This document was prepared for the ETI by third parties under contract to the ETI. The ETI is making these documents and data available to the public to inform the debate on low carbon energy innovation and deployment.

Programme Area: Marine

Project: ReDAPT

Title: Learning from the ReDAPT Programme

Abstract:

A presentation of learnings from the ReDAPT project covering site measurements; hydrodynamic modelling; turbine and electrical design; testing; operation; maintenance and site working; and marine operations and environment.

Context:

One of the key developments of the marine energy industry in the UK is the demonstration of near commercial scale devices in real sea conditions and the collection of performance and environmental data to inform permitting and licensing processes. The ETI's ReDAPT (Reliable Data Acquisition Platform for Tidal) project saw an innovative 1MW buoyant tidal generator installed at the European Marine Energy Centre (EMEC) in Orkney in January 2013. With an ETI investment of £12.6m, the project involved Alstom, E.ON, EDF, DNV GL, Plymouth Marine Laboratory (PML), EMEC and the University of Edinburgh. The project demonstrated the performance of the tidal generator in different operational conditions, aiming to increase public and industry confidence in tidal turbine technologies by providing a wide range of environmental impact and performance information, as well as demonstrating a new, reliable turbine design.

Learning from the ReDAPT Programme

Learning from the ReDAPT Programme

Introduction to Alstom Ocean Energy

1. Site Measurements
2. Hydrodynamic Modelling –Device Scale
3. Turbine Design
4. Electrical Design
5. Test
6. Operation
7. Maintenance / Site Working
8. Marine Operations
9. Marine Environment

Alstom global marine renewable offering

TIDAL IN STREAM

OFFSHORE WIND

TIDAL BARRAGE

Alstom 1MWe turbine at the heart of the ReDAPT* programme

ReDAPT

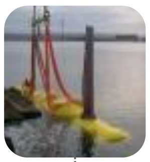
- Demonstrating commercial scale device in real sea-state conditions.
- To provide the industry with a wide range of environmental impact and performance information, as well as demonstrating the reliability of the turbine.
- 1st deployment in January 2013 at the EMEC (European Marine Energy Centre – Orkney, Scotland).
- Testing programme :
  - Power curve demonstrated
  - Over 1.2 GWh produced
  - Autonomous running
  - Validation of design tools
  - Installation process and free ascent demonstrated
  - Gathering data on performance, site characteristics and environmental interactions

* Reliable Data Acquisition Platform for Tidal co-funded by the Energy Technologies Institute (ETI)

Alstom tidal technology - A phased learning journey

Tidal Generation Ltd. (TGL) formed In Bristol

TGL/R-R **500kW first tests**

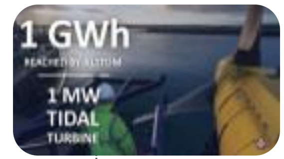


Alstom Ocean Nantes formed R&D activity

500 kW turbine tests completed: 250MWh

Alstom Acquisition of TGL: ETI **1 MW demo turbine trials** start at EMEC

1 GWh achieved



Raz Blanchard pilot array **OCEADE™ 18 – 1.4MW**

2005 …. 2009 2010 2011 2012 2013 2014 2015 2017 / 18

Tidal Generation

ROLLS ROYCE

ALSTOM

PROVE → IMPROVE → EVOLVE

Phased development working towards a reliable cost effective commercial offering

* European Marine Energy Centre – Orkney, Scotland

Ocean dedicated teams

- An integrated team in France and UK, 12 years of combined experience in Tidal:
  - **Prove**: has Run 500kW & 1MW tests at EMEC. 1.4GWh + injected to the grid
  - **Improve**: Finalising design of commercial tidal platform and interconnection solution (Subsea Hub)
  - **Evolve**: Running an R&T program, focusing on cost reduction, yield and reliability improvement
- Tidal R&D in Nantes:
  - 40 tidal engineers
- Tidal R&D in the UK
  - 40 tidal engineers

Next Generation - Oceade™18 - 1.4MW

Built on over 10 years combined knowledge and experience in the UK and French tidal teams:

- **1.4MW rated at 3.1m/s**, 3-bladed machine
- **18m diameter rotor**, scalable up to 23m
- **Industrialisation**: fully modular design
- **Reliability** and redundancy on key systems
- **Maintainability**
  - Line-replaceable "plug-and-play" units or module interchange for rapid turn-around times
  - Rear door and man-hatch for enhanced maintainability
- **Oceade™ a platform concept**
  - Flexibility and optimum exploitation of the tidal resource

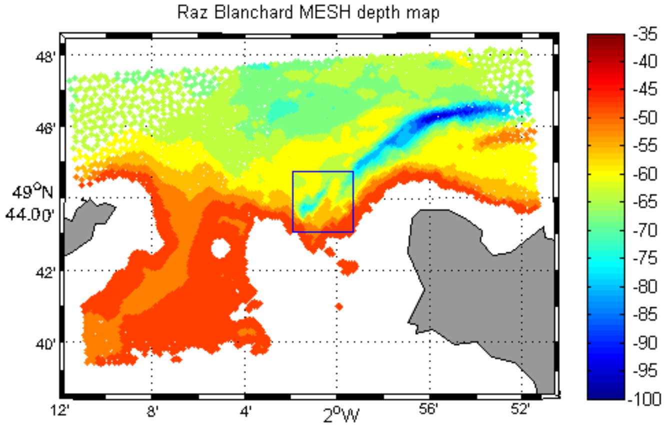
Oceade™18 - 1.4MW - Yawing nacelle

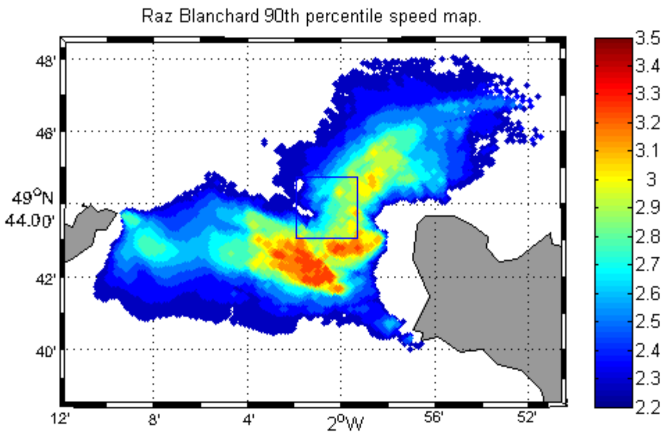
- **Buoyant design**
  Rapid turbine deployment and retrieval system
  - Patented system to winch the nacelle down to its seabed support structure and lock it in place
  - No need for high cost heavy-lift vessels; diverless operation
  - The lowest risk and most flexible O&M solution
- **Yawing nacelle**
  Based on proven technology, thruster rotates the nacelle to face the incoming tide
- **Pitching blades**
  Control load on the turbine and optimise use of the tidal conditions locally

