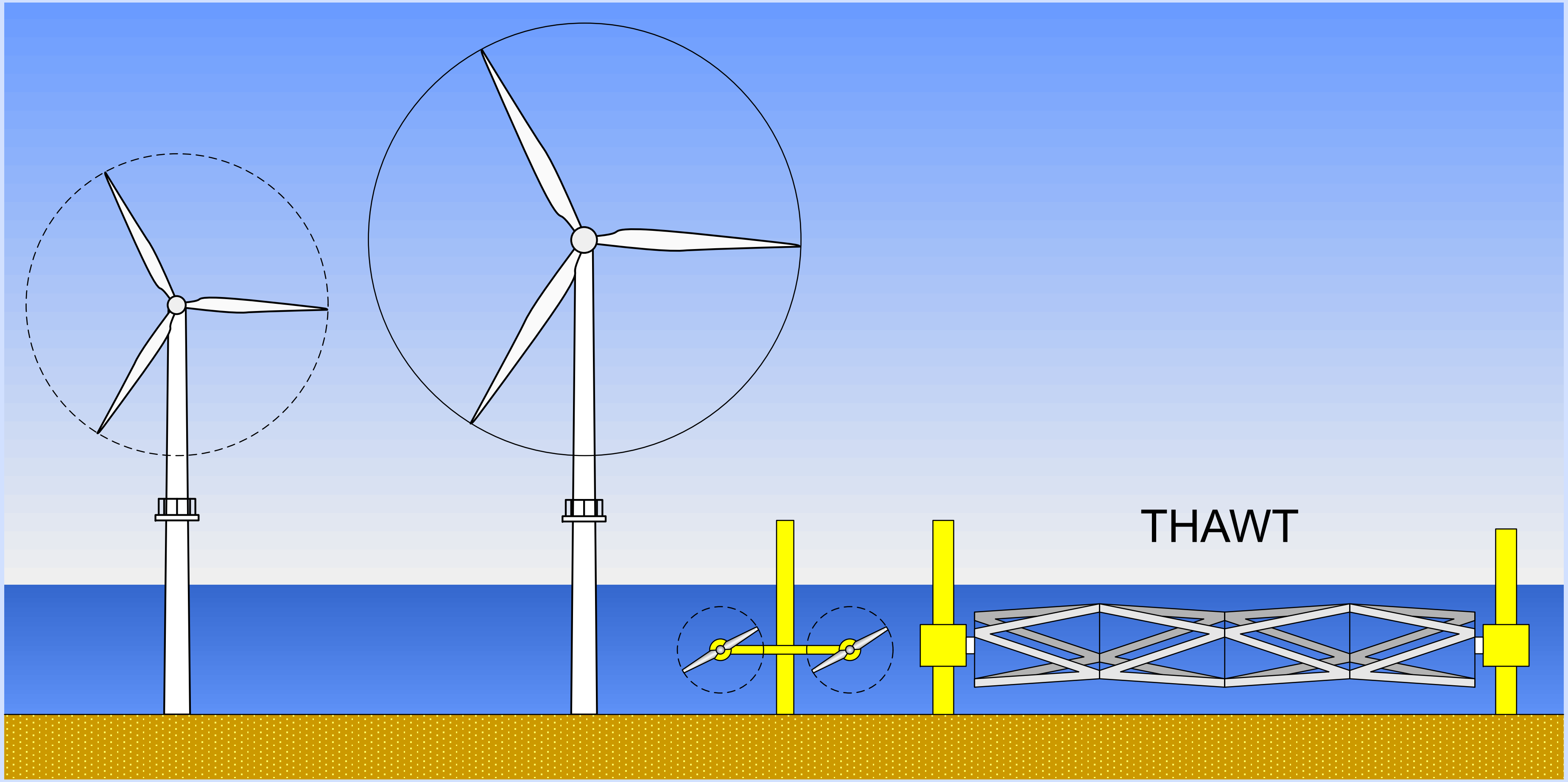


- Weird variants
  - Tidal Sails
  - Atlantis “Aquanator”

Scalability of tidal devices



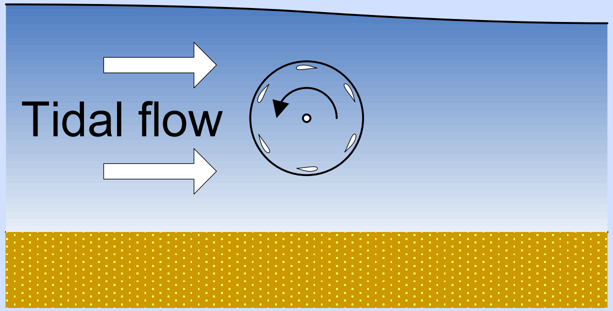
Scalability of tidal devices

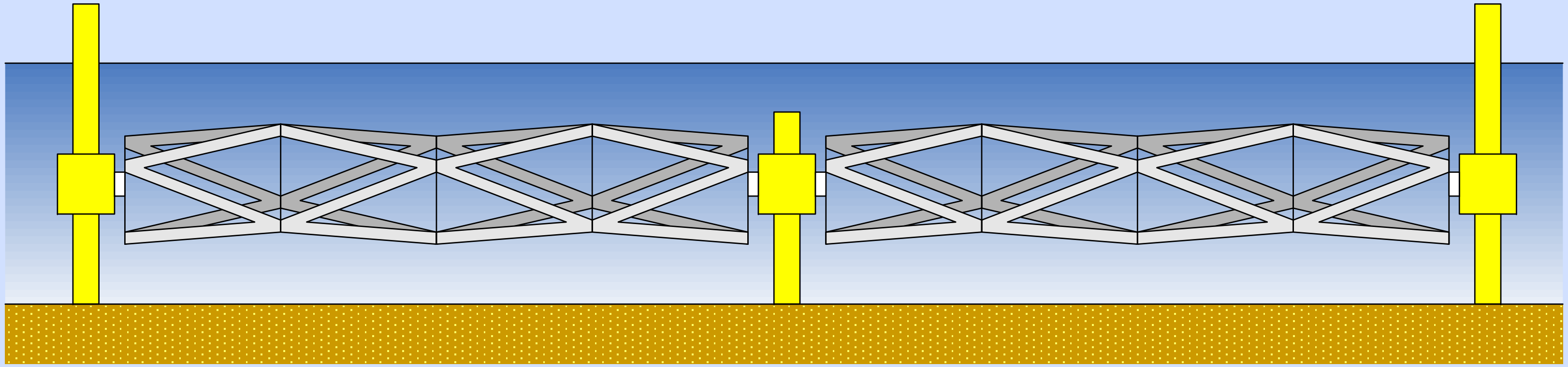


THAWT Concept

Transverse Horizontal Axis Water Turbine

- Turn axis of Darrieus vertical axis wind turbine (VAWT) through 90° to lie horizontally across a tidal flow
- Stretch across the flow



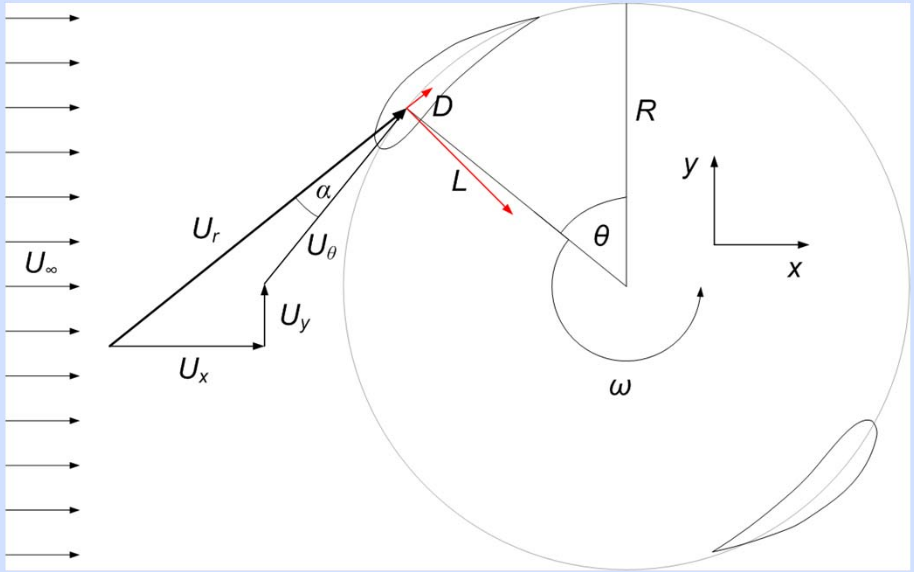


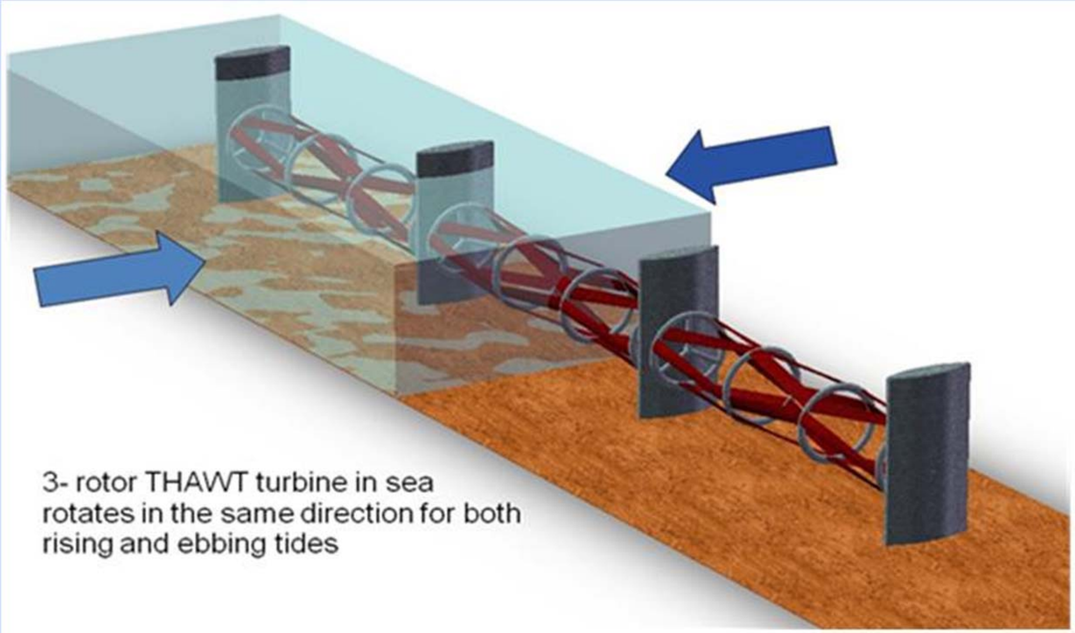
- Length limited only by **stiffness of structure** and **width of channel**
- THAWT is **scalable** horizontally

