The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific
and Cultural Organization

International Atomic
Energy Agency

**ICTP Experts Meeting on "Science & Renewable Energy"**
**January 15 - 18, 2007**

**Venue: ICTP Adriatico Guest House - Lundqvist Lecture Hall**

**310/1905**

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# "Marine Energy Conversion"

***A. S. Bahaj***
**University of Southampton**
**United Kingdom**

Introduction

Wave Energy

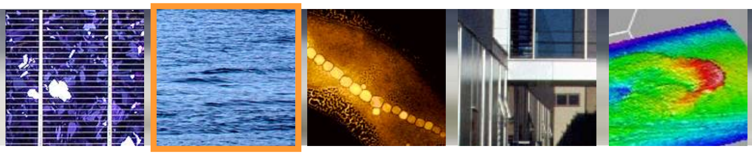
Tidal Stream Energy

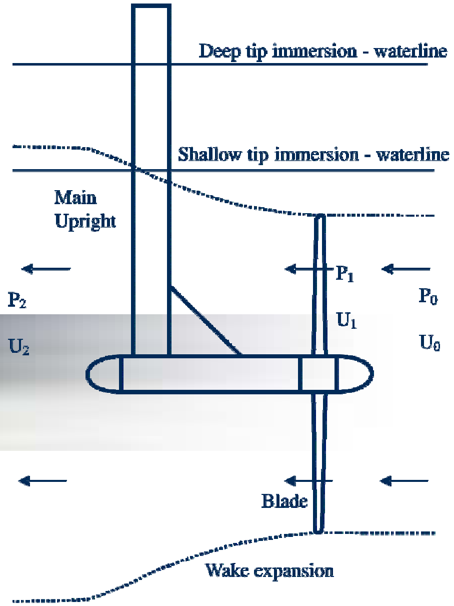
R & D in universities and industry

Current Research Areas

Conclusion

# Marine Energy Conversion



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**www.energy.soton.ac.uk**

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# SERG - Research Fields

- Photovoltaics
- Marine Energy
- Micro Generation Technologies
- Smart Building Technologies
- Thermal and Light Modelling
- Renewable Energy Education

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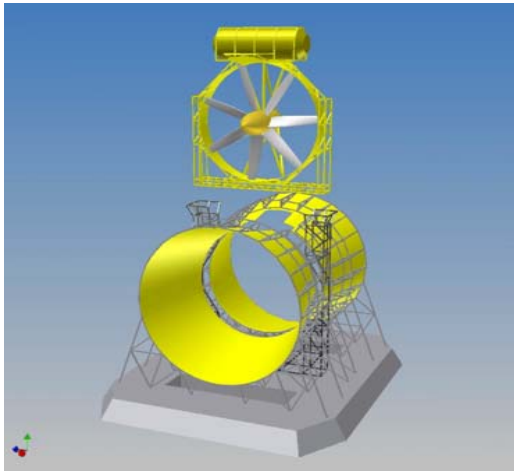
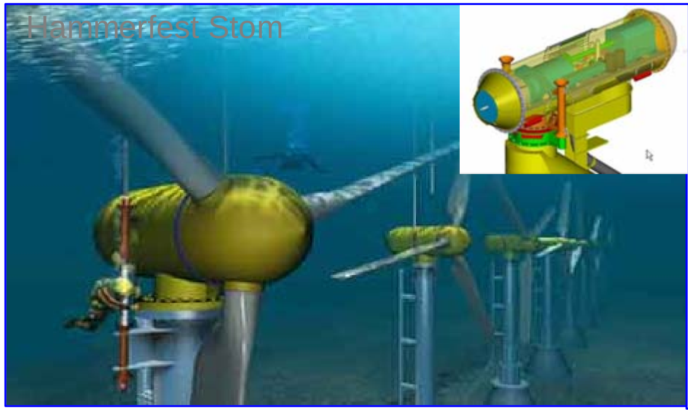
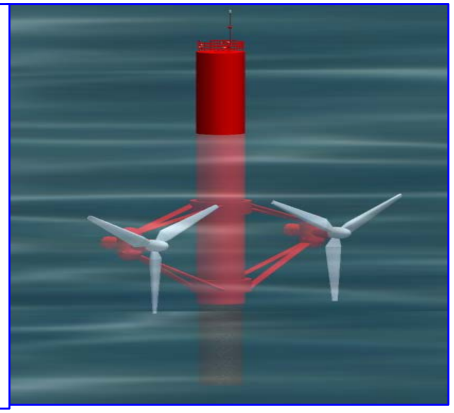
# Ocean Energy



## Ocean Energy Conversion





# Drivers for R&D activities in marine renewables

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- Commitment to achieve 10% electricity from renewables
- Climate Risk: emissions in $CO_2$ to reduced by 60% by 2050
- To maintain reliable energy supplies
- The promotion of competitive markets in the UK

**Wave and tidal resource have large potential for electrical power generation**

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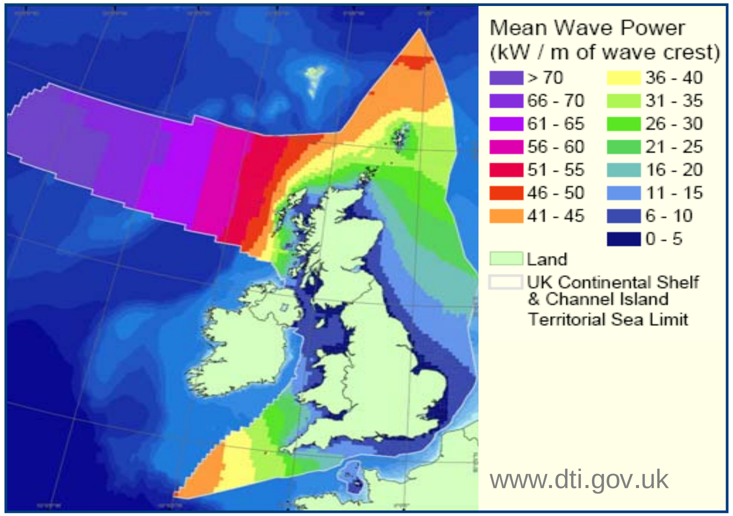
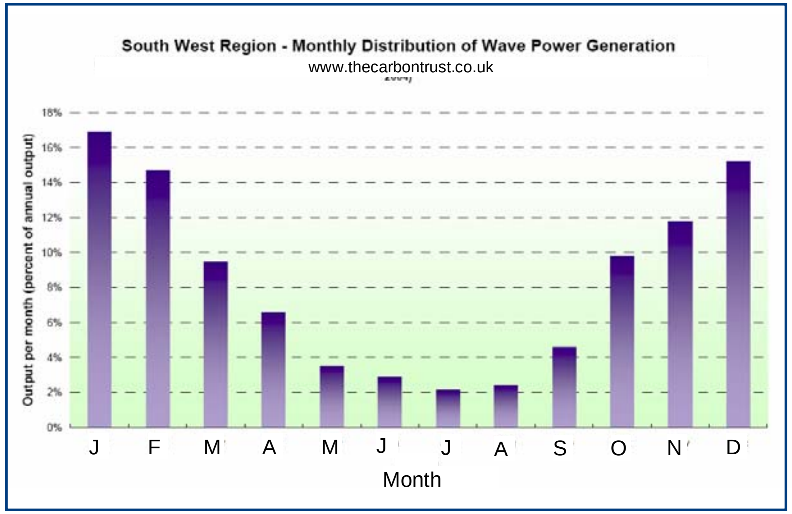
## Wave energy




Strong resource

Most power available during winter months



University of Southampton

# Drivers for R&D activities in marine renewables

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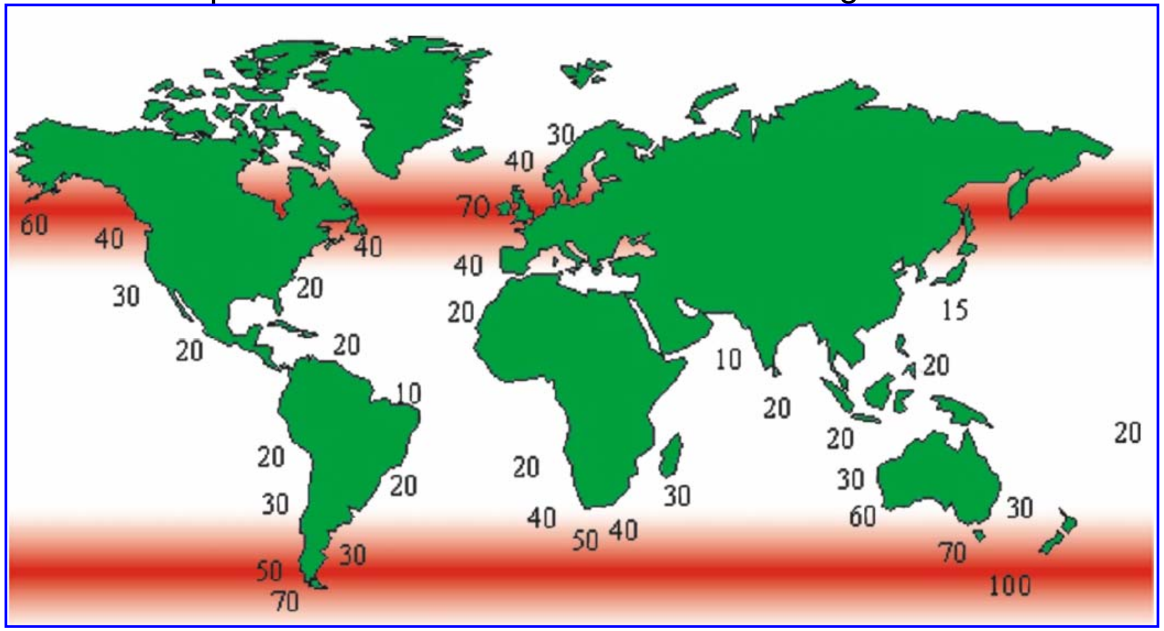
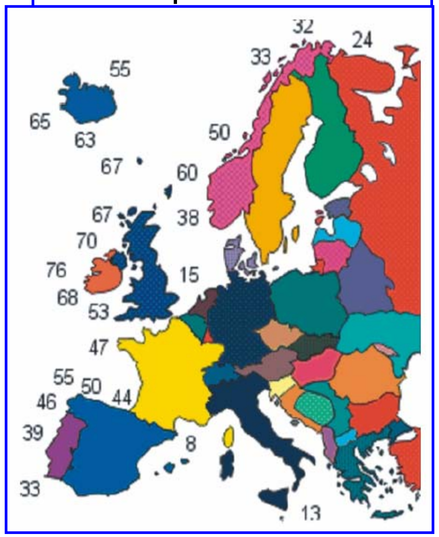
## Wave energy

Global wave power distribution in kW/m of crest length




Wave power levels in kW/m of crest length in European waters.