Efficient, simple and reliable energy production

Oceade™ Platform

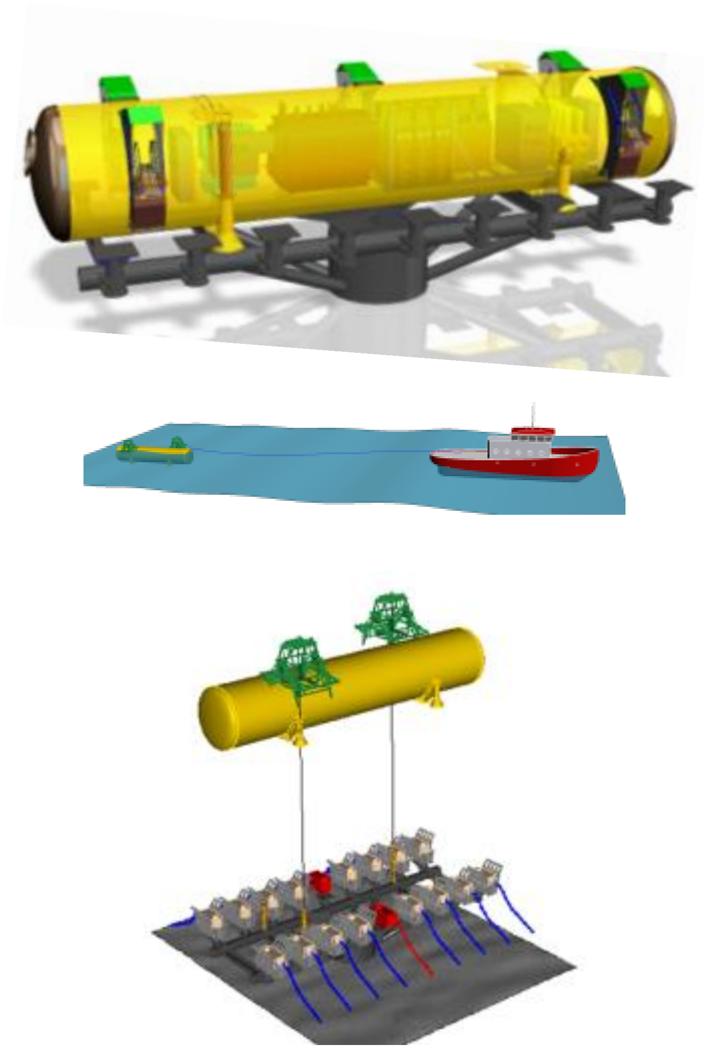
Optimise yield by adapting to local conditions and farm layout





- Develop a family of turbines to address the versatility of tidal sites conditions in depth and water velocity
- Optimise a commercial farm output with different diameters and rated powers
- Develop the number of common parts to decrease the cost of electricity and ease maintenance

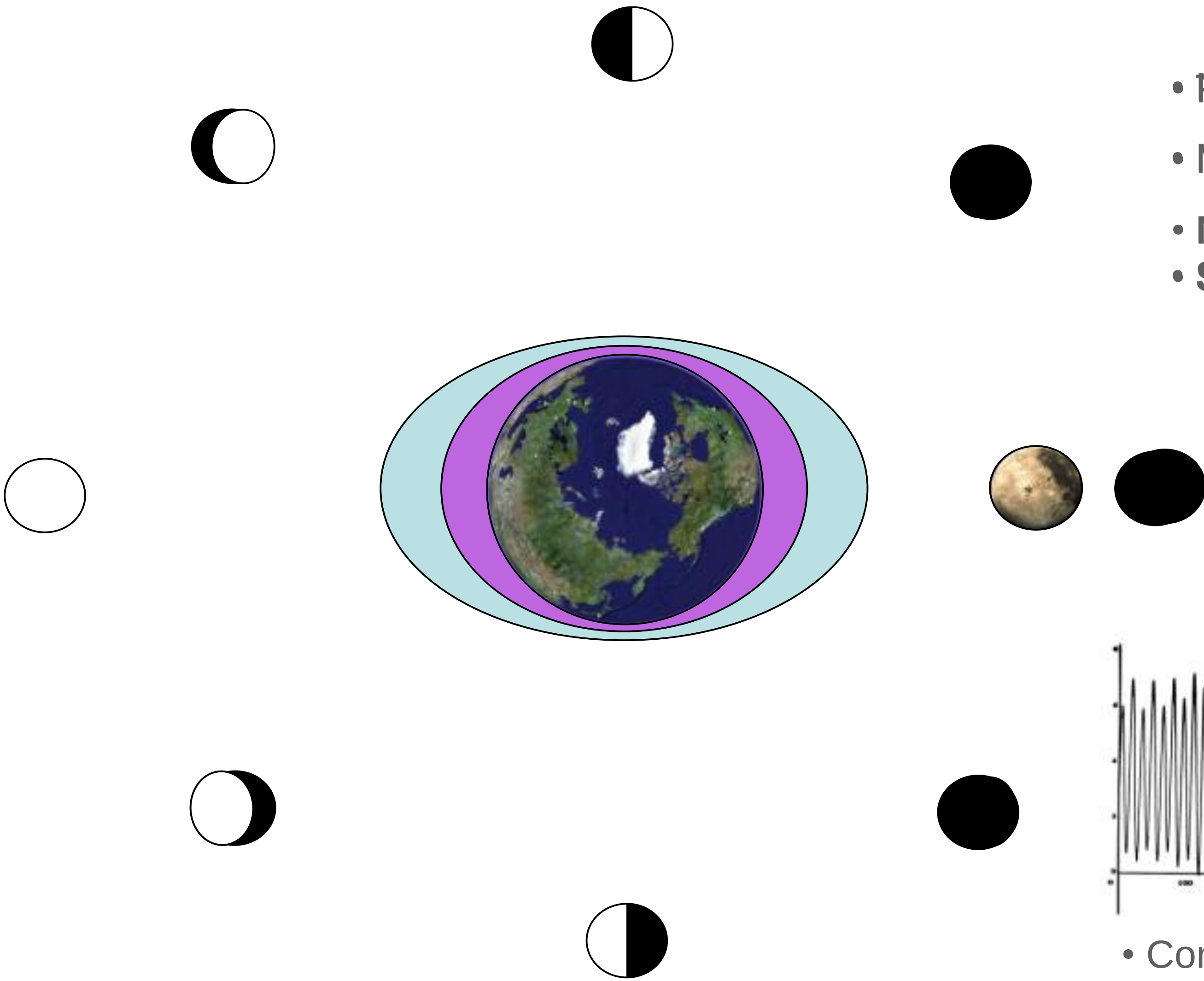
Sub-sea Hub – Develop enabling technology for arrays



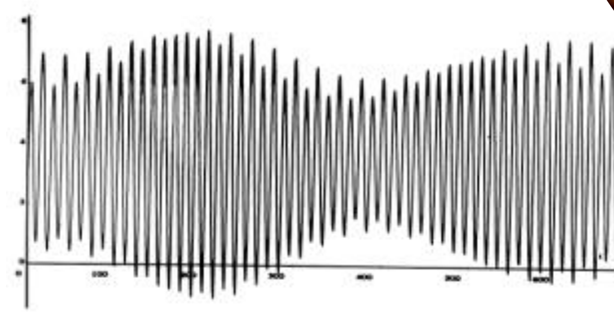
- **Subsea Hub R&D programme supported by Innovate UK (MESH) and French ADEME (PRISMER)**
- **Solve the problem of interconnecting** an array of turbines to a single export cable and therefore enable sales of Oceade™ turbines into commercial farms
- **Use of the proven buoyant solution to deploy and retrieve**
- Subsea Hub available for the first pilot arrays

Tidal resource – the physics bit

VIDEO



- New Moon / First Quarter / Full Moon / Third Quarter
- Moon in conjunction / opposition / quadrature
  = syzygy
- Neap Tide
- Spring tide