Fluid Mechanics of Darrieus Cross-Flow Turbine

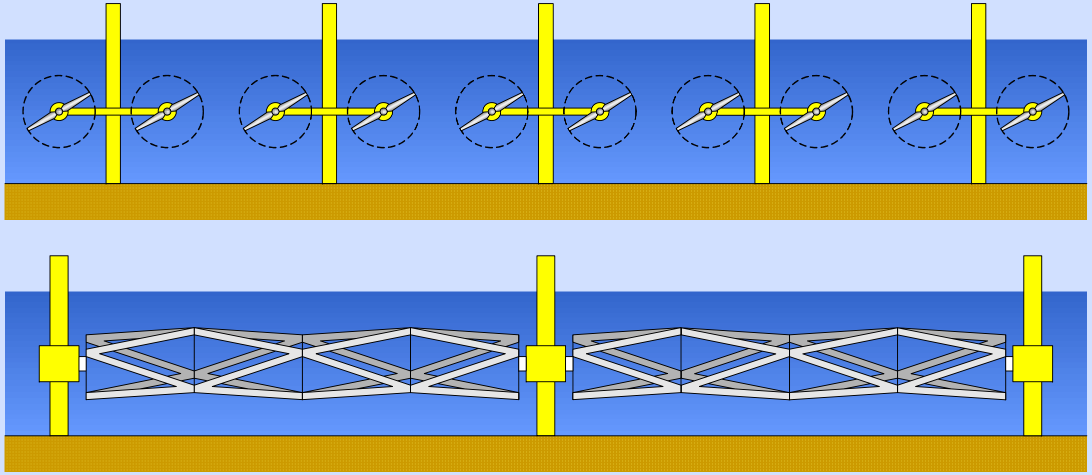
Driving mechanism:

Torque per blade = $R\,(L \sin\alpha - D \cos\alpha)$





A comparison: axial flow turbine *v.* THAWT

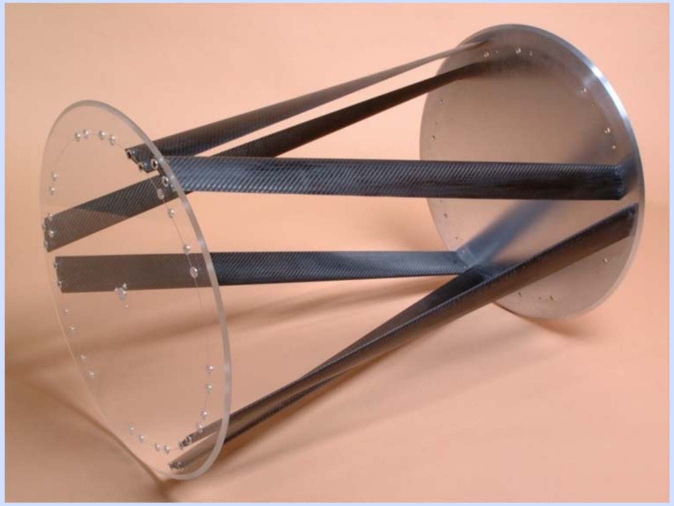


- Advantages:
  - fewer foundations
  - fewer (larger) generators
  - fewer moving parts

	THAWT	Generic Axial Flow
Tidal velocity (m/s)	2.5	2.5
Depth (m)	20	20
Rotor Dia. (m)	10	10
Rotor length (m)	60	
Number of rotors	2	10
Flow area intercepted sq. m)	1200	785
Total length (m)	128.0	125.0
Power Output (MW)	**7.0**	**3.7**
Number of foundations	3	5
Number of generators	1	10
Number of primary seals	4	30
Estimated manufacturing costs	60%	100%
Estimated maintenance costs	40%	100%

Tests at Newcastle University at 1/20th scale

- Tests on a single turbine bay
  - 0.5m diameter
  - 0.875m length
  - up to 1m depth
- Power curves recorded using servo motor/generator control of turbine speed
- Performance in a range of realistic flow conditions explored
- Turbine optimisation explored



Froude number scaling of flow conditions

- Choice between Froude number $\mathrm{Fr} = \frac{u}{\sqrt{gh}}$

  or blade Reynolds number scaling $\mathrm{Re} = \frac{u_{blade} Chord\ \rho}{\mu}$

- Maximum power available to a device in an open channel flow only a function of Froude number and blockage ratio

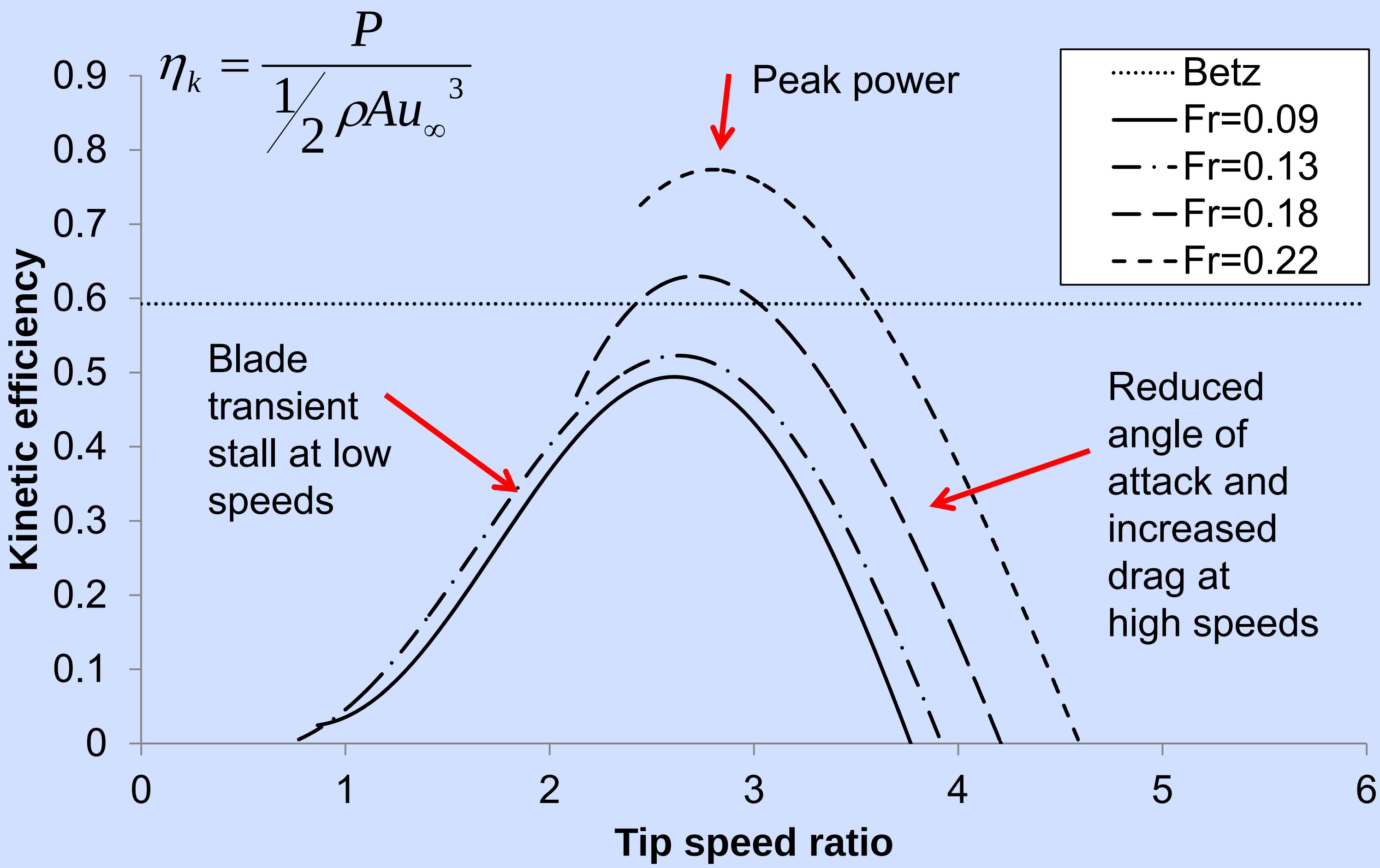
  (G.T. Houlsby et al. (2008). Application of Linear Momentum Actuator Disc Theory to Open Channel Flow, University of Oxford Internal report, OUEL 2296/08)