The long-term annual wave power level increases from about 25 kW/m off the southernmost part of Europe's Atlantic coastline (Canary Islands) up to 75 kW/m off Ireland and Scotland.

In the North Sea, the resource changes significantly, varying from 21 kW/m in the most exposed (northern) area to about the half of that value in the more sheltered (southern) area.

# Why marine tidal energy - History



In 1993, the United Kingdom Energy Technology Support Unit (ETSU) has concluded that tidal current power could supply a major proportion of the UK's electricity requirement, albeit at a high cost (at least 10 p/kWh and probably much more).

Tidal currents represent a substantial European energy resource. In 1996, an EU study of 106 sites indicated that the European resource could represent a potential for 12.5 GW installed capacity.

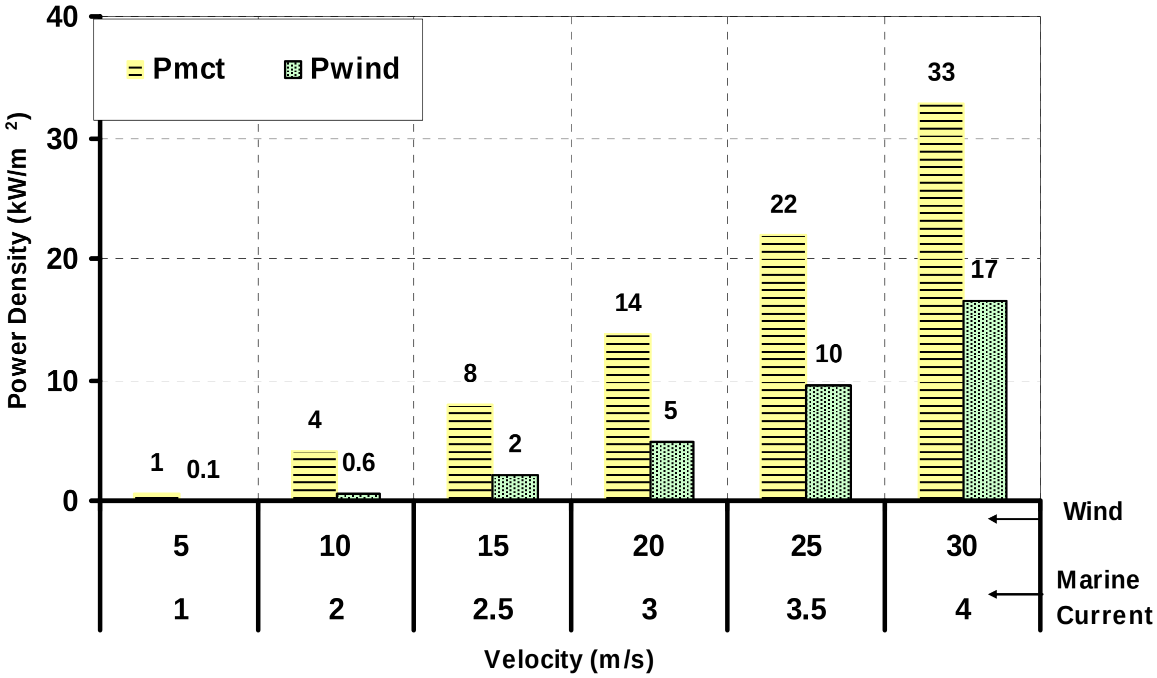
The Tidal resource is variable but predictable which when compared with other renewables could act as a dependable base line supply system.

The extraction of energy from tidal currents is analogous to the exploitation of wind power. Hence, most of the theory and methodology used can be applied with appropriate modification.

# Power in marine currents

**Power** $P_T = [\frac{1}{2}\,\rho\,A\,V^3].\,C_p$

*Cp* is the *power coefficient.* Represents the fraction of power extracted by the turbine.



# Power in marine currents



# Drivers for R&D activities in marine renewables

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- Predictable - gravitational forces
  - Not weather related unlike wave & wind
  - Better terms for Power Purchase Agreement contracts than other Renewables
- 40 TWh/y UK & Europe extractable resource (Black & Veatch 2004)
  - UK total demand 350TWhr – $32bn/y revenue market
  - UK wind – approx 5 TWh/y – c.>$3bn
- UK government financial incentives – specific focus on marine renewables
  - Security of supply, government targets
  - 50% of wind turbine sites rejected - radar issues
- Sub sea location may removes environmental and social impact

# Drivers for R&D activities in marine renewables

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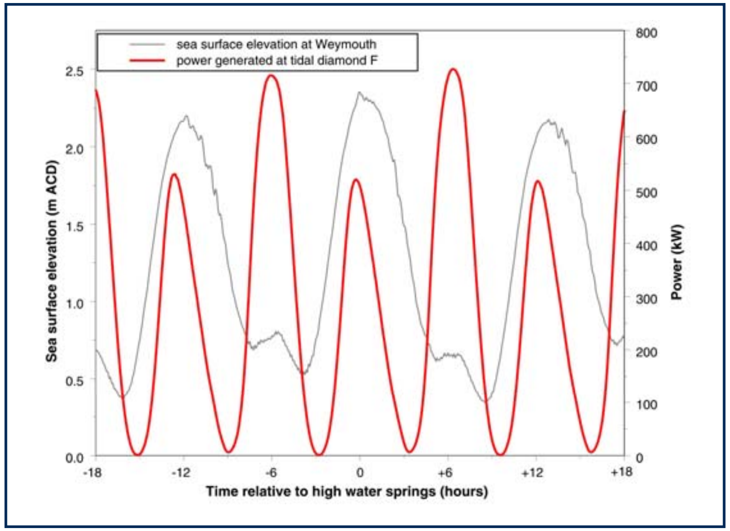
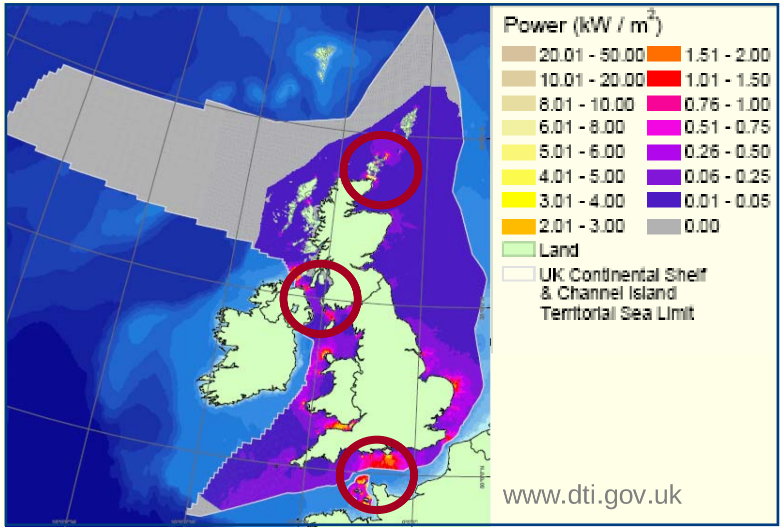
## Marine current energy