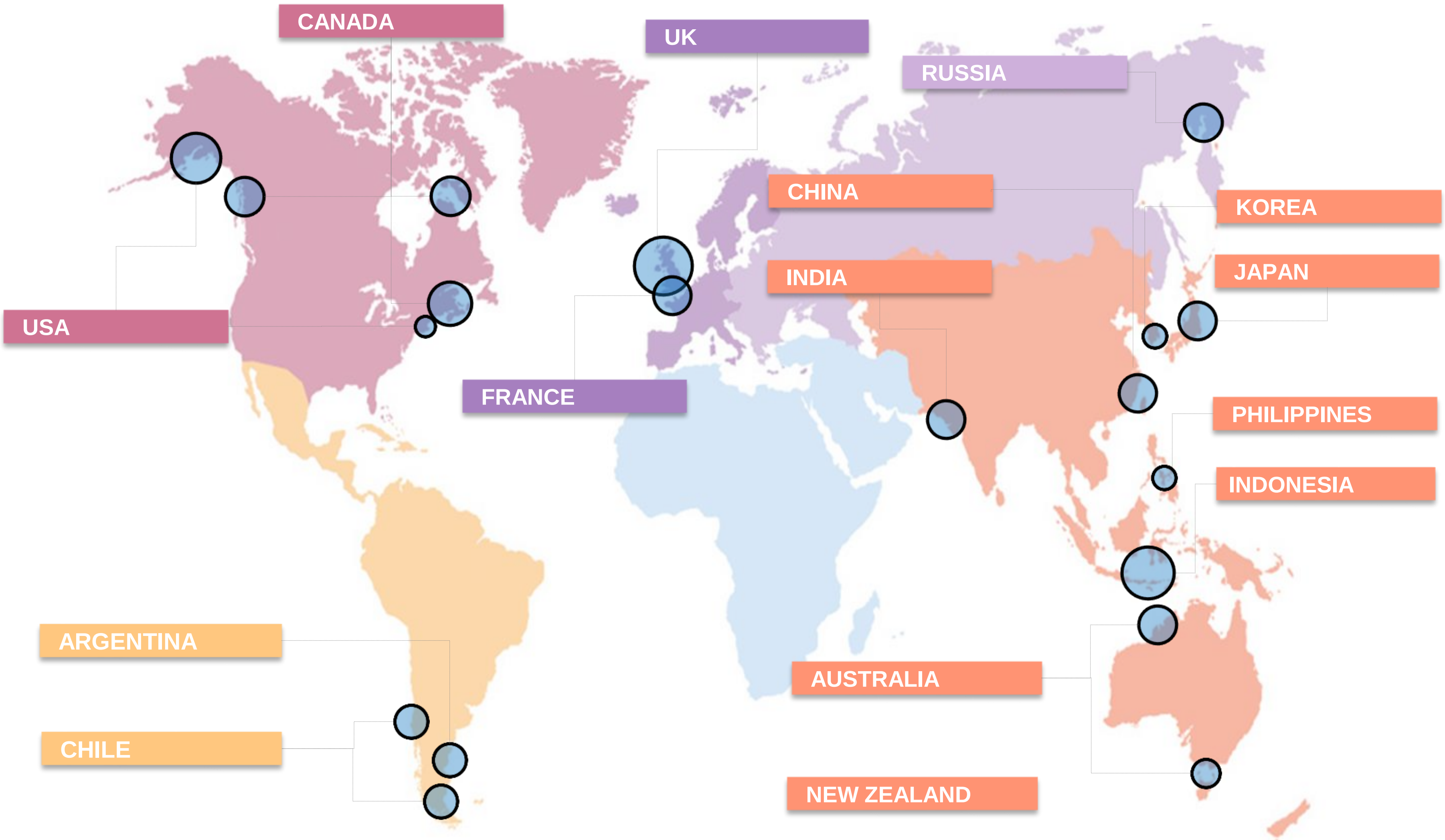


- Complete cycle takes 29.5 days

Tidal energy – reliable, predictable, inexhaustible

ReDAPT

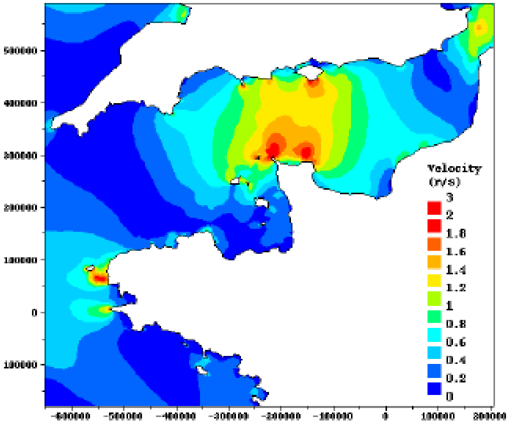
Tidal energy: high potential location

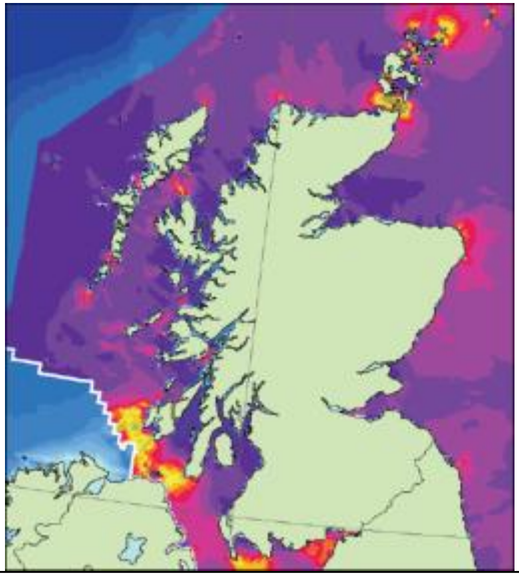


Exploitable potential from 50 to 100GW

UK and French markets

- In France estimated resource > 5 GW
  - Mainly concentrated in the Basse-Normandie Region with Raz Blanchard (3GW+) and Raz de Barfleur (0.5-1GW)
  - also Bretagne region with the passage du Fromveur (0.2-0.5GW)
- In UK estimated resource > 10GW
  - Mainly concentrated in Scotland (Pentland Firth and Orkney Waters) and Western Scotland
  - Also Northern Ireland, Anglesey, Isle of Wight and Alderney Races