- Froude number scaling

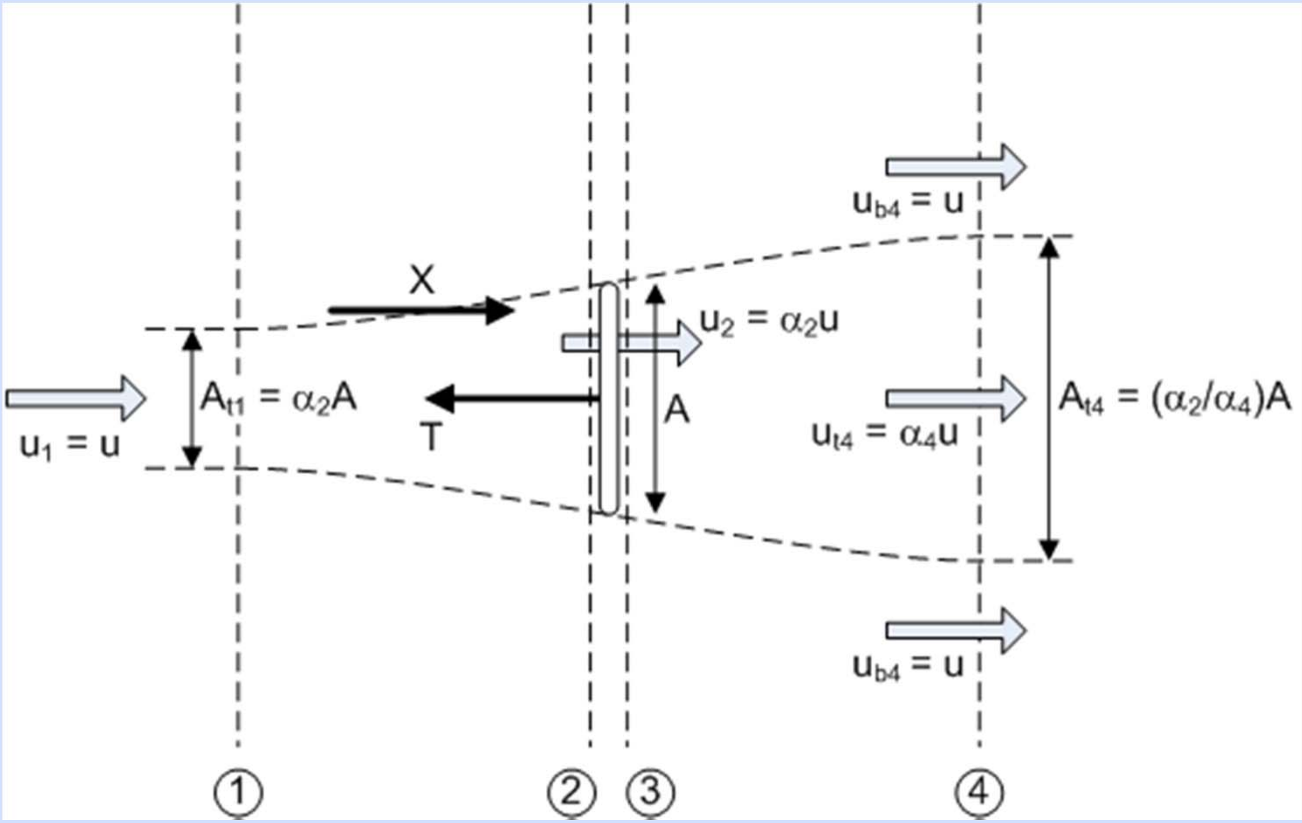
	Scale Model	Full Scale
Flow depth	1m	20m
Froude number range	0.09 - 0.22	0.09 - 0.22
Flow velocity range (m/s)	0.3 – 0.7	1.3 - 3.1

- Lower Reynolds number flows result in poor hydrofoil performance and a conservative estimate of the full scale performance

Effect of flow rate on Truss THAWT performance



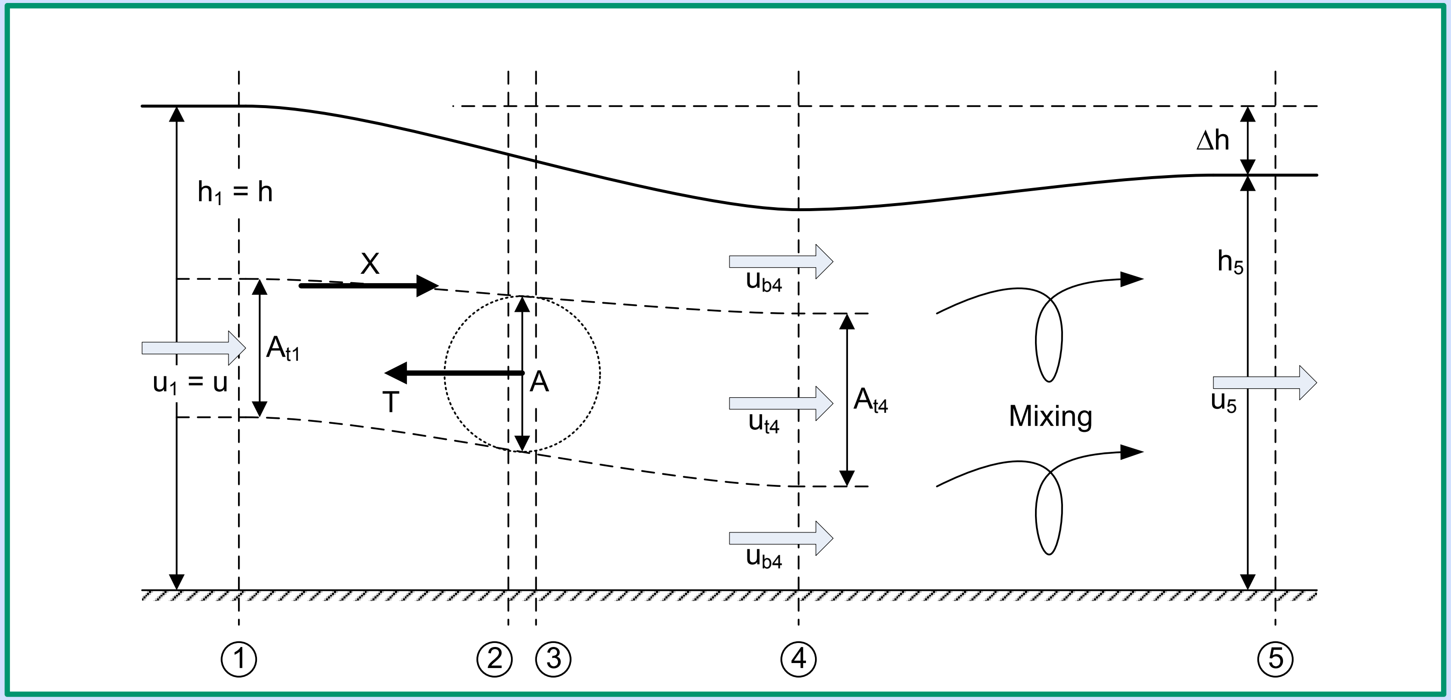
What about the Betz limit?



For **wind turbine** in free air, mass/momentum analysis shows that stream tube area increases and velocity decreases through the turbine.

Max power is the Betz limit $P \le \frac{16}{27}\left(\frac{1}{2}\rho A u^3\right)$