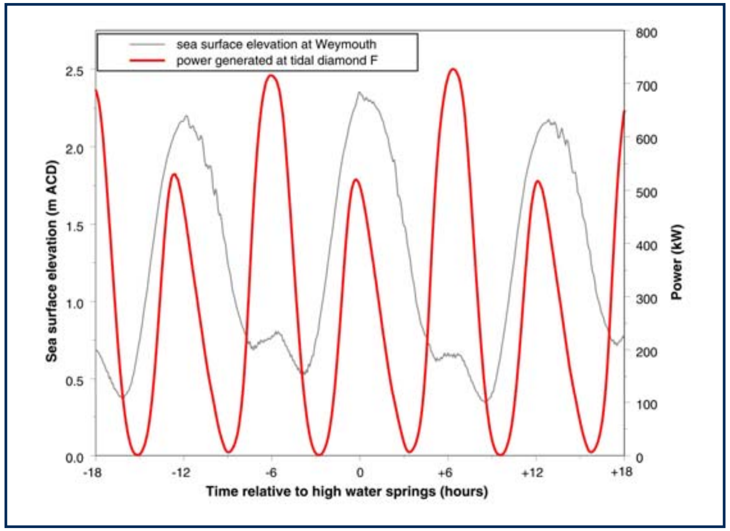


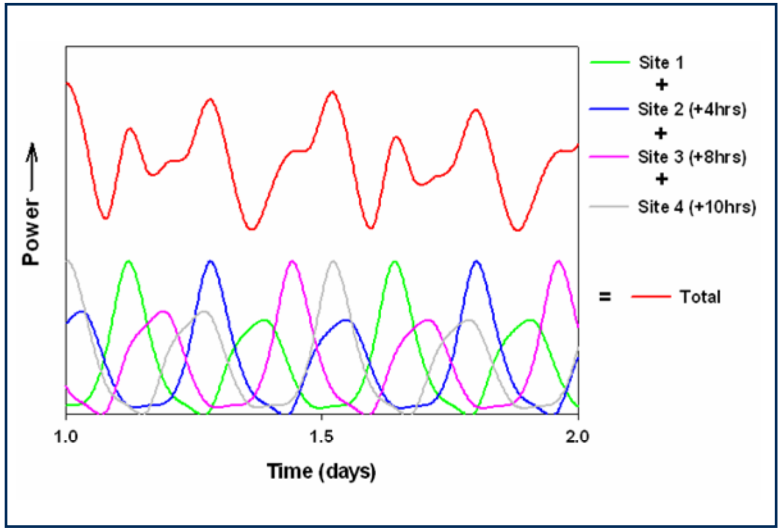

Predictable resource

Offset times of peak generation around the UK will smooth `output

## Marine current energy




Predictable resource




Offset times of peak generation around the UK will smooth output

# Drivers for R&D activities in marine renewables

- Introduction
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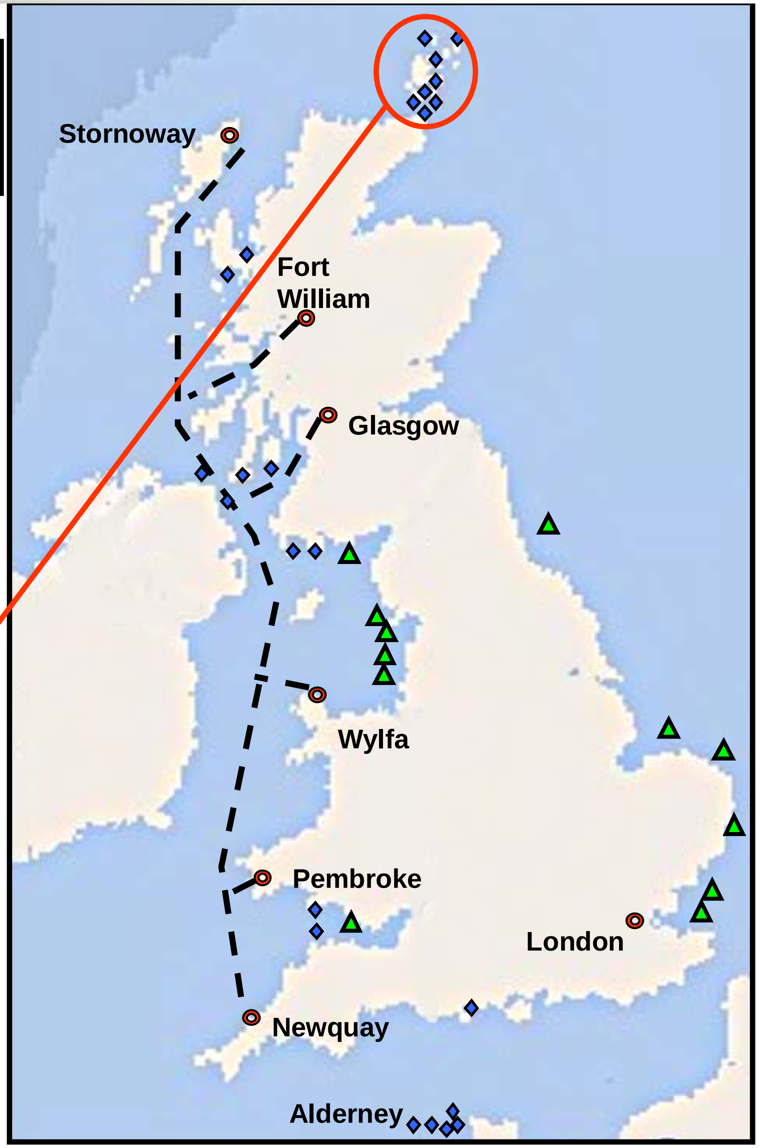



- Harnessing the energy from currents in the Pentland Firth in Scotland could supply 10% of UK electricity alone.

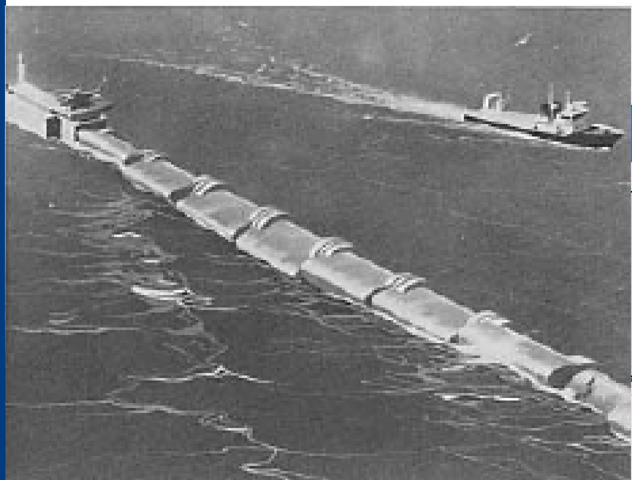
# Ocean Energy Devices

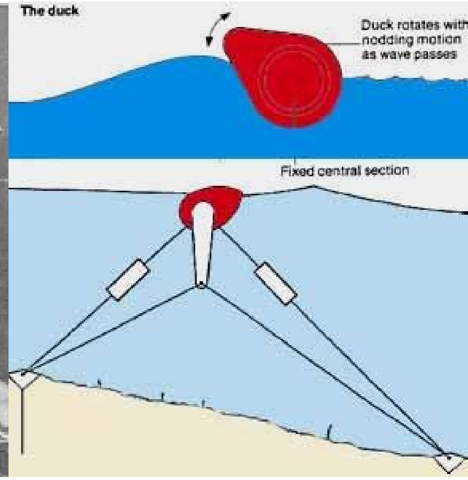


1. **Energy Capture** – Structure that converts the wave motion or tidal stream into mechanical action e.g. a horizontal axis rotor, an OWC tube or a structure that focuses waves.
2. **Power take off** – Mechanical motion is transferred to a type suitable for input to a stage where electrical energy is produced. This sub-system may include a gearbox, a set of lever arms and pistons driving hydraulic fluid or an air driven turbine.
3. **Control Systems** – Some devices may be actively controlled and so require components to regulate energy capture and perform other tasks. Data necessary for such control may be stored within the device or possibly gathered from exterior sensors.
4. **Electrical conversion** – a generator. It may be mechanically or hydraulically driven and be of a fixed or variable speed type.
5. **Electrical transmission** – generated electricity conveyed to the national grid. This subsystem includes power electronics, cables transformers, circuit breakers etc.
6. **Fixing/Moorings** – How each device will be fixed in place in the marine environment. It may include various types of piles, gravity structures, anchors and cables.

# Wave Energy R&D – Historical steps

1970’s - Government funded projects (UK, Norway, Japan).
Lack of offshore experience, high costs.






Salter Duck

www.mech.ed.ac.uk/research/wavepower

Development of Wells turbine

1970 1980 1990 2000

# Wave Energy R&D



1980’s – Funding dried up. A few projects continued.

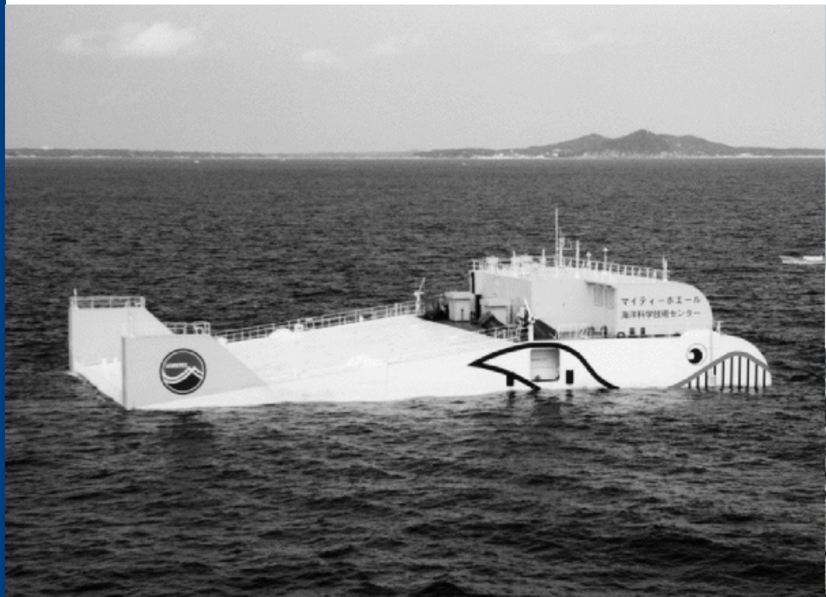

Norwegian Tapchan (85-89)

Japanese Sakata OWC (88)

# Wave Energy R&D



1990's - Renewed interest in wave energy



Mighty Whale (98-2000)

Limpet (2000)

www.wavegen.co.uk

# Wave Energy R&D

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**Wave Energy**

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Conclusion

2000 - Race to commercialisation

Pelamis

www.oceanpd.com

Wavedragon

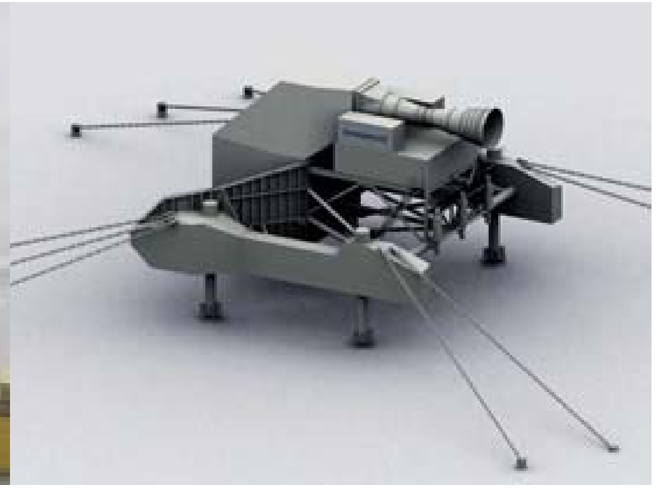
www.wavedragon.net

# Wave Energy R&D



2000 - Race to commercialisation





Powerbuoy

www.oceanpowertechnologies.com

Energetech

www.energetech.com.au

# OffShore Devices


Picture courtesy of OPD Ltd

The **Pelamis** WEC developed by Ocean Power Delivery Ltd is a horizontal slender articulated cylinder, held on station in the water surface by a compliant mooring system that allows the machine to weathervane to align itself head-on to incoming waves.

- The **Pelamis** hinged joints have two perpendicular degrees of freedom, pitch and yaw, linking the segments of the machine.
- The wave-induced motion at the joints is resisted and controlled by hydraulic rams that pump high-pressure oil into smoothing accumulators.
- The hydraulic motors drive electrical generators to produce electricity.
- Power from all the joints is fed down a single umbilical cable to a junction on the seabed.
- Several devices can be connected together and linked to shore through a single sub-sea cable.

# OffShore Devices

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The **survivability** of the machine is as central to the design as the power extraction.

A full-scale prototype 120m long and 3.5m in diameter, with a rated power of 750kW, is presently deployed at the European Marine Energy Centre in Orkney, Scotland .