50 to 100GW worldwide

1 Site Measurements

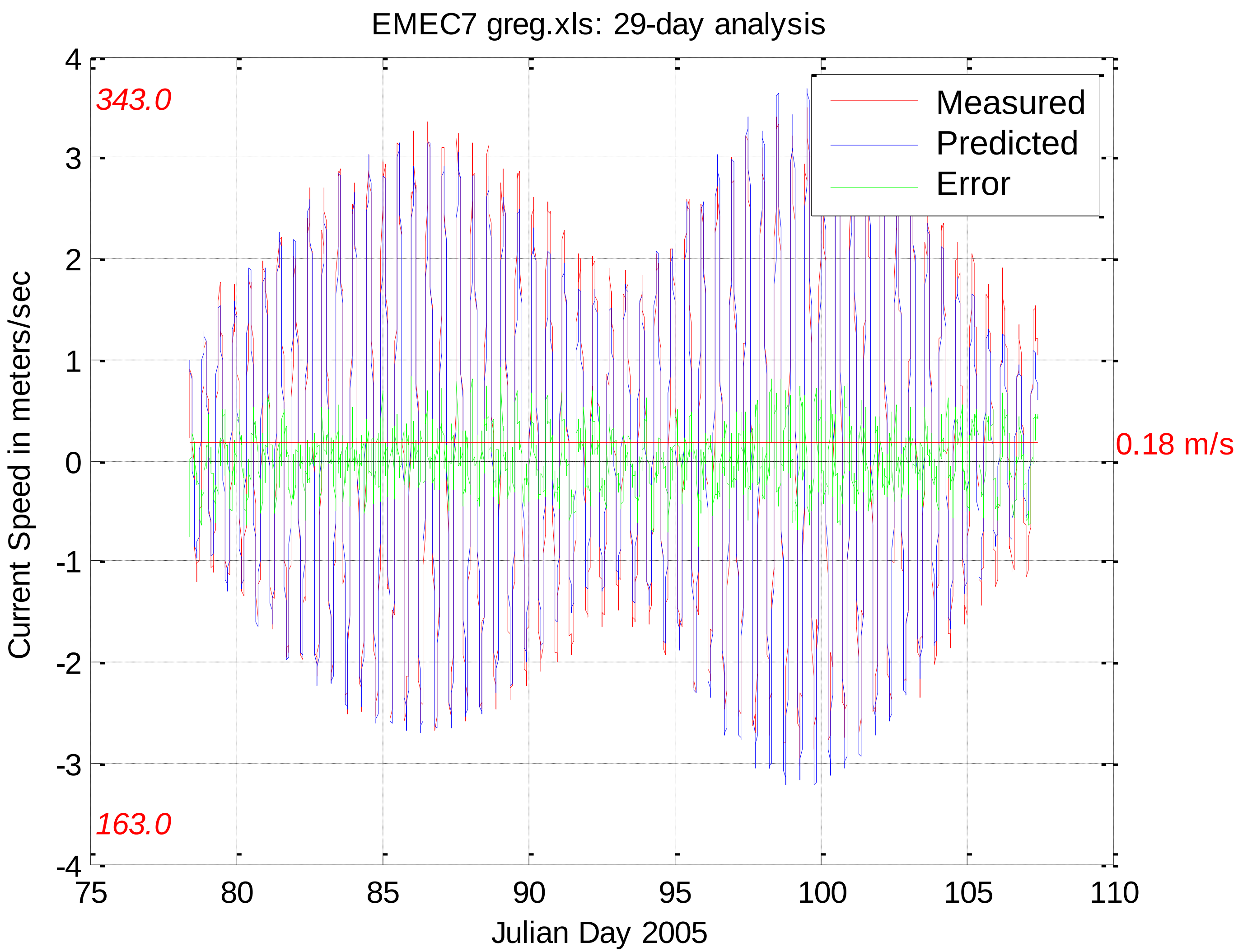
1.9 Long Term Flow Prediction

- Collect at least 29 days of Tidal flow data for the area of interest.
  - The most significant tidal harmonic constants have periods of less than 29 days so this much data gives a good prediction.
- Produce a power weighted rotor average flow velocity from the data.
- Perform Tidal Harmonic analysis on the data (eg. Using World Currents) to produce an estimate of the tidal harmonic constants that define the tidal flow at the site.
- Use these tidal harmonic constants to predict the flow into the future using a program such as World Currents.
- Apply the turbine efficiency curve to this prediction to estimate turbine energy production over the period.

1.9 Long Term Flow Prediction

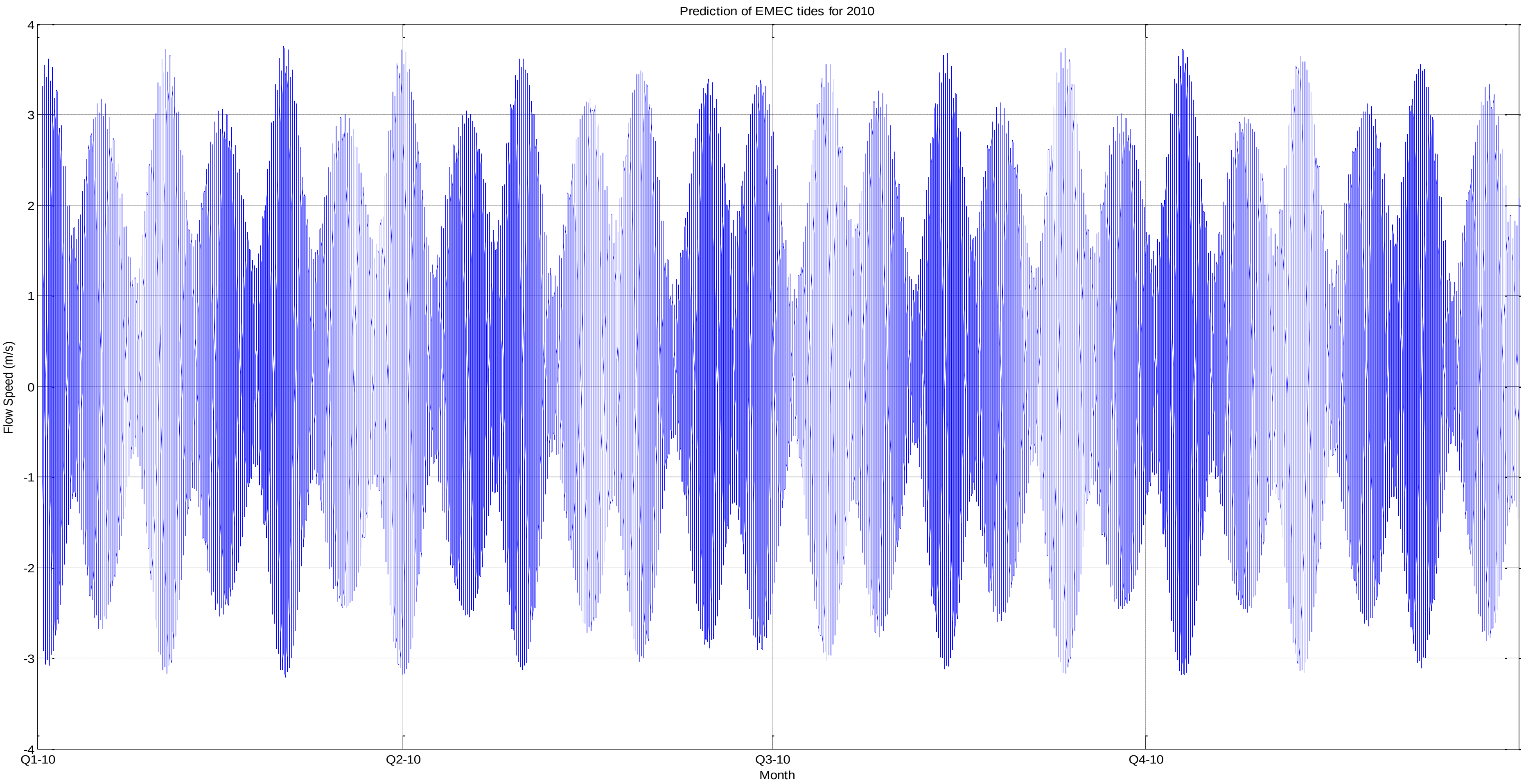
Example analysis of EMEC Tidal data from a 29 day dataset using World Currents.

The blue line is made up of a number of tidal harmonic constants.



1.9 Long Term Flow Prediction

- Prediction of EMEC flow speed in 2010 using World Currents



1.10 Choice of reference velocity

Why use a reference velocity?

- Defining the environment:
  - Flow speed distribution
  - Turbulence intensity: $\frac{u'}{U_0}$
- Turbine definition:
  - Cut-in velocity
  - Rated velocity
  - Relation of loads and performance to velocity

1.10 Choice of reference velocity

What can be used?

- Depth-averaged velocity
- Surface velocity

Easily measured for a given environment

- Hub-height flow speed
- Rotor-area-average flow speed
- Power-weighted rotor-area-average

Relate to turbine definition (hub-height and rotor diameter)

As tidal flows are unsteady the reference velocity should also be averaged for a suitable time period.