Betz limit does not apply to tidal flows

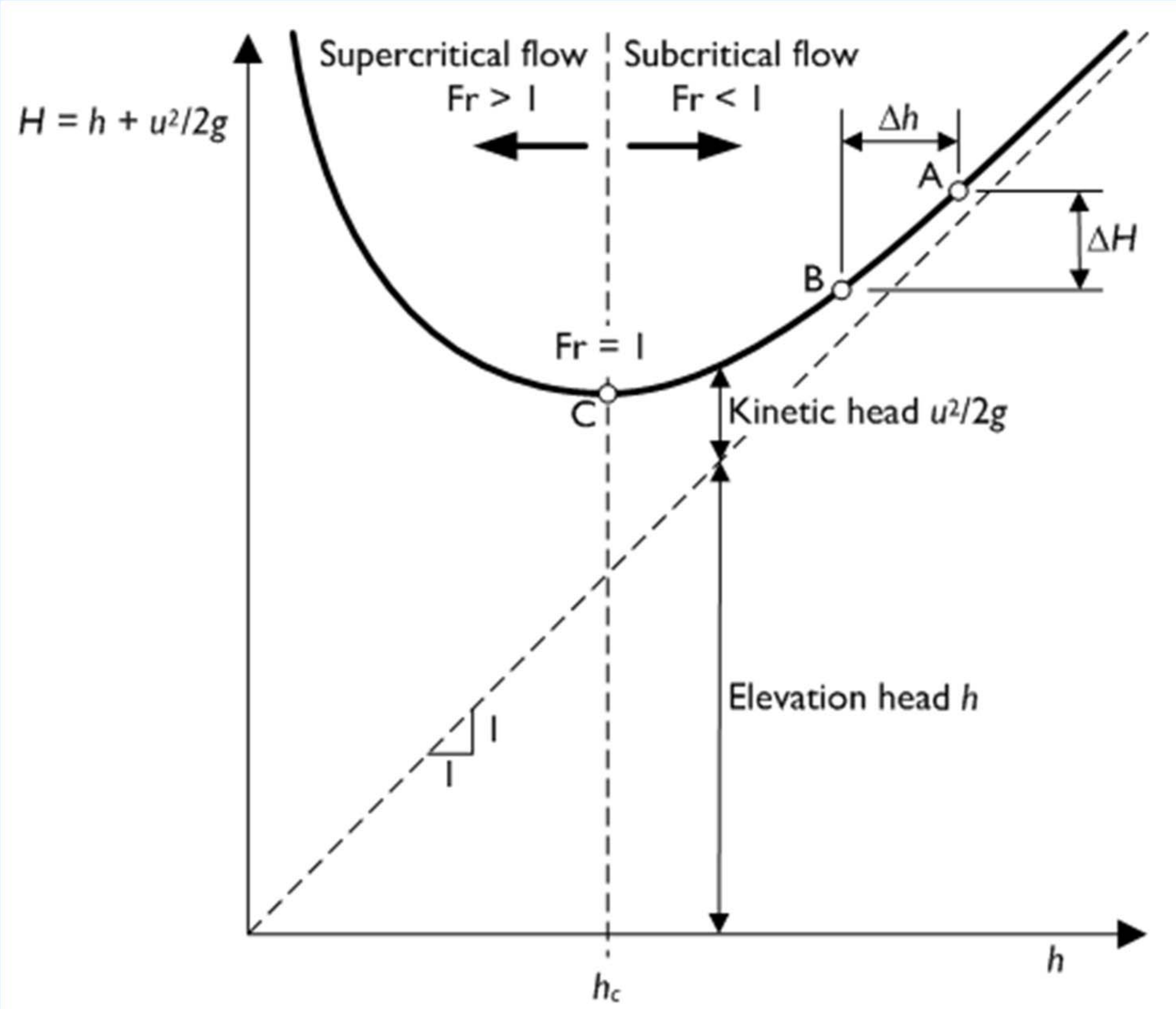


Power extracted from turbine best represented by Head efficiency

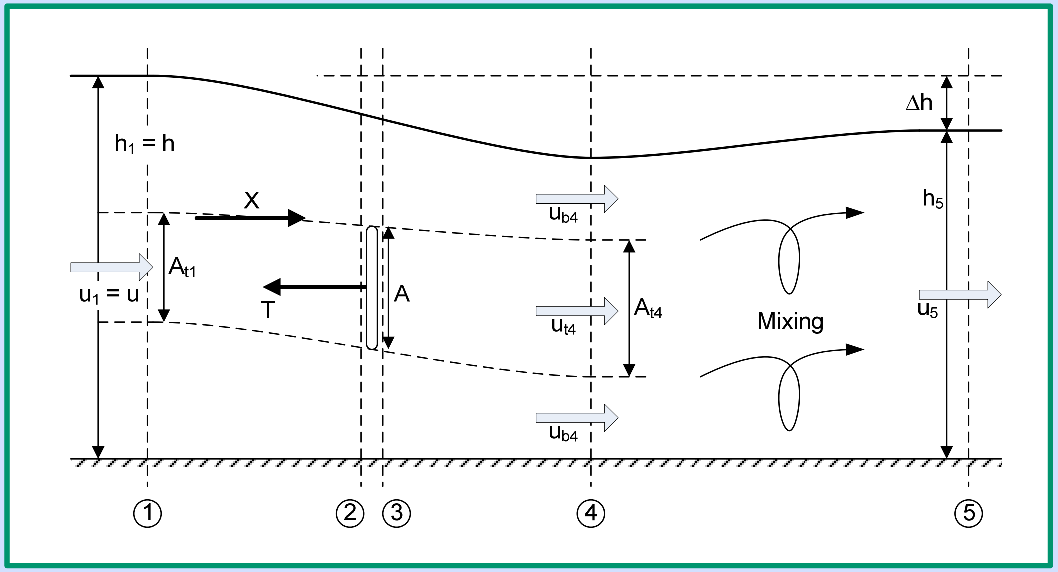
$$P \approx \eta\, g\, (\rho b h u)\, \Delta h$$

Head Efficiency — Mass flow rate — Change in depth

Tidal flows are subcritical



Downstream Mixing and Efficiency



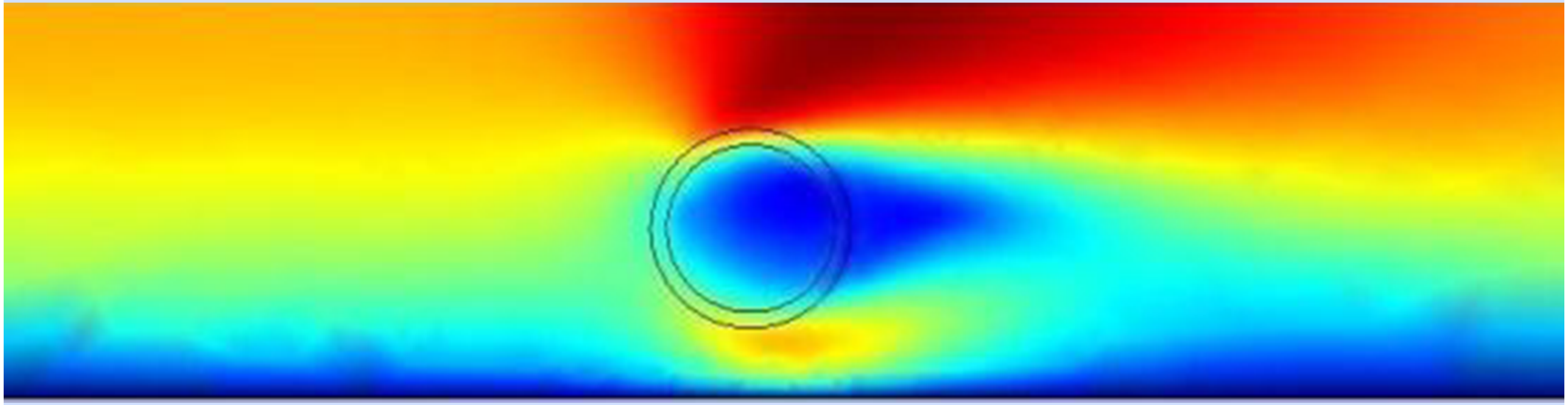
$$\frac{1}{2}\left(\frac{\Delta h}{h}\right)^3 - \frac{3}{2}\left(\frac{\Delta h}{h}\right)^2 + \left(1 - Fr^2 + \frac{C_T B Fr^2}{2}\right)\frac{\Delta h}{h} - \frac{C_T B Fr^2}{2} = 0$$

$$\eta = \frac{P}{P + P_W} = \frac{P}{\rho g u b h \Delta h}\left(1 - Fr^2 \frac{1 - \Delta h / 2h}{(1 - \Delta h / h)^2}\right)^{-1}$$

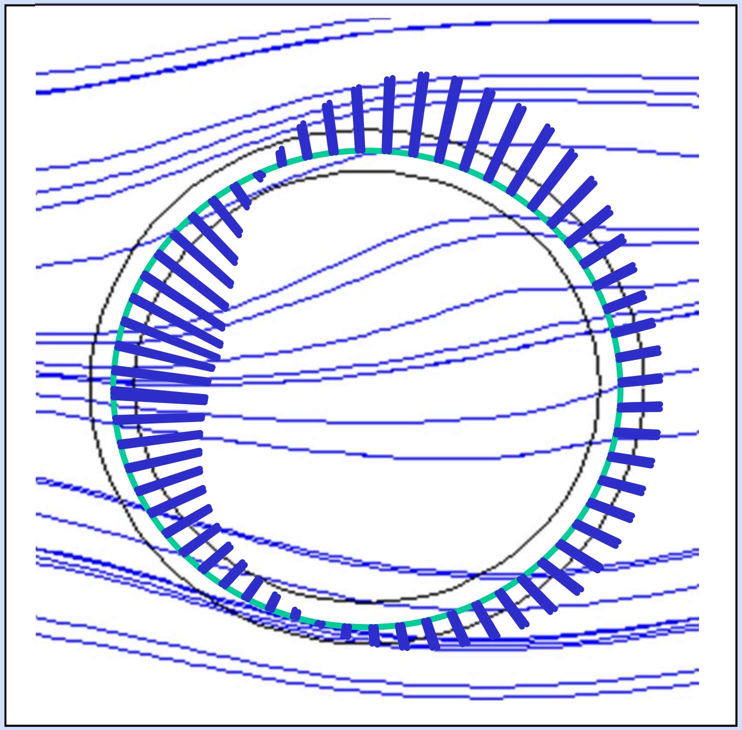
Depth change may become an extremely important measure in light of environmental considerations

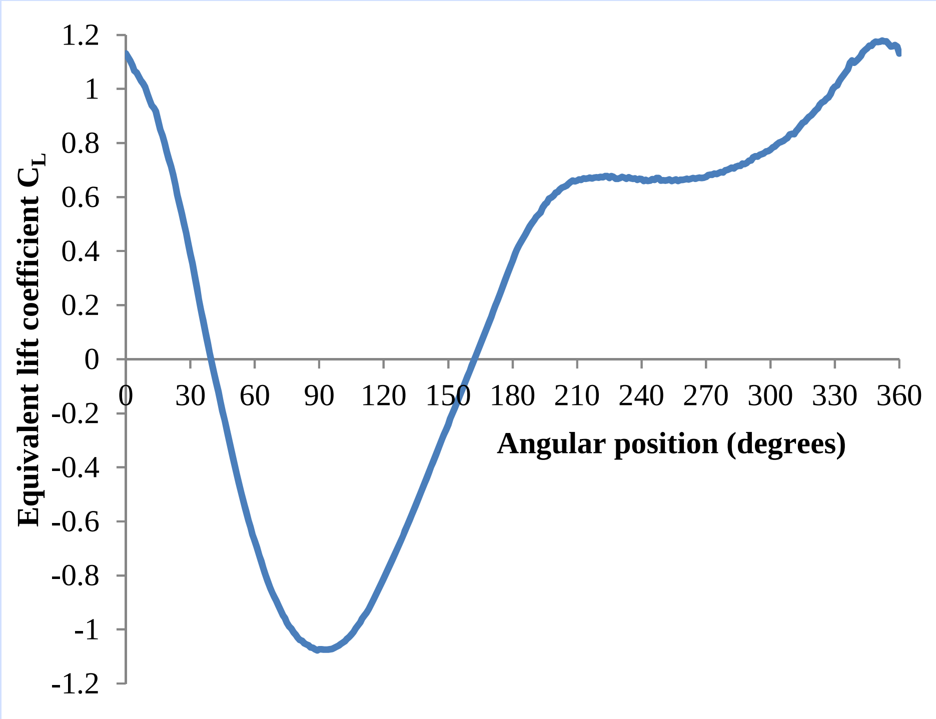
CFD : Computational Fluid Dynamics

- Calculation of flow through turbine is difficult
  – Unsteady, three dimensional, free surface, wide range of length scales
- Simplified analysis to calculate:
  – Power
  – Forces on blades