# Economic Assessment

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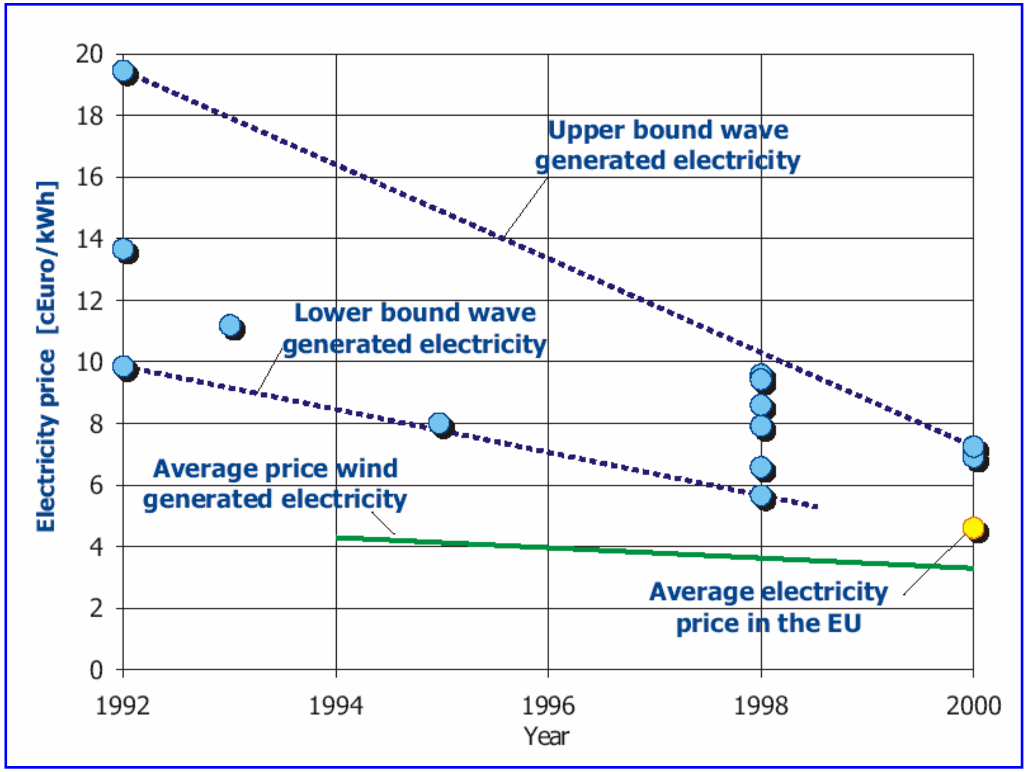



- The resulting costs against the year in which the design of a device was completed shows a significant reduction in generating costs.
- At best, this is similar to improvement of generating costs for wind turbines,
- There are now several wave energy devices with predicted costs of about 8,5 cEUR/kWh or less at 8% discount rate, if the devices achieve their anticipated performance.

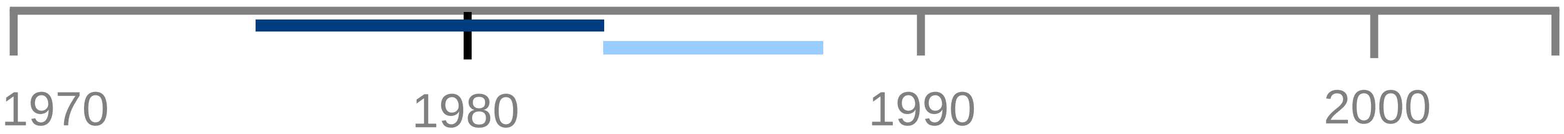
# Tidal Stream R&D

Early pioneers – river based vertical axis

Irrigation pumping

Canadian project

www.itpower.co.uk



# Tidal Stream R&D

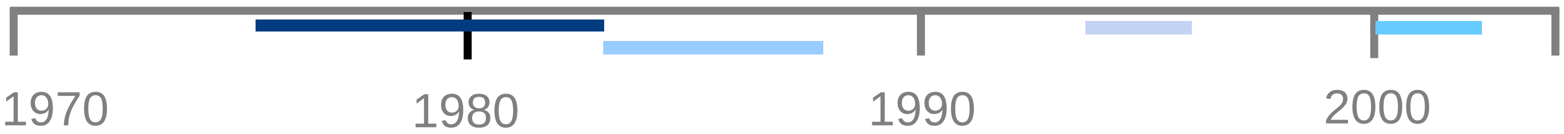
Further development


Loch Linnhe 15kW

www.itpower.co.uk

ENERMAR vertical axis

http://pontediarchimede.com



# Tidal Stream R&D



## 2000 onwards - Commercial scale

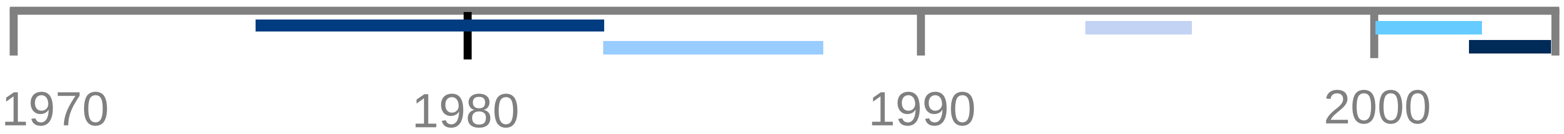


MCT Ltd - Seaflow

www.marineturbines.com

Hammerfest Strom

www.e-tidevannsenergi.com



# Tidal Stream R&D

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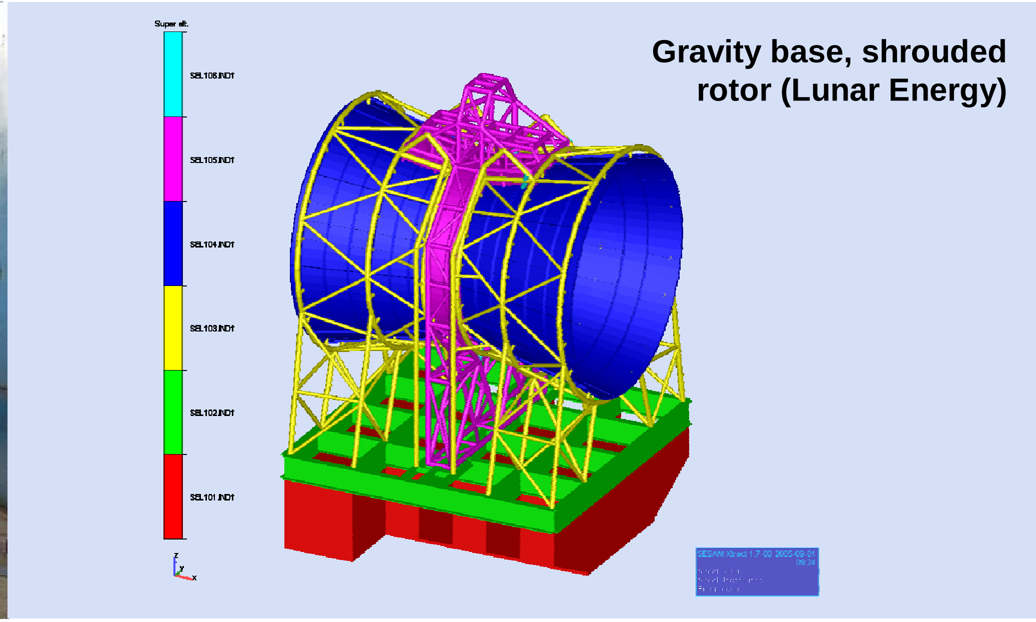
## 2000 onwards - Commercial scale

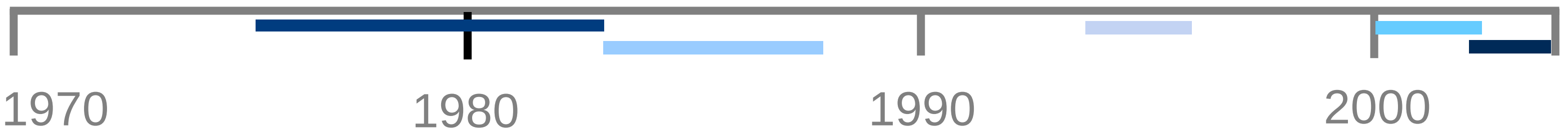




TidEL

www.smdhydrovision.com

Lunar Energy

www.lunarenergy.co.uk

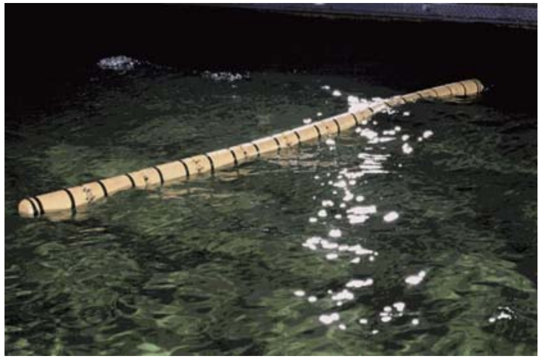


# Universities Industry Interaction?

## Collaboration Structure

| Activity | Universities | Industry |
|---|---|---|
| Device Scale | Model | Prototype |
| Work Approach | Investigation | Commercial focus |
| Time Constraints | Low | High |
| Facility Costs | Discounted | Business rates |
| Manpower | Large | Small |

## Cross Collaboration



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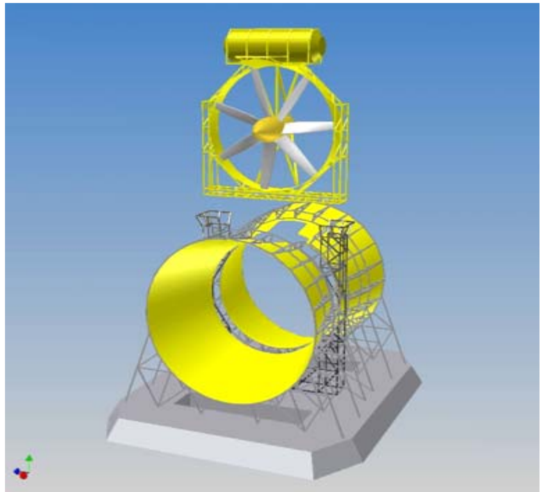
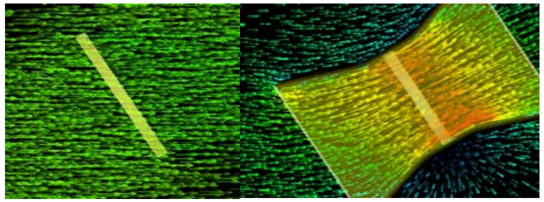




Introduction

Industrial R&D

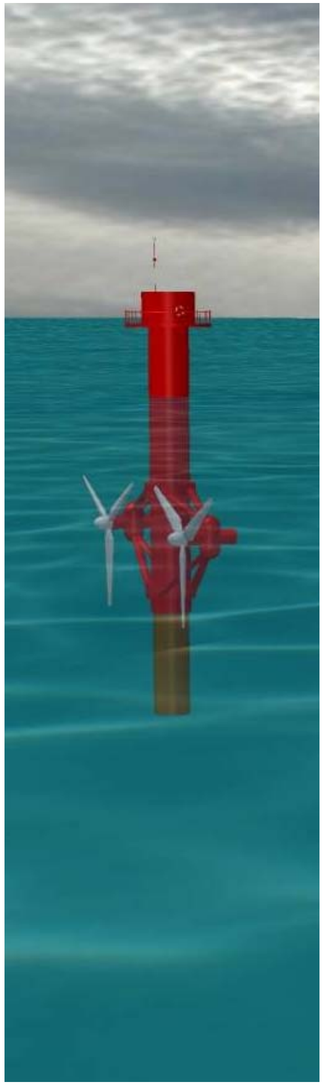
Power

Elements of Research

Initial Estimation

# Expected power from a device?

| Diameter (m) | Speed (knots) | Speed (m/s) | Power (kW) | Force (kN) |
|---|---|---|---|---|
| 10 | 4 | 2.1 | 140 | 170 |
| 20 | 4 | 2.1 | 561 | 682 |
| 30 | 4 | 2.1 | 1263 | 1534 |
| 10 | 5 | 2.6 | 274 | 266 |
| 20 | 5 | 2.6 | 1096 | 1065 |
| 30 | 5 | 2.6 | 2466 | 2397 |