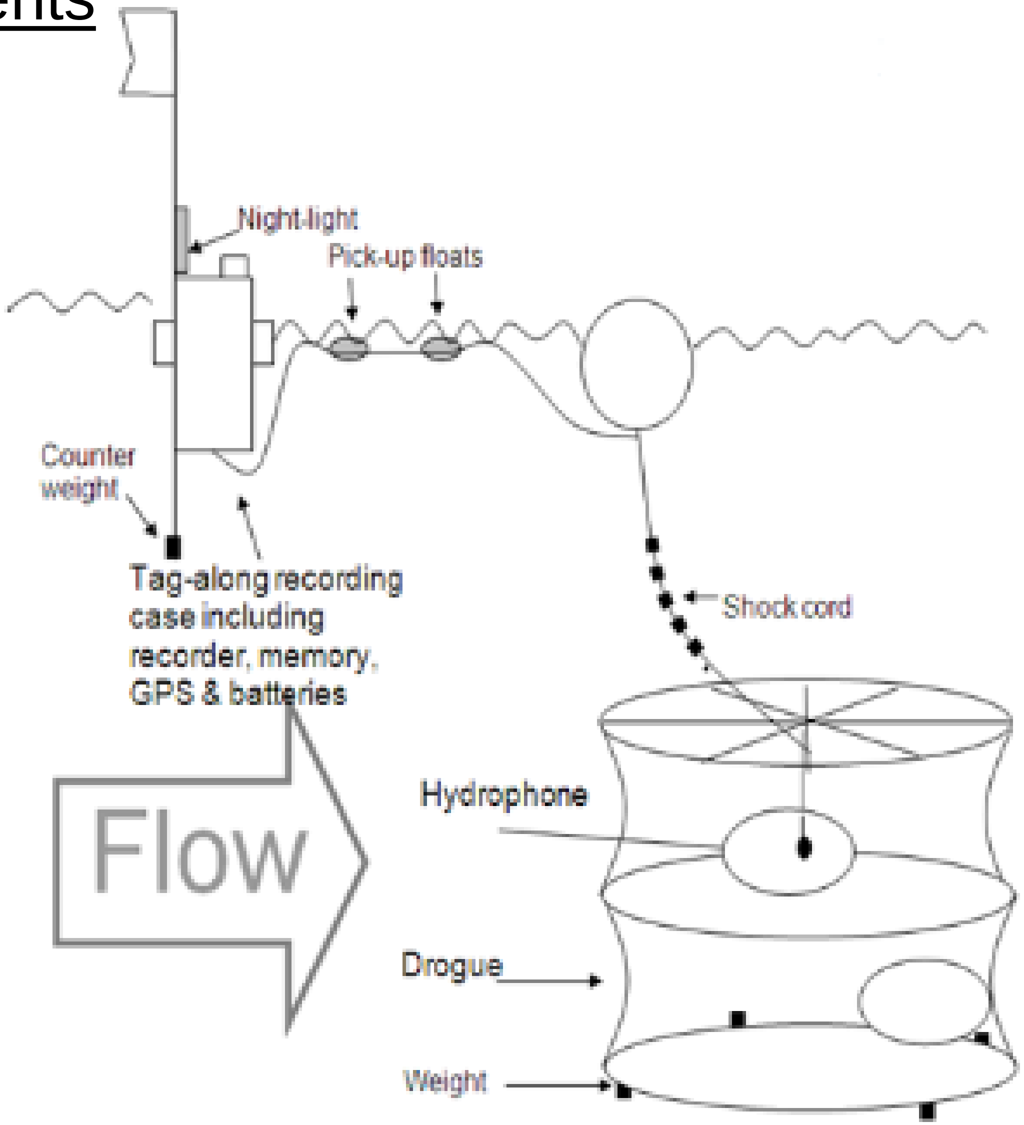
1.10 Choice of reference velocity

Power-weighted rotor-area-average:

- Physical representation of the power available to the turbine’s swept area.
- Recommended by IEC/TS 62600-200 for power curve measurement.
- Repeatable correlations between turbine parameters if used.
- Standard procedure “method of bins” for measuring using a current flow profiler.

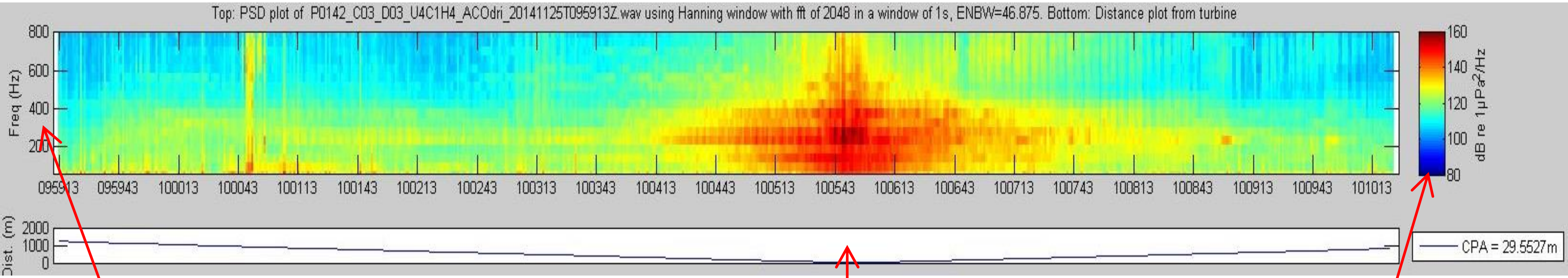
1.11 Acoustic Measurements

The noise signature of the tidal turbine was compared to the background noise of the site using drifting hydrophones

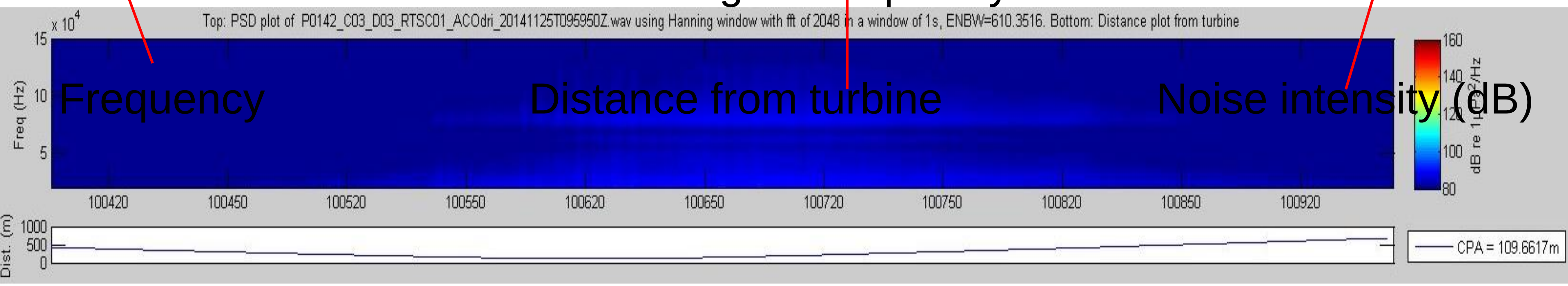


1.11 Acoustic Measurements - Noise Characterisation

For this turbine the majority of noise is in low frequency region (~250Hz)



There are also bands of noise at higher frequency



The noise levels from a single turbine are equivalent to the quieter end of shipping noise and cover a smaller frequency range.