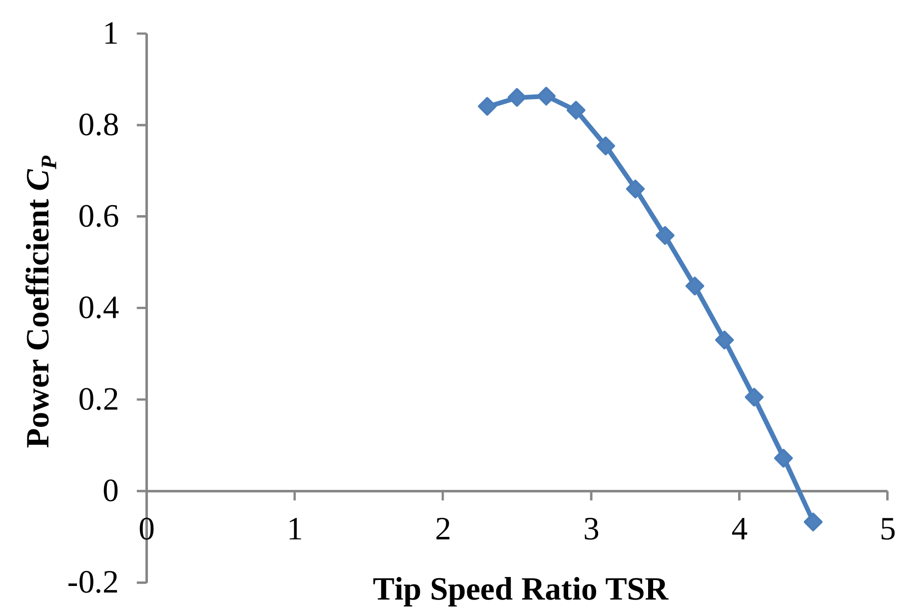
CFD : Computational Fluid Dynamics

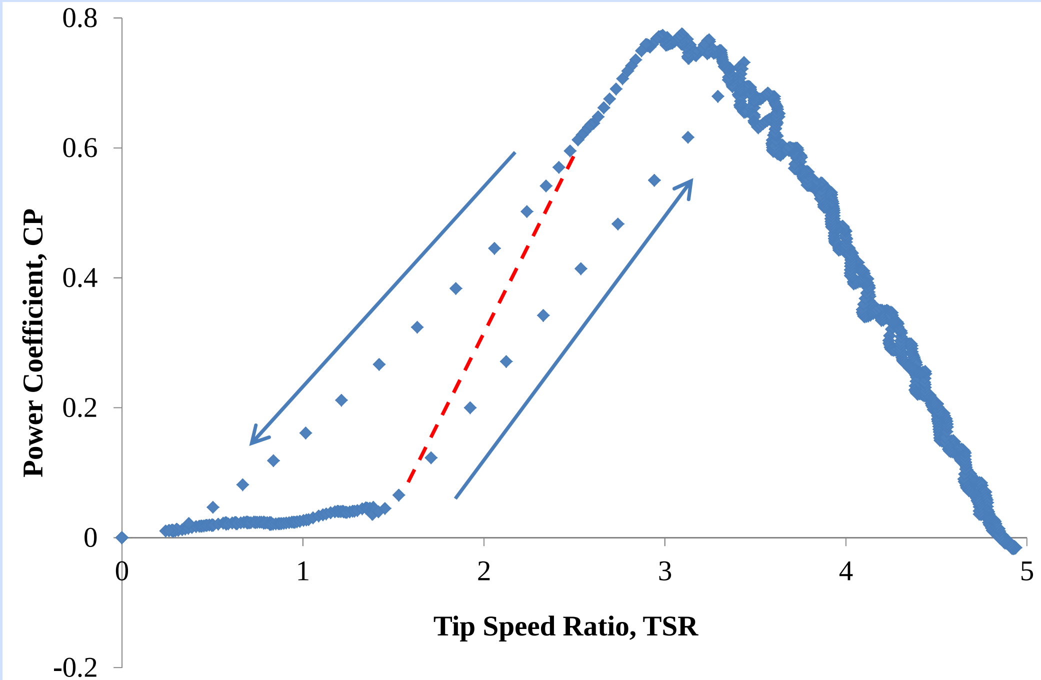




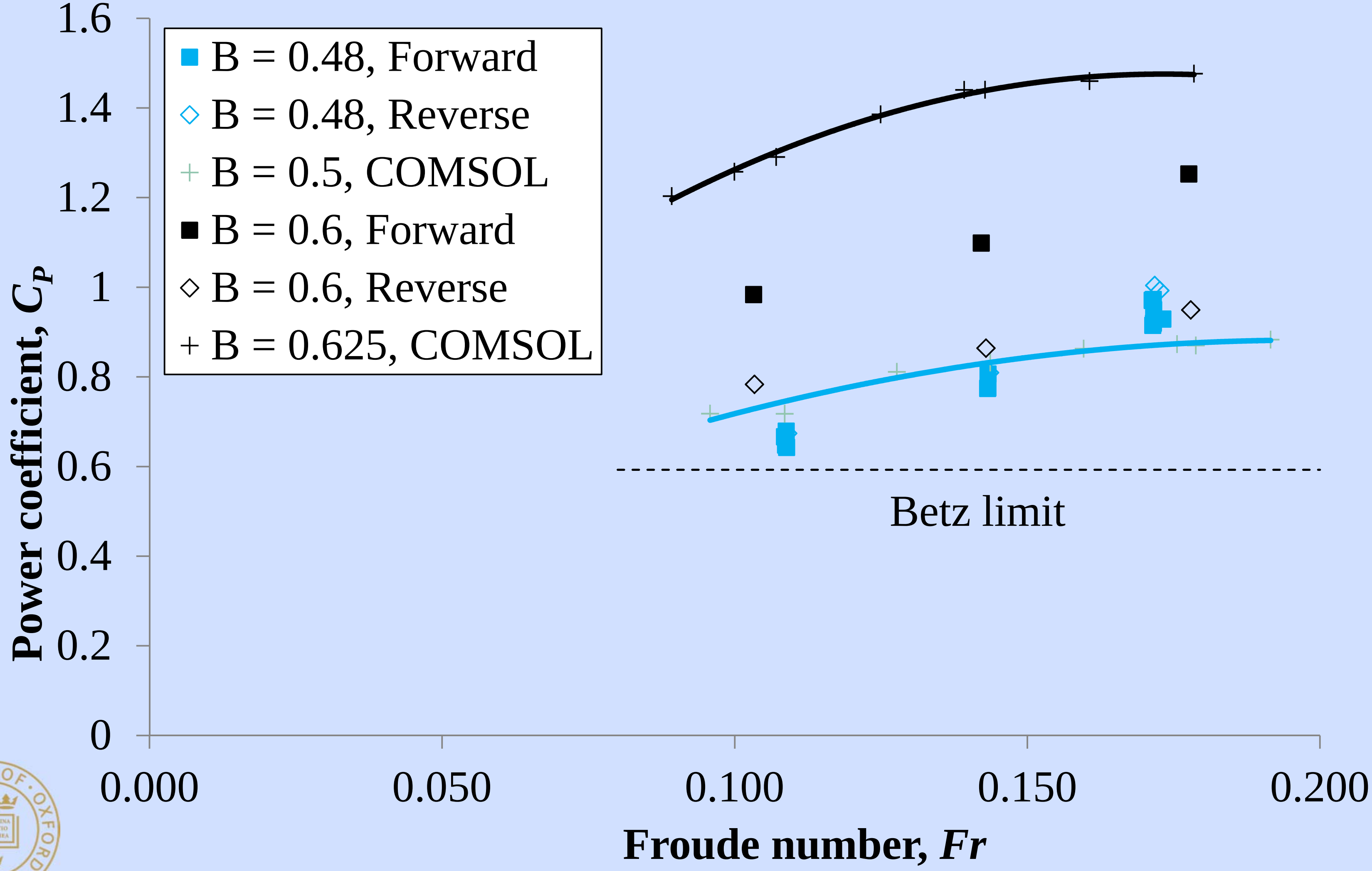
Phase 2 testing at Newcastle

Power curves

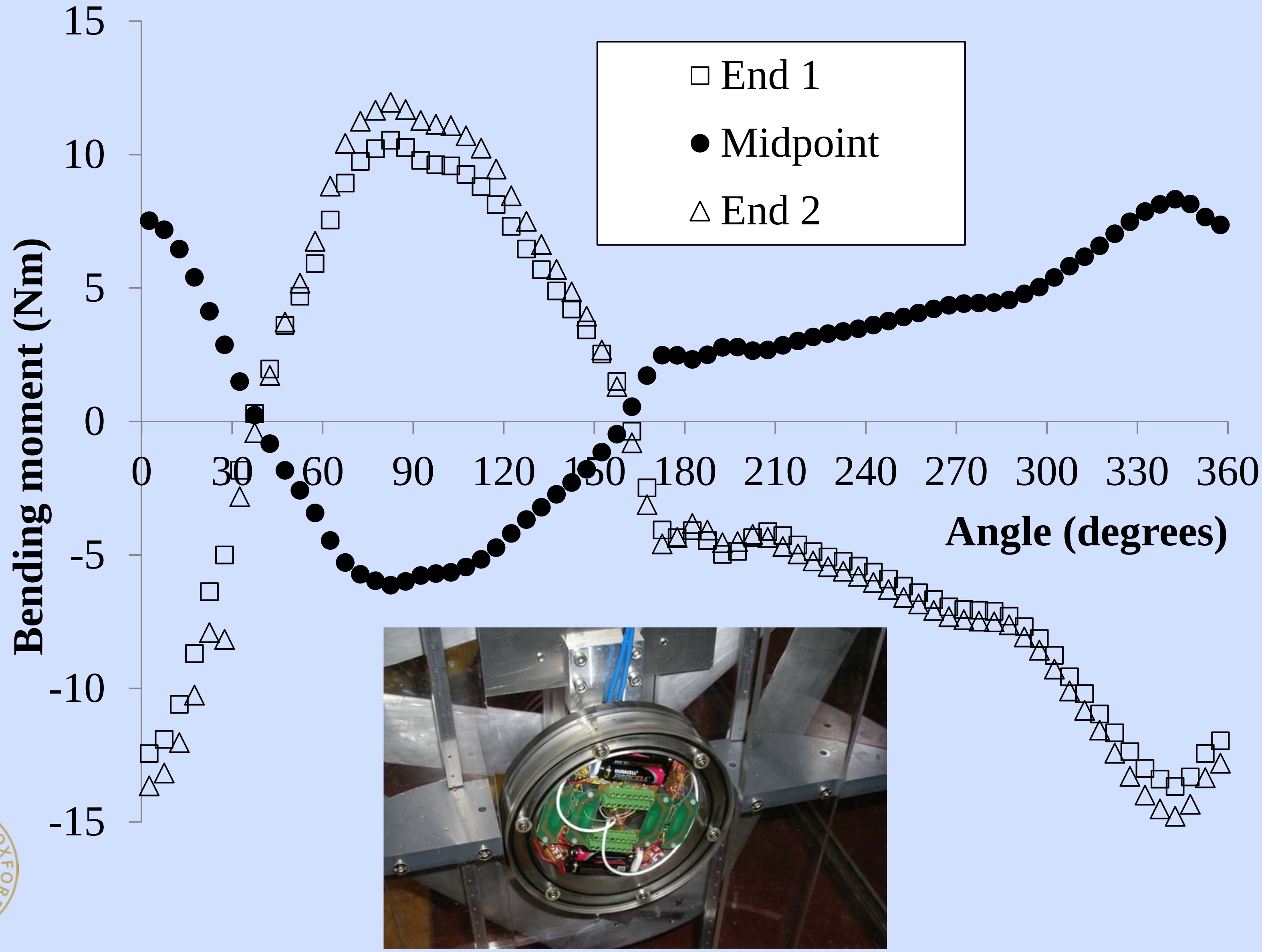




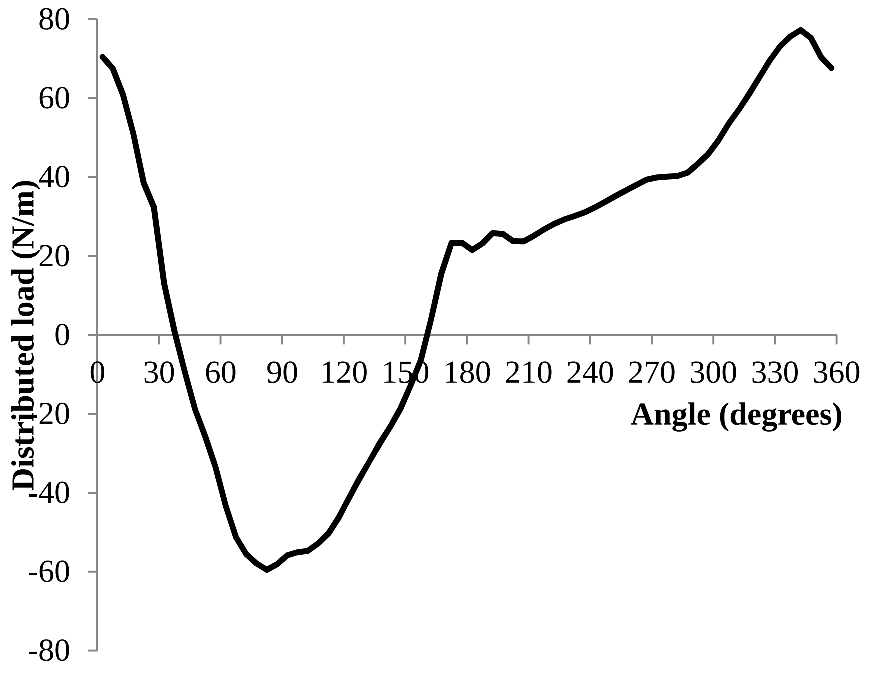
Exceeding the Betz limit