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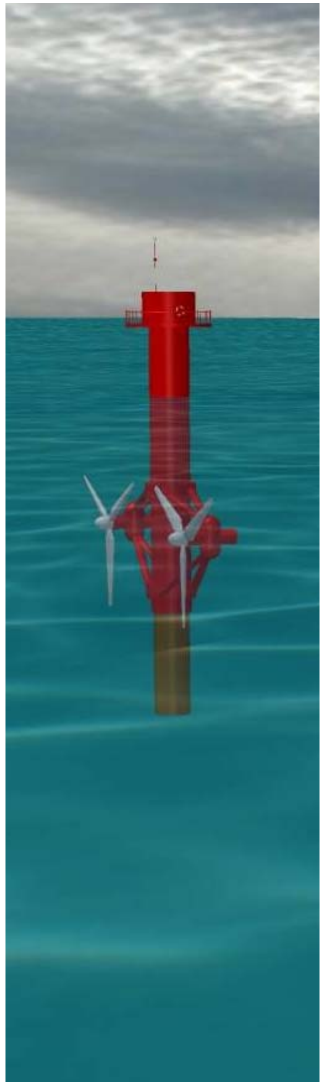

# Model Tests

## Single Device Performance

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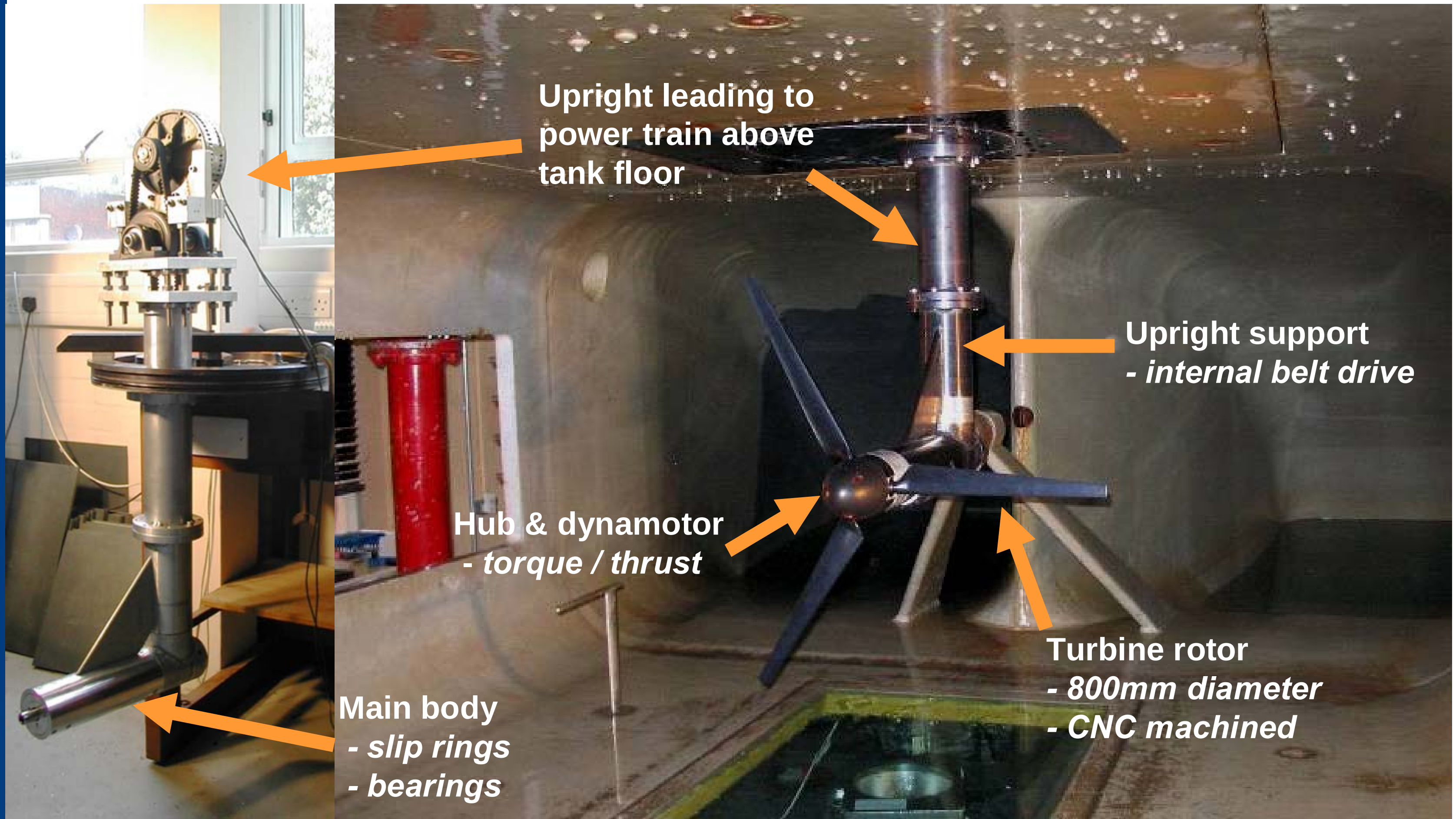

# Power and Thrust - Experiment vs Theory

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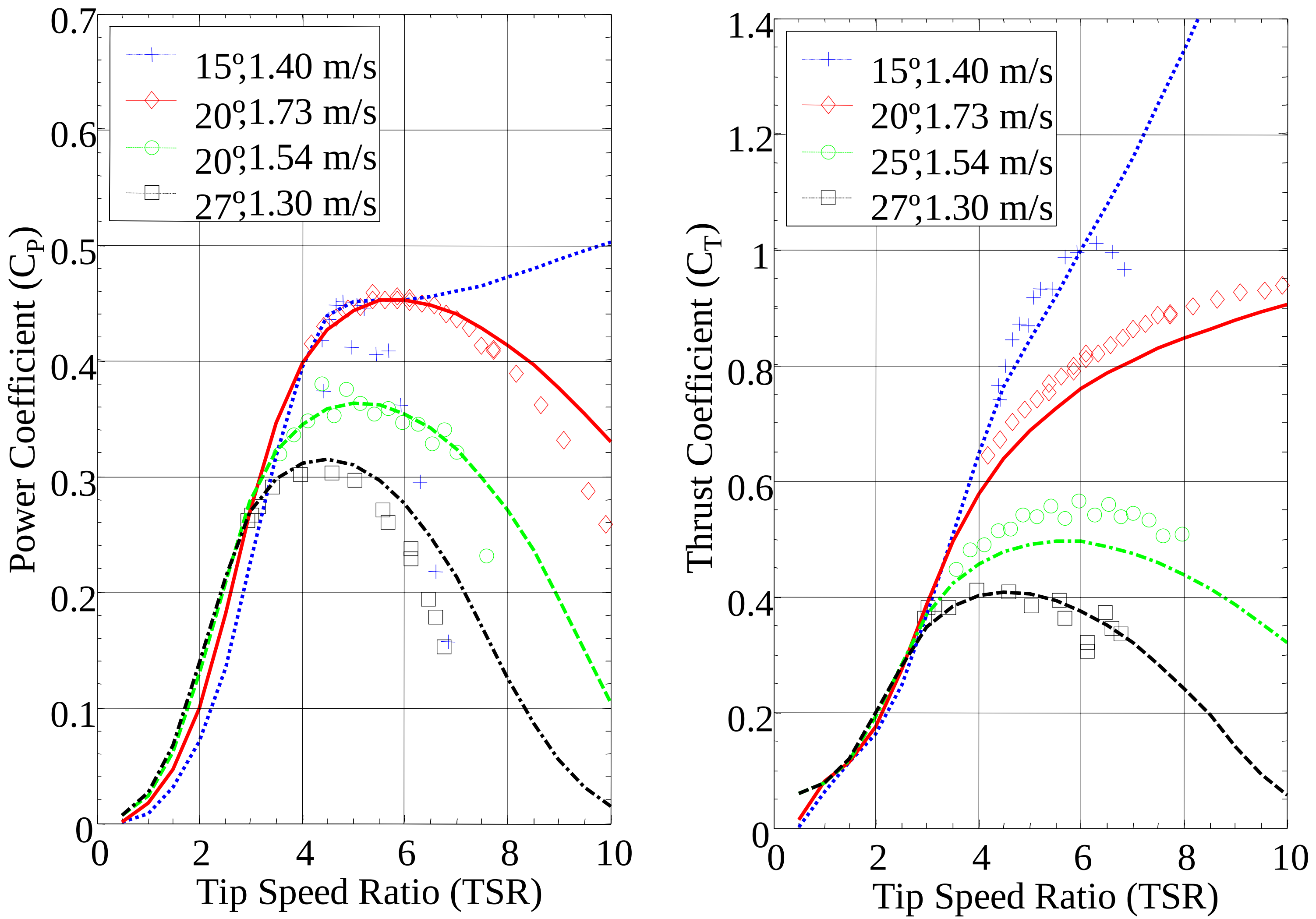
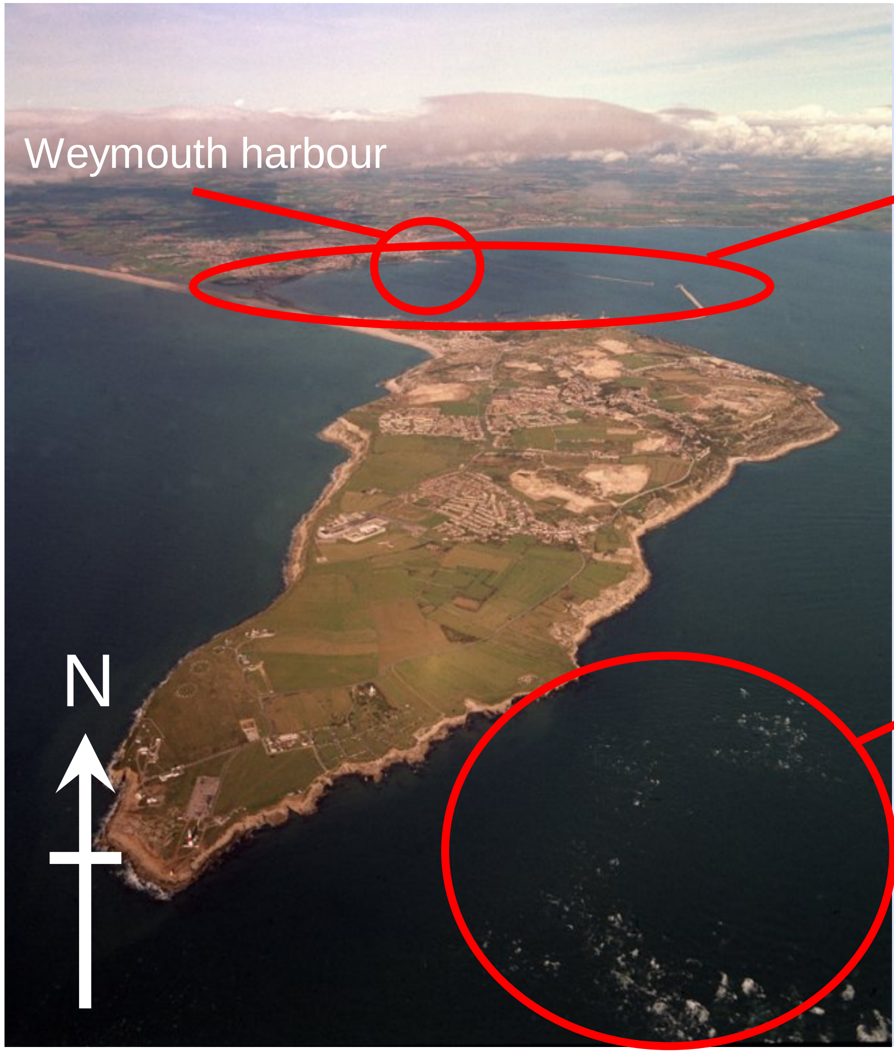