2 Hydrodynamic Modelling – Device Scale

2.1. Numerical Methods
2.2. Turbulence Models
2.3. Free Surface
2.4. Shear Propagation
2.5. RANS / LES
2.6. Wake Modelling
2.7. Mesh (CFD) / model (BEMT) generation
2.8. Verification and Validation
2.9. Uncertainty Quantification

2.1 Numerical Methods

- Why is device-scale modelling important?
  - Performance predictions
  - Calculation of loads
  - Wake modelling
  - Testing control-systems
  - Better understanding of flow physics

2.1 Numerical Methods

- Why is device-scale modelling important?
  - Performance predictions
  - Calculation of loads
  - Wake modelling
  - Testing control-systems
  - Better understanding of flow physics

- What numerical methods are available?
  - Computational Fluid Dynamics
  - Blade Element Momentum Theory (BEM)

2.1 Numerical Methods

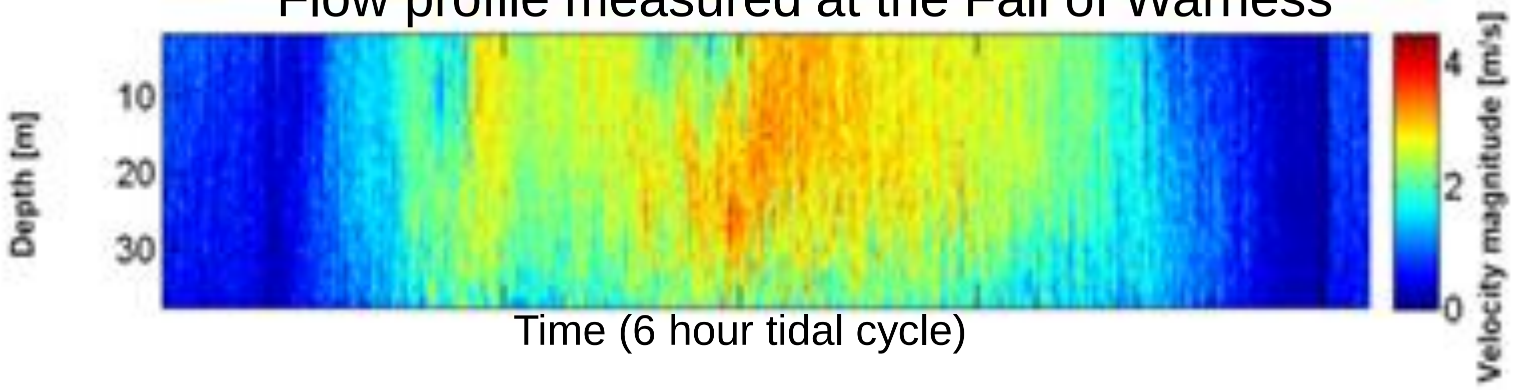
- Computational Fluid Dynamics
  - ReDAPT used EDF’s open-source CFD tool *Code_Saturne*
  - Large computations to understand governing physics

- Blade Element Momentum Theory
  - ReDAPT used DNV-GL’s Tidal Bladed
  - Quasi-steady assumption
  - Input force coefficients for blade definition
  - Fast results

2.2 Turbulence Models

- Tidal channels have Reynolds numbers in the order of 10s of millions
- Turbulence models are there to simplify the complex (somewhat random and coherent) unsteadiness in flow.
- Several types of models were investigated:
  - Large Eddy Simulation
  - Reynolds Averaged Navier-Stokes
  - Statistical models

Flow profile measured at the Fall of Warness



Time (6 hour tidal cycle)

2.2 Turbulence Models

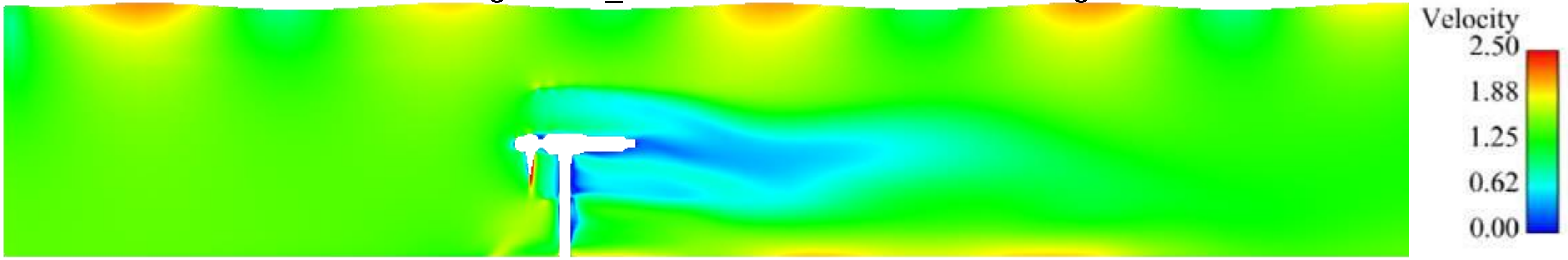
- Large Eddy Simulation (LES):
  - Resolves the large eddies in the flow and models the small-scale turbulence.
  - Highly dependent on the mesh
  - Great for unsteady flow
- Reynolds Averaged Navier-Stokes (RANS):
  - Many models often developed for specific types of flow (wall bounded, external, buoyancy driven)
  - Best for steady-mean flows but able to capture unsteady feature
- Statistical Models
  - Statistical approach derived from field and / or experiments
  - Generates unsteady fluctuations to apply to mean flow field
  - Tidal Bladed uses the von Karman model

2.3 Free surface

- *Code_Saturne:*
  - Free-surface movement through the use of moving meshes
  - Impact of waves on loading and wake was observed
  - Computationally expensive and sensitive to divergence

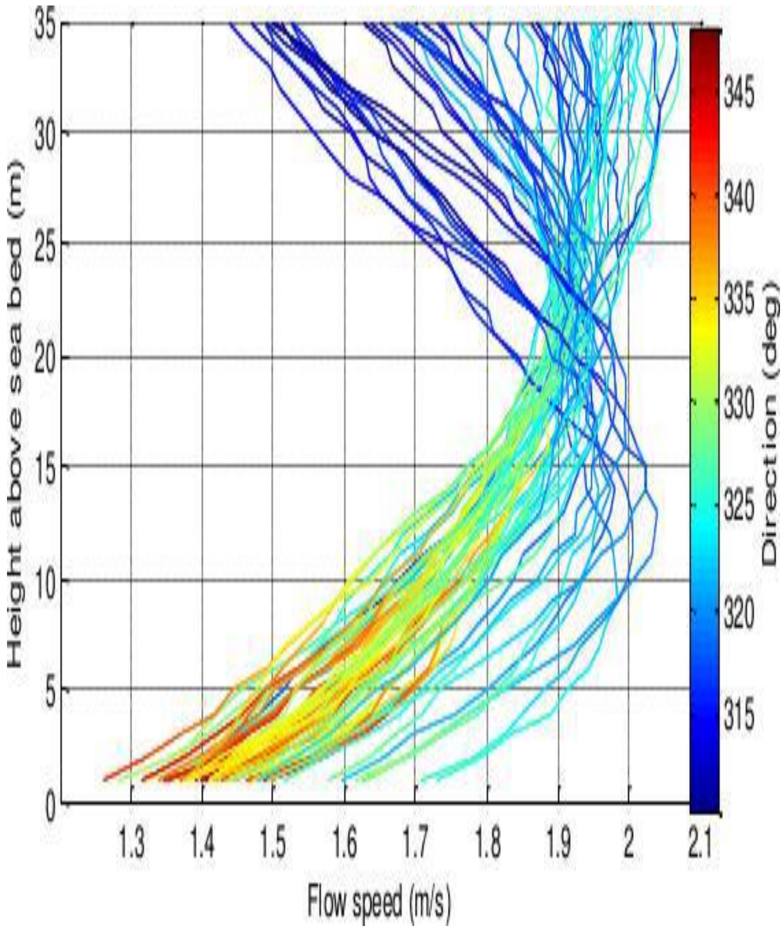
- Tidal Bladed:
  - Wave spectrum applied to flow field
  - No wave-current interaction for the irregular waves
  - Loading on turbine structure through Morison's equations