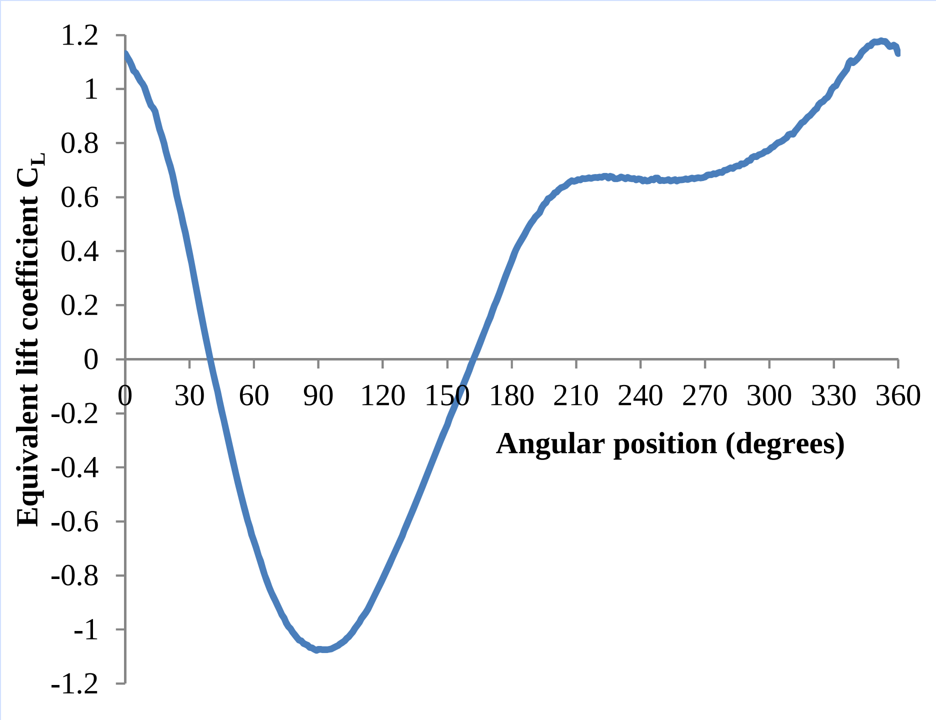


Measurements of bending moment



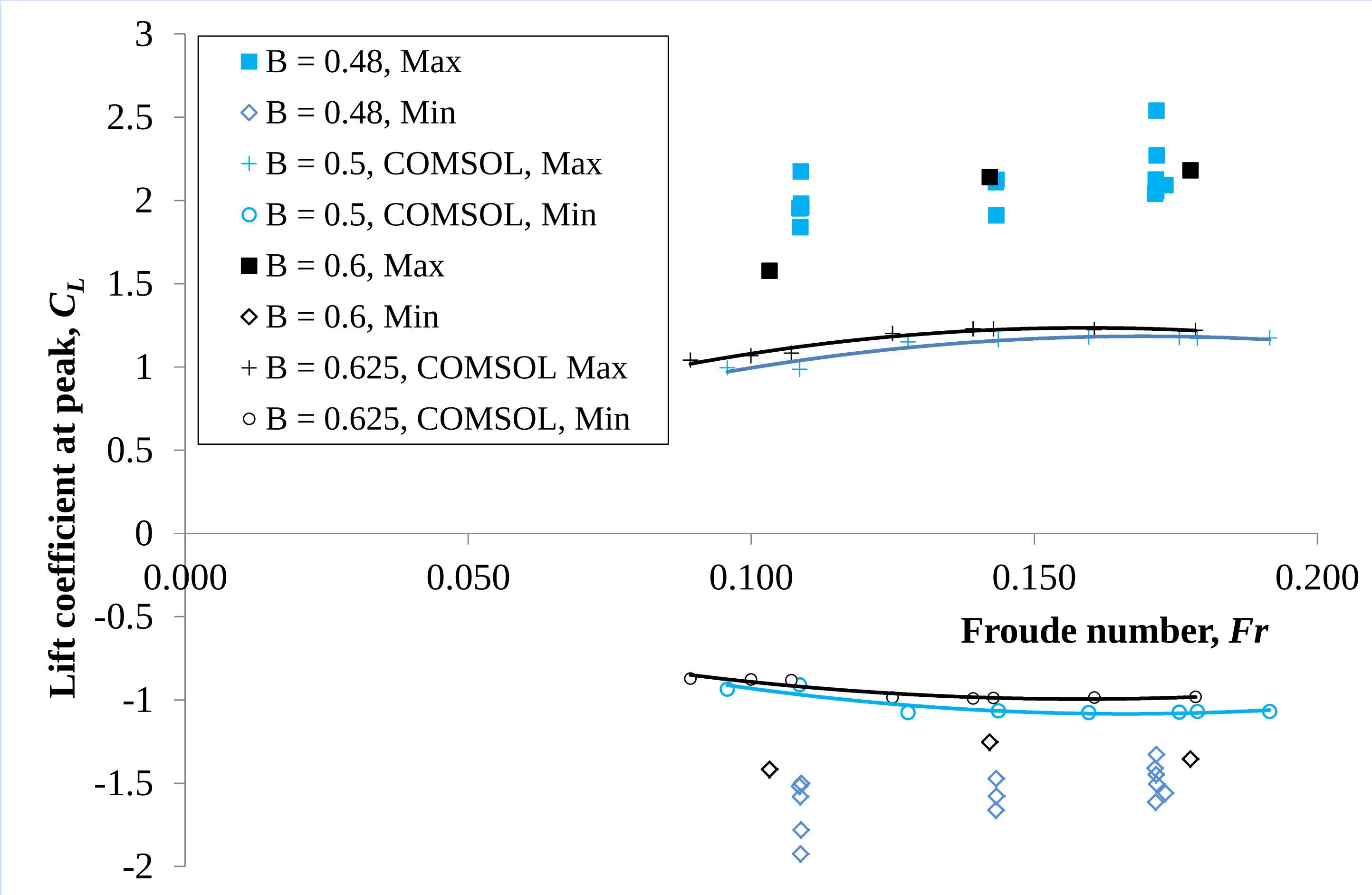
Measured loads on blades



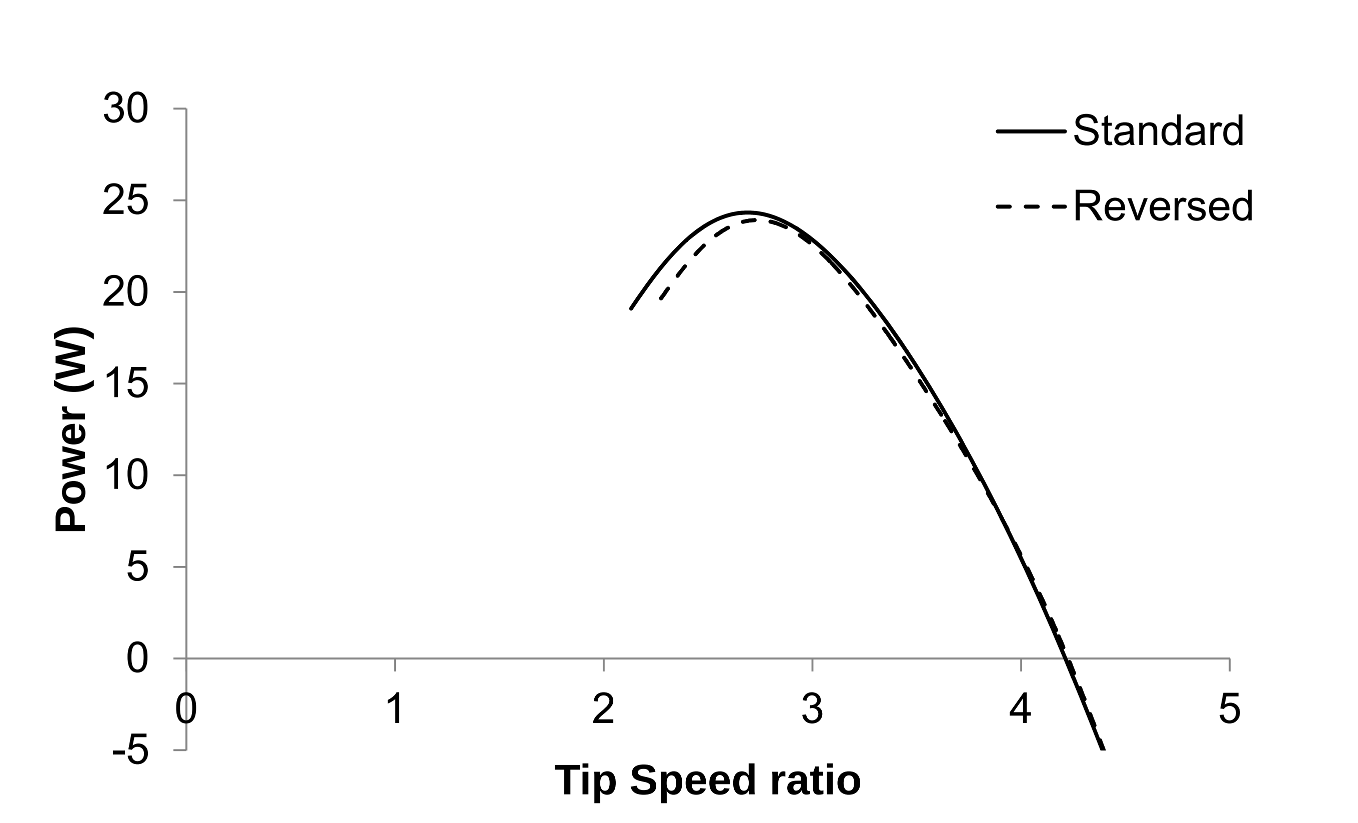


Measured "Lift Coefficients"

$$C_L = \frac{w}{\tfrac{1}{2}\rho c(\lambda u)^2}$$

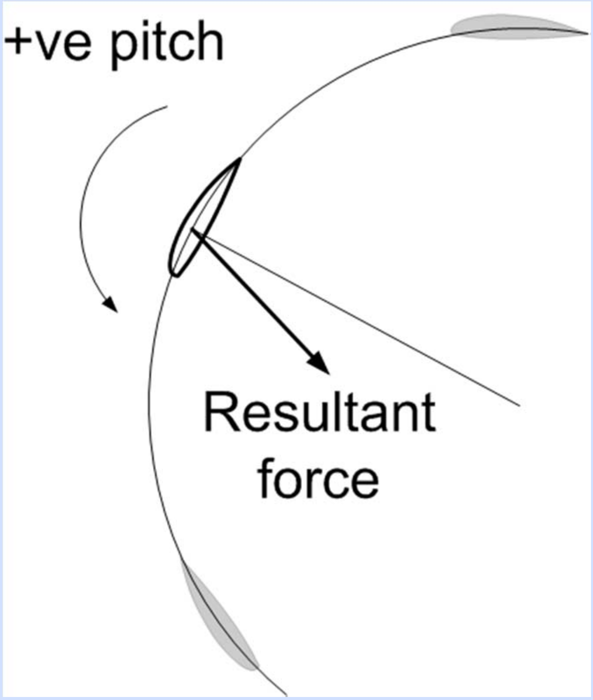