# Current Research Areas - Resource Assessment

- Introduction
- Industrial R&D
- Power
- **Elements of Research**
- Initial Estimation

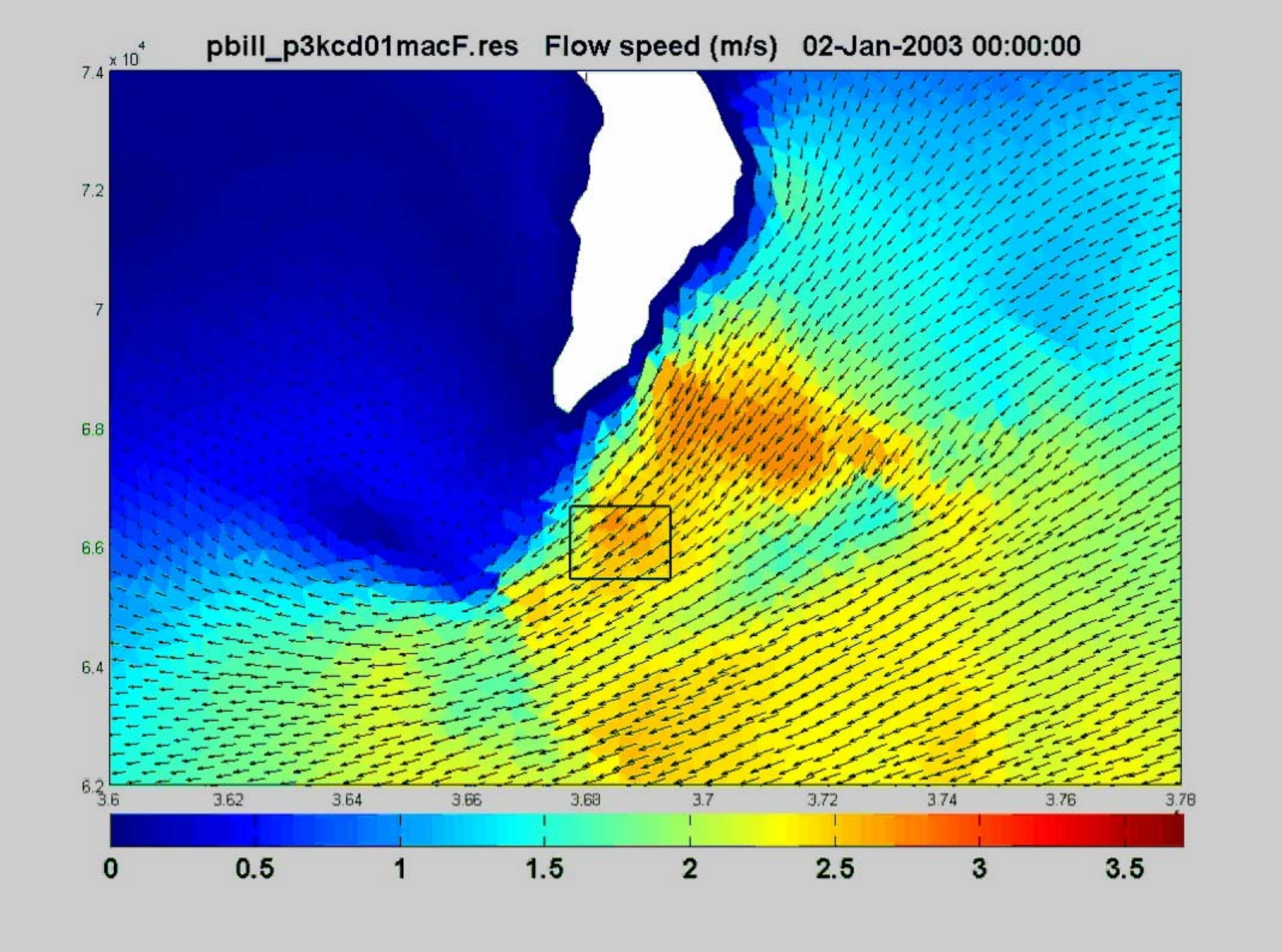



Portland harbour

Overfalls

Case Study – Portland Bill

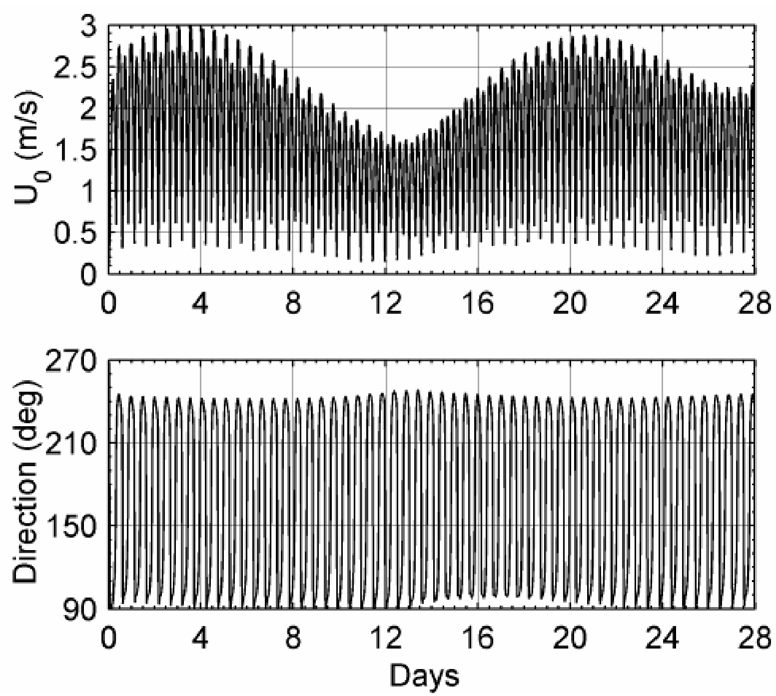
# Portland Bill with no energy extraction