Section through Code_Saturne CFD simulations showing flow velocities



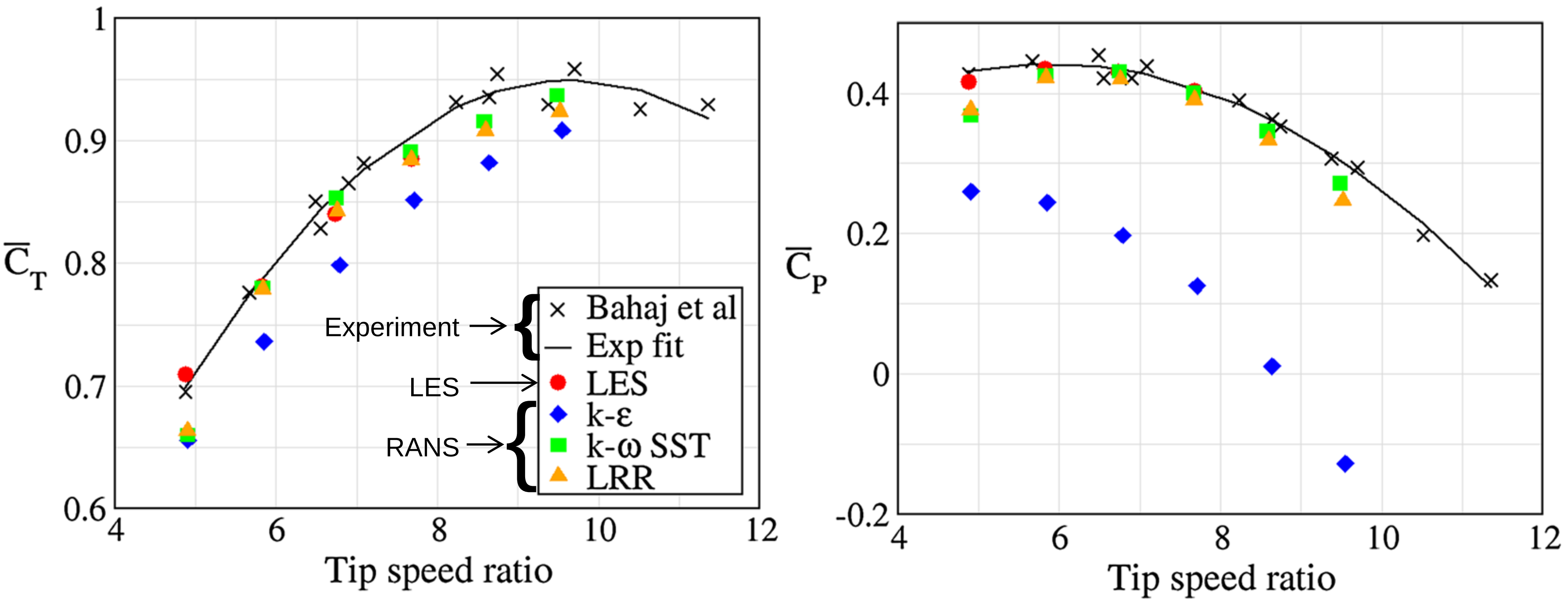
2.4 Shear Propagation

- In both CFD and BEMT any shear profile may be placed at the inlet
- In CFD the profile develops as it approaches the turbine, this depends on inlet turbulence, turbulence model and channel geometry.
- In BEMT the inlet profile is projected onto the rotor plane combined with unsteady fluctuations from the waves and turbulence model



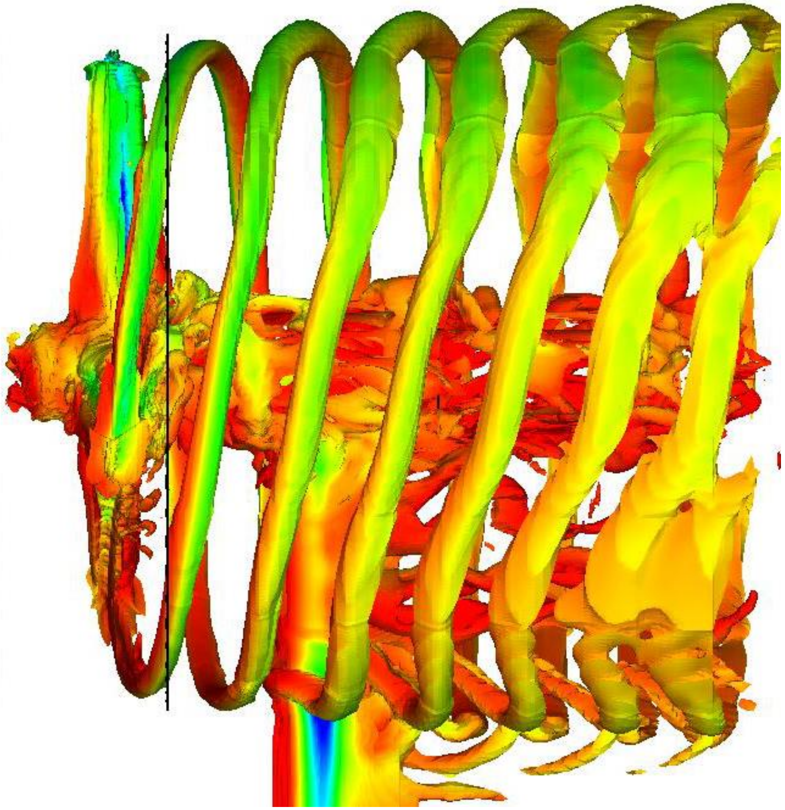
2.5 RANS / LES

- Both RANS and LES are capable of capturing mean loading on tidal turbines, shown by the comparison to the experiment of Bahaj *et al*



2.5 RANS / LES

- Both RANS and LES can capture tip vortices although LES (right) identifies more vortical structures from the support than RANS (left)

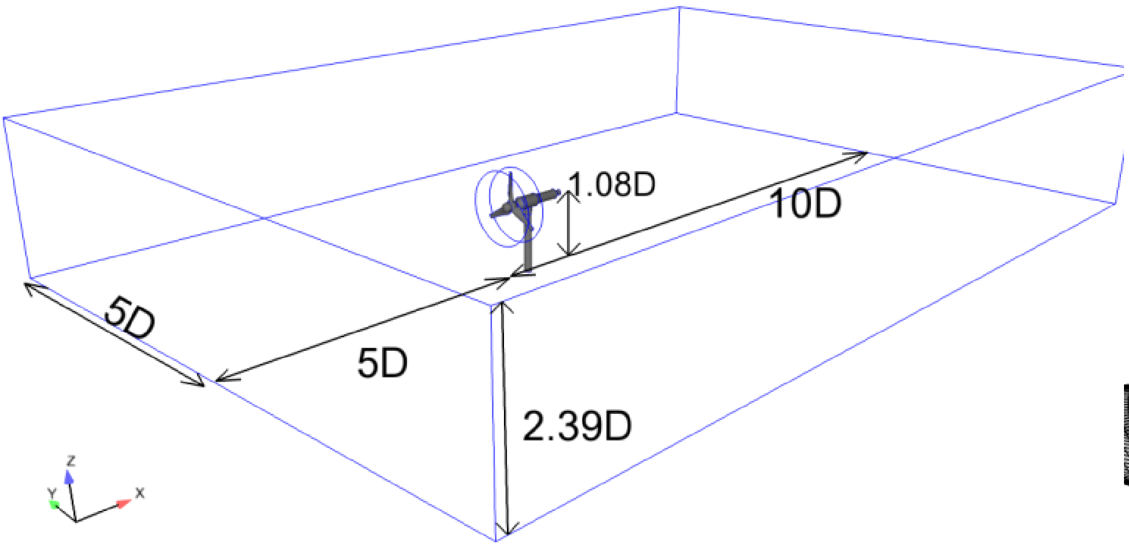


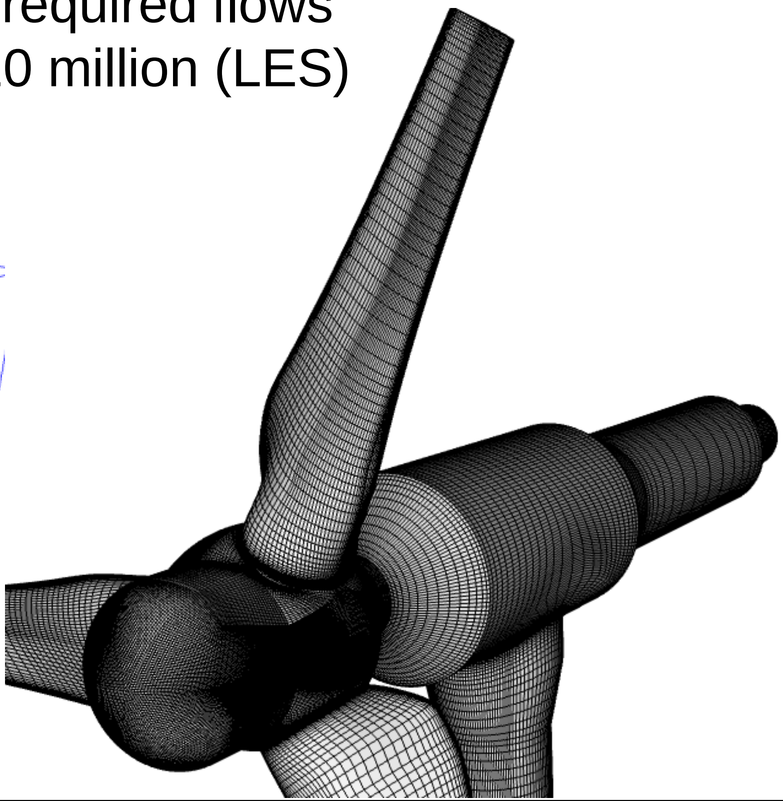
2.6 Wake Modelling

ReDAPT didn't cover wake modelling but James can add some stuff if desired?

2.7 Mesh (CFD) / model (BEMT) creation

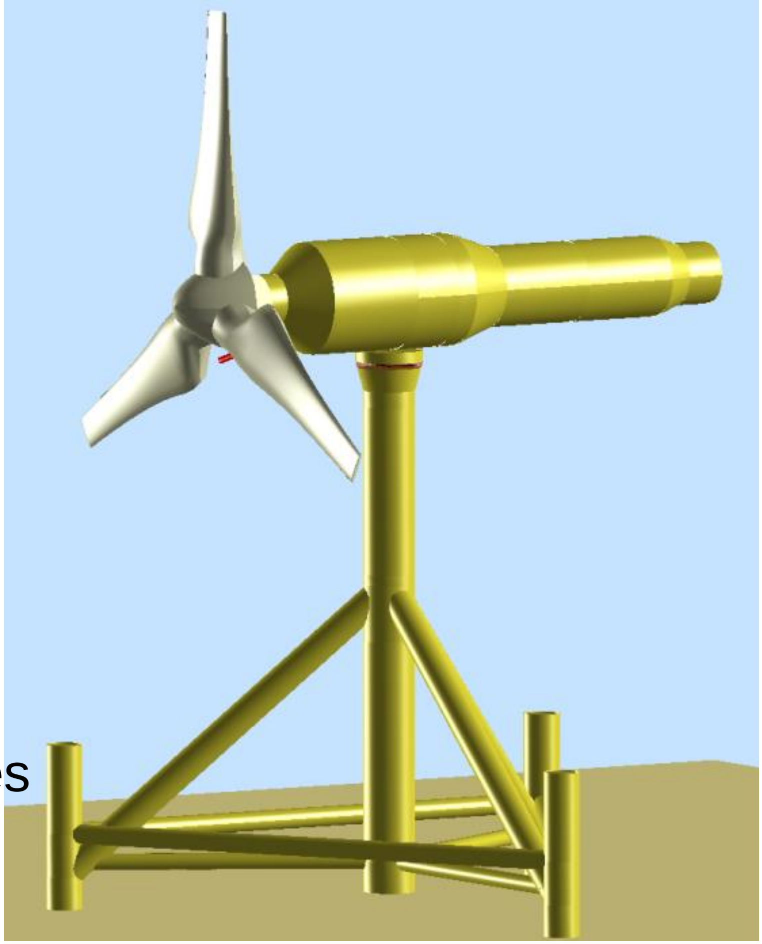
- Full domain modelled including an inlet, outlet and surface
- Mesh must be fine enough to capture the required flows
- Typical meshes had 5 million (RANS) to 20 million (LES) number of cells





2.7 Mesh (CFD) / model (BEMT) creation

- Turbine definition:
  - Blades:
    - Hydrofoil force coefficients
    - Thickness, twist and chord length
  - Hub:
    - Drag coefficient
    - Centre of mass and buoyancy
  - Tower:
    - Dimensions, masses
    - Material properties
  - Powertrain:
    - Electrical and mechanical efficiencies
    - Gearbox ratio
  - Control system



2.7 Mesh (CFD) / model (BEMT) creation

- Environment definition:
  - Flow:
    - Mean velocity profile
    - Speed and direction
    - Depth
  - Turbulence:
    - Choice of statistical models
    - Turbulence intensity and lengthscales
  - Waves:
    - Regular or irregular
    - Direction, wave height and period

2.8 Verification and Validation

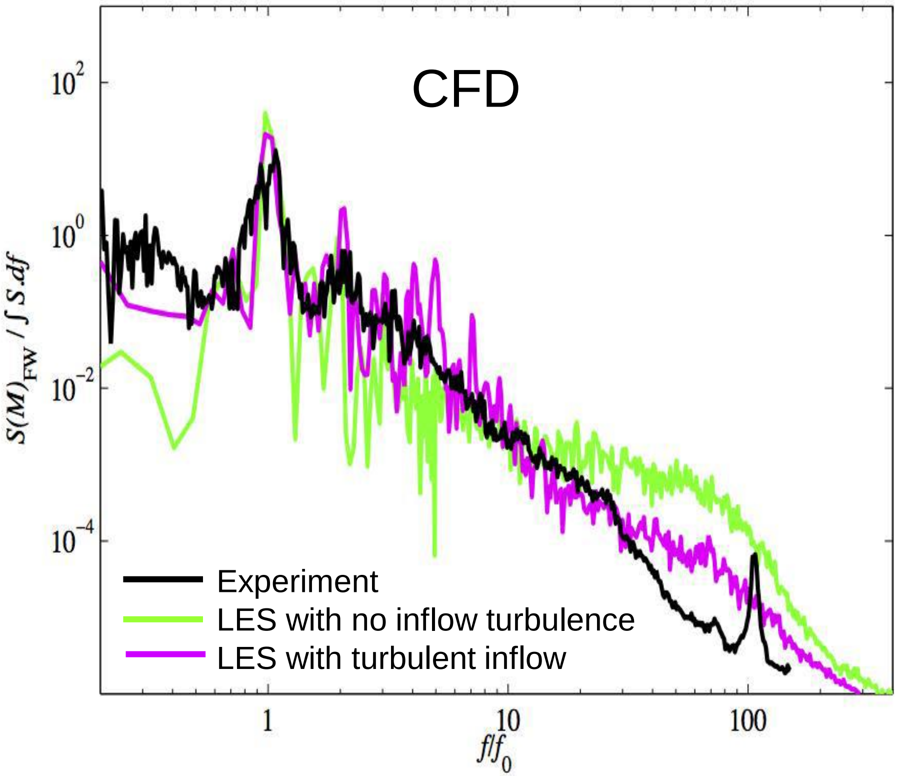
- **Verification** is the process to ensure the model is doing what was intended of it
- **Validation** is the process in determining how accurate the model's results are when applied to real-world applications