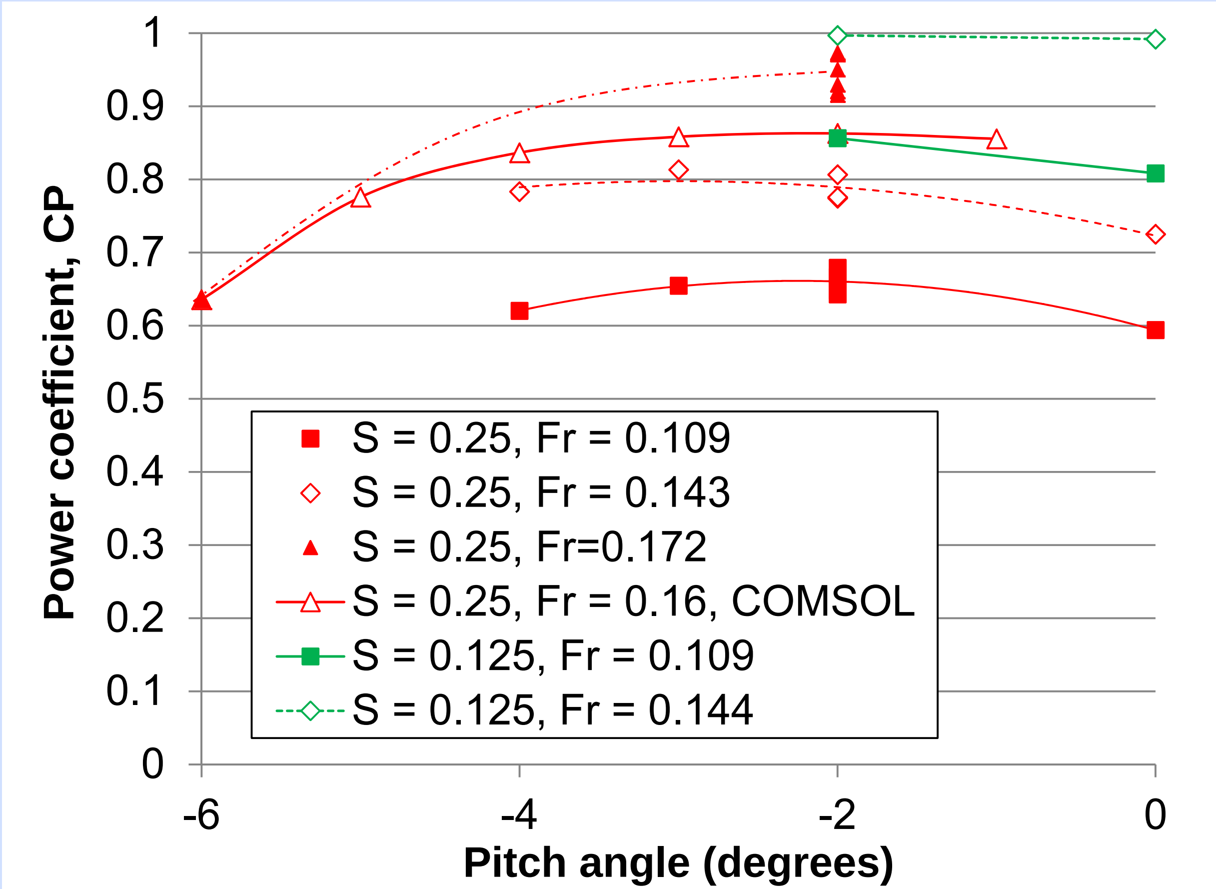
Performance in a reversed flow



Truss device tested in standard and reversed configurations at Fr = 0.18

Varying the fixed offset blade pitch





1/20th Scale Test Conclusions

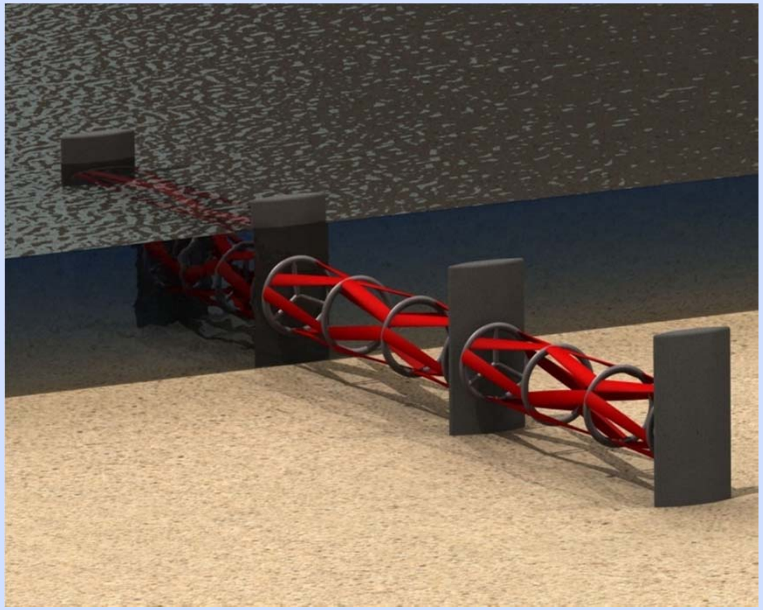
- Device is capable of exceeding the Betz limit by utilising blockage effects