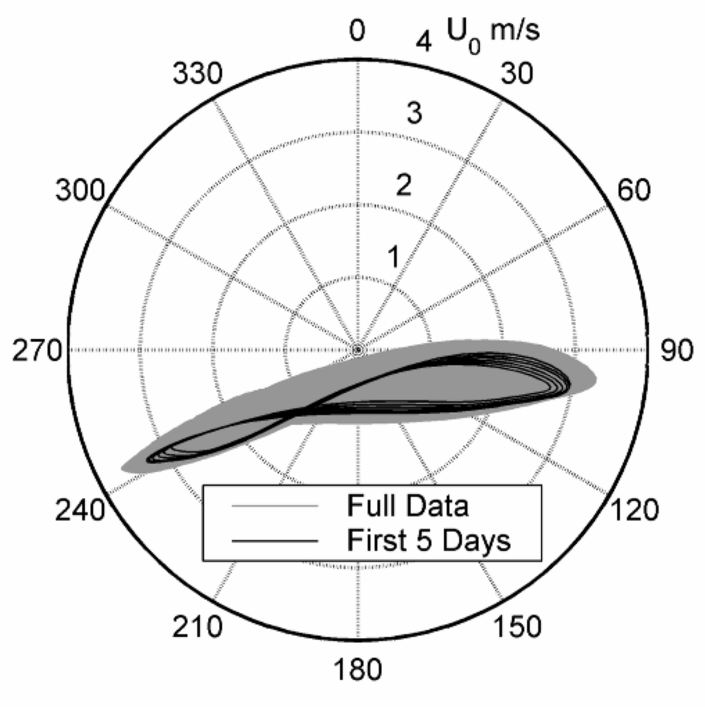
# Resource Estimates and Forecasting

## Portland Bill

### 28 Day Prediction



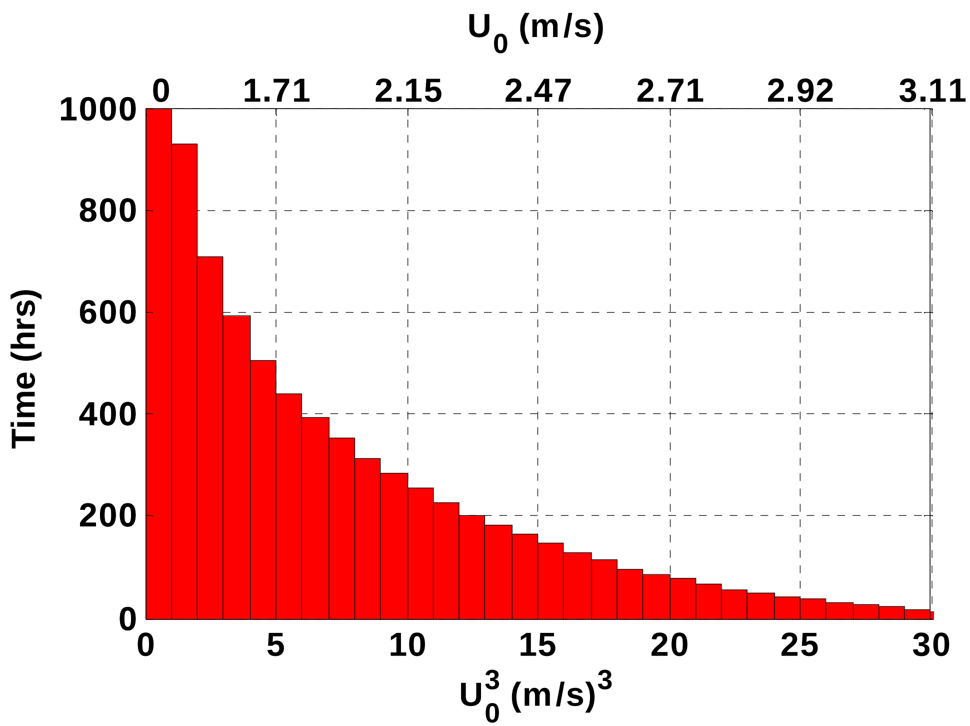

### Hodograph



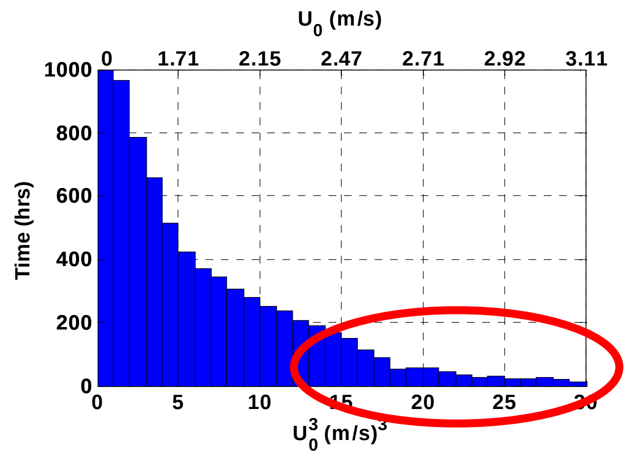
# Resource Estimates and Forecasting

## Portland Bill

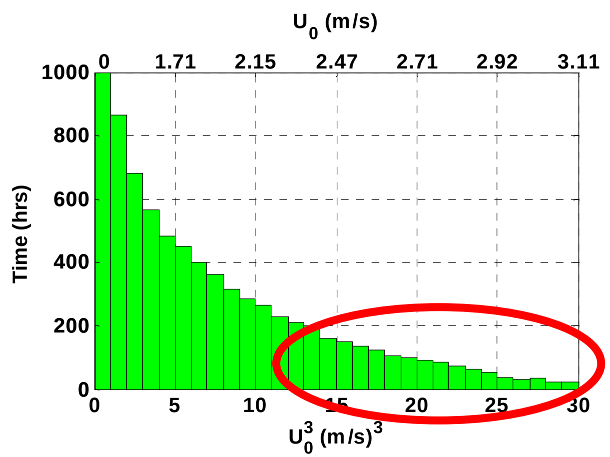
### Annual Average for 18 years




### Prediction for 2006




### Prediction for 2016



# Resource Estimates and Forecasting
## Portland Bill

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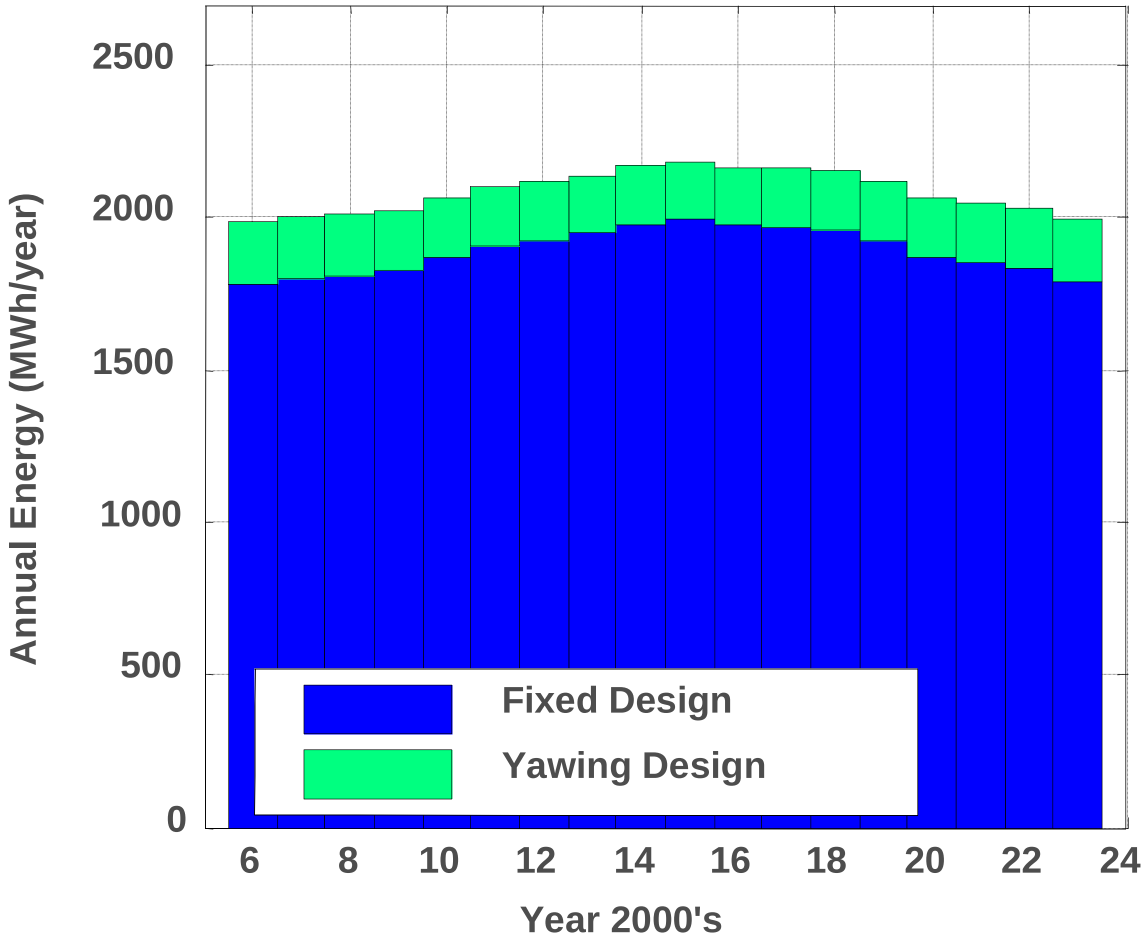
Initial Estimation

- **Example energy 16m Turbine rated at 2.5m/s**



Introduction

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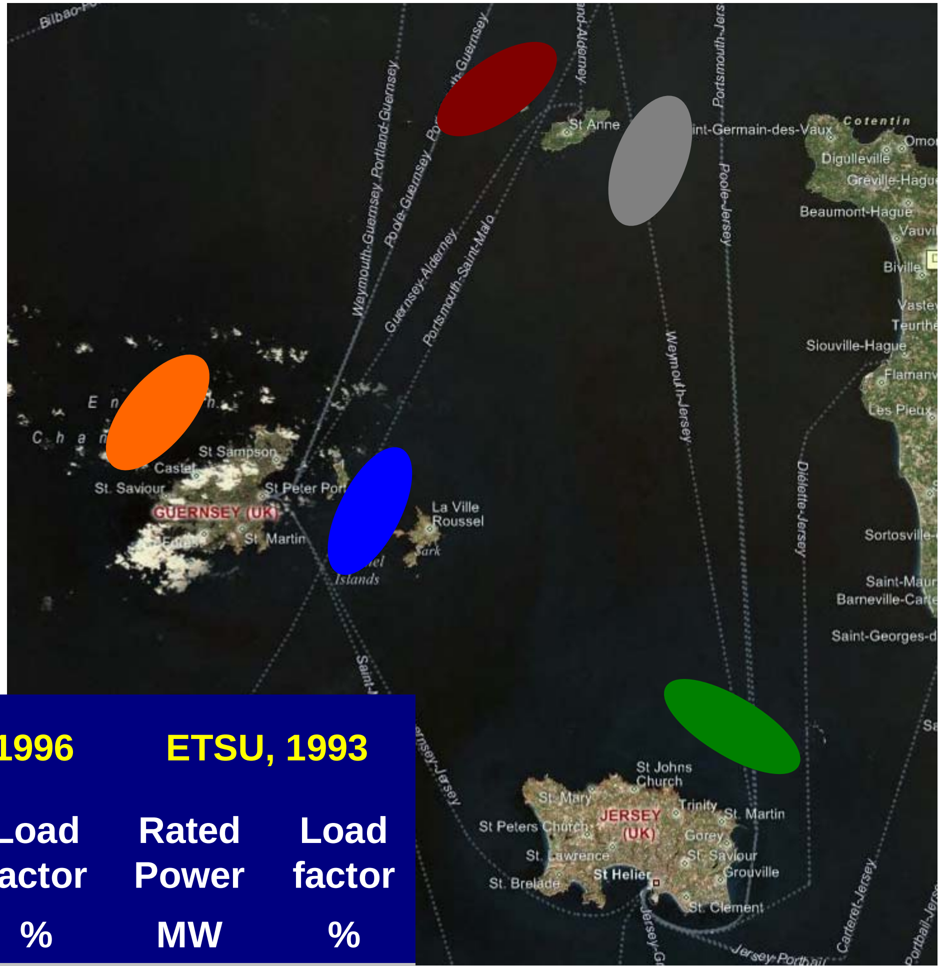
**Initial Estimation**