- THAWT has comparable performance to a parallel bladed equivalent

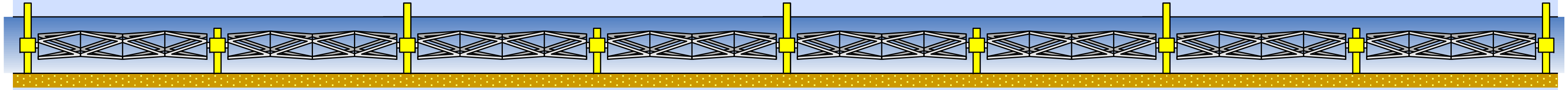
- Performance of the device may be improved using a fixed offset pitch

- Due to Reynolds number issues the results here are a conservative estimate of the full scale performance of the device

- Blade loading measurements have been made

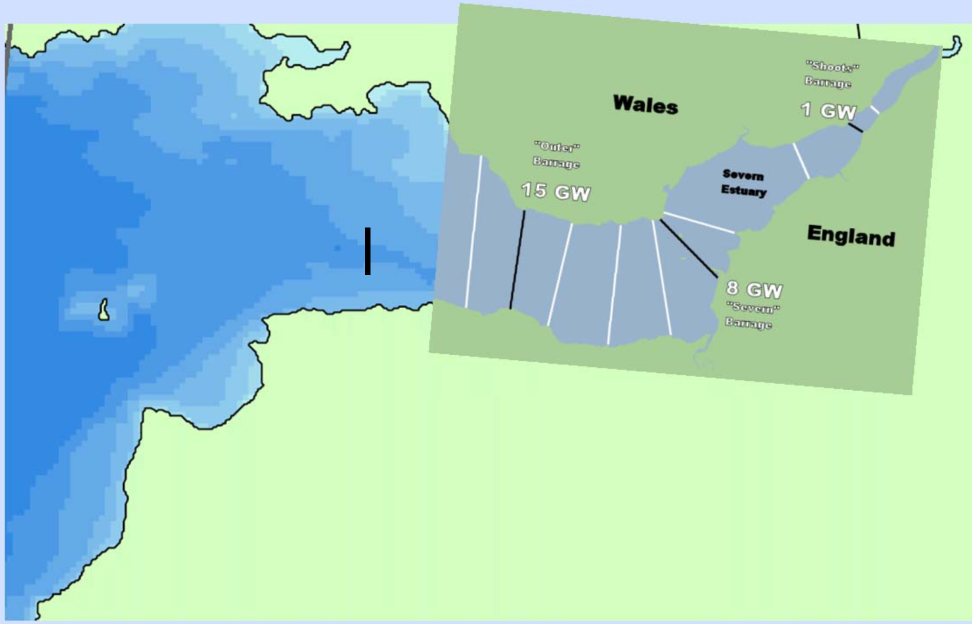


100 MW from 1 km long array across Bristol Channel

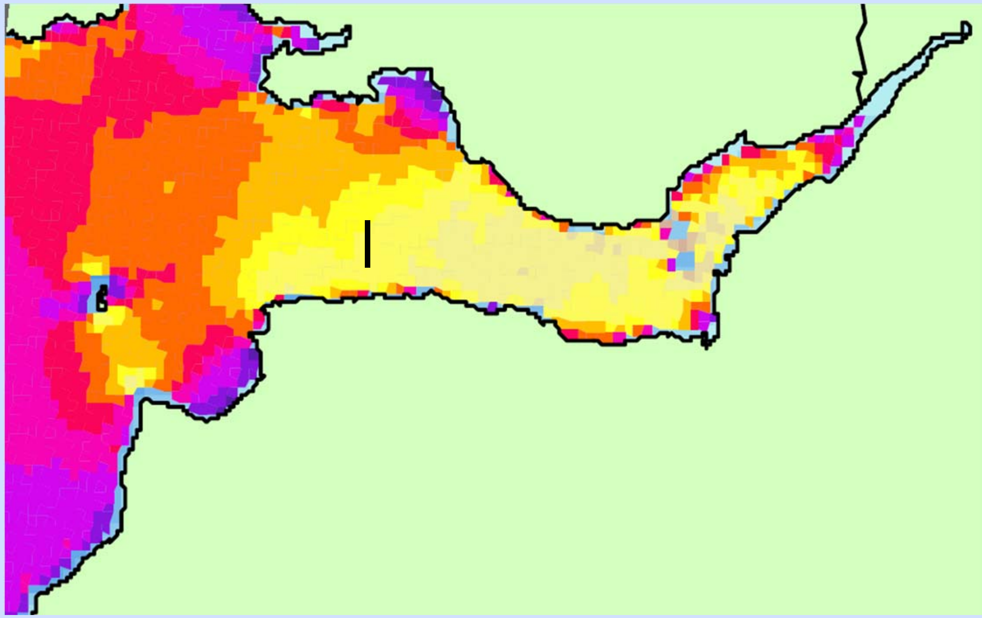


- Linear array extracts potential energy by surface level drop
- Greater power than from kinetic energy only
- Exceeds "Betz" wind turbine theory limit
- Bristol channel example:
    - 10m diameter
    - 1km long array in 20m deep water
    - 2m/s flow
    - 0.5m total head drop
    - 53% efficiency (modified theory) would give **102 MW**

THAWT in the Bristol Channel



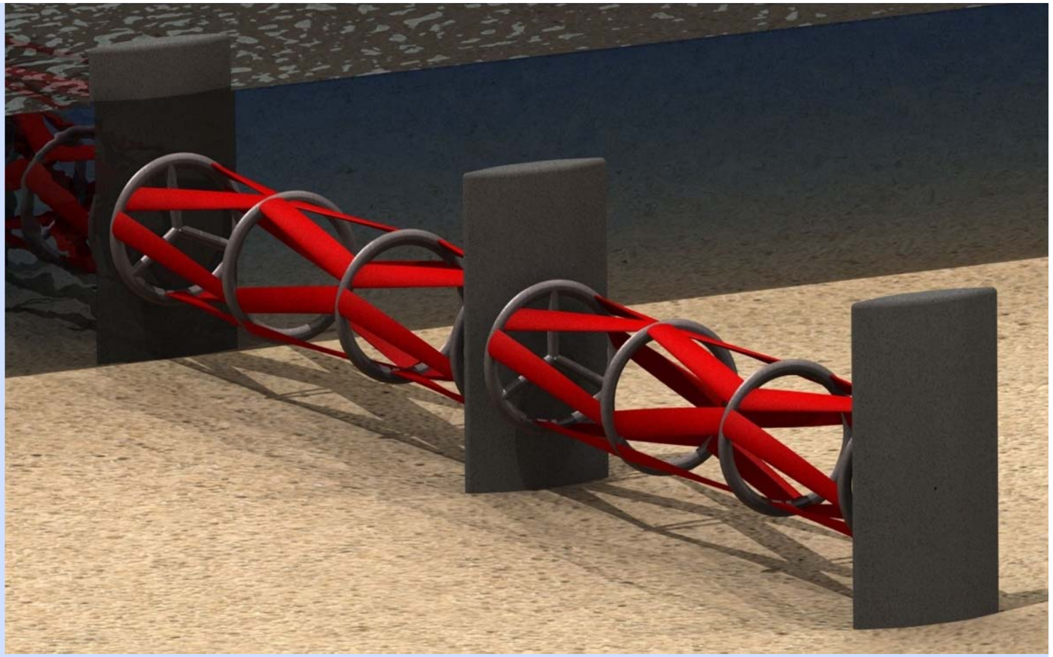
1 GW installation?



Acknowledgements

- Oxford Tidal Engineering Group:
  - Staff
    - Richard Willden, Alistair Borthwick, Martin Oldfield, Malcolm McCulloch
  - Students/RAs
    - Ross McAdam, Claudio Consul, Scott Draper, Yihui Shi, Esteban Ferrer, Clarissa Belloni, Tom Adcock, Simon McIntosh, Sena Serhadlioglu, Conor Fleming, Justine Schluntz, Chris Vogel, Taka Nishino
  - THAWT Commercial Team
    - Sean Westrope, Peter Dixon, Stuart Wilkinson, James Mallinson
- Sponsors:
  - EPSRC, Oxford University UCSF, Isis Innovation Ltd., RCUK, John Fell OUP Fund, Rhodes Trust, Energy Technologies Institute, Royal Academy of Engineering, German Academic Exchange Service, Oxford Martin School, TSB, Kepler Energy Ltd.

Conclusions



- Tidal stream could provide at least 6% of UK electricity
- Efficient and robust devices like THAWT need to be developed
- The available resource needs to be properly understood