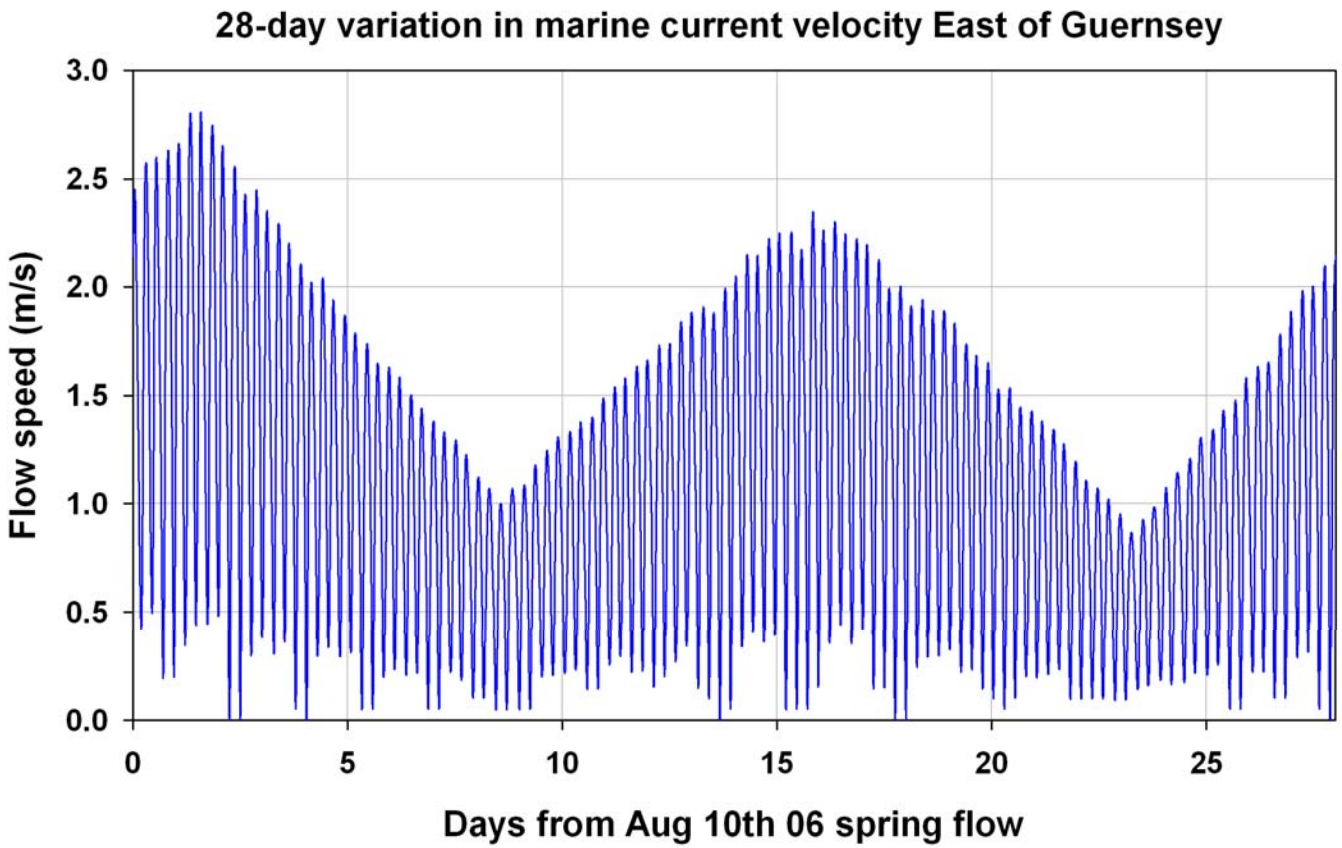
# Previous work on the Channel Islands resource

- Five sites around channel islands have been identified.
- Expected 1st generation tidal sites to have tidal speed from 2-3 m/s.




| Tidal Race | Area | Max. Speed | Black and Veatch 2004 Rated Power | Black and Veatch 2004 Load factor | Joule 2, 1996 Rated Power | Joule 2, 1996 Load factor | ETSU, 1993 Rated Power | ETSU, 1993 Load factor |
|---|---|---|---|---|---|---|---|---|
| | km² | m/s | MW | % | MW | % | MW | % |
| Race of Alderney | 102 | 4.4 | 394 | 49 | 1973 | 44 | 2407 | 23 |
| Casquets | 190 | 2.6 | 538 | 35 | 370 | 50 | 2943 | 13 |
| NW Guernsey | 222 | 2.1 | 170 | 33 | 422 | 54 | 2186 | 22 |
| Big Russel | 59 | 2.6 | 101 | 43 | 219 | 47 | 1001 | 22 |
| NE Jersey | 58 | 3.1 | 57 | 33 | 196 | 45 | 1179 | 13 |

# Example case study : Big Russel - East Guernsey




- **Tidal predictions from *TOTALTIDE***
  - This software interpolates from admiralty tidal data
  - Good for initial estimations but not detailed calculations

Introduction

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**Initial Estimation**

# Predicted energy output from small arrays

| Rated device parameters | | | Annual electrical outputs | | | |
|---|---|---|---|---|---|---|
| Flow speed (m/s) | Power kW | Thrust kN | Single device (MWh) | 20 device array (MWh) | 40 device array (MWh) | Load factor |
| 2.5 | 644 | 579 | 879 | 17,570 | 35,140 | 0.16 |
| 2.4 | 570 | 534 | 866 | 17,311 | 34,622 | 0.18 |
| 2.3 | 501 | 490 | 849 | 16,977 | 33,955 | 0.20 |
| 2.2 | 439 | 449 | 827 | 16,532 | 33,065 | 0.22 |
| 2.1 | 382 | 409 | 798 | 15,956 | 31,912 | 0.24 |
| 2 | 330 | 371 | 763 | 15,252 | 30,505 | 0.27 |

- **Possible configurations for a small farm of turbines in the Big Russel using *TOTALTIDE* data**
- **Calculations assumed a 16m turbine always facing the tidal flow.**

# Predicted energy output from small arrays

| Rated device parameters | | | Annual electrical outputs | | | |
|---|---|---|---|---|---|---|
| Flow speed (m/s) | Power kW | Thrust kN | Single device (MWh) | 20 device array (MWh) | 40 device array (MWh) | Load factor |
| 2.5 | 644 | 579 | 879 | 17,570 | 35,140 | 0.16 |
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| 2 | 330 | 371 | 763 | 15,252 | 30,505 | 0.27 |

Turbine costs

Energy output

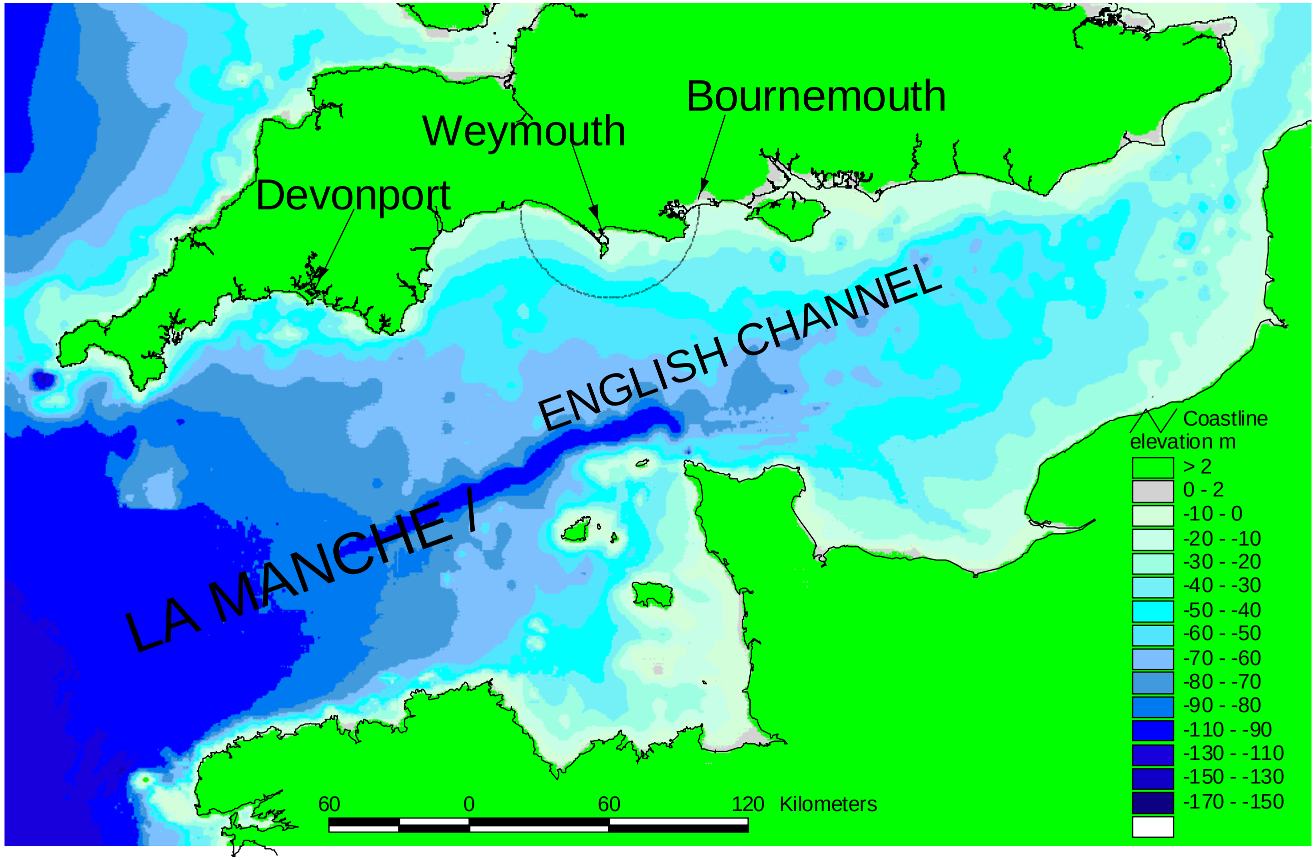
- **Possible configurations for a small farm of turbines in the Big Russel using *TOTALTIDE* data**
- **Calculations assumed a 16m turbine always facing the tidal flow.**
- **Optimum turbine design is a complex balance and without appropriate recourse assessment almost impossible**

# Resource evaluation



- A major factor in determining the economic viability of a tidal stream array or 'farm'
- Helps developers to optimize the placement of energy conversion devices with confidence, which
- Reduces risk for investors in tidal stream energy
- Direct measurements are expensive to obtain and are also discrete
- Numerical modelling can provide a continuous velocity field and include the effect of momentum sinks
- Cheap and quick to use… but must be validated

# Resource location : regional




- Introduction
- Wave Energy
- Tidal Stream Energy
- R & D in universities and industry
- Current Research Areas
- Conclusion

Introduction

Wave Energy

Tidal Stream Energy

R & D in universities and industry

Current Research Areas

Conclusion

# Future:

- Prototype devices to date appear promising, attracting finance
- UK Government Marine Deployment Fund

## DTI - £50m funding

### Capital grants

- 25% system costs
- £5M maximum award per developer

### Revenue support

- £100/MWh generated (10p/kWh)
- Fixed for 7 yrs
- Can also claim ROCs

**DTI to publish costs of projects such as O&M, availability of device etc.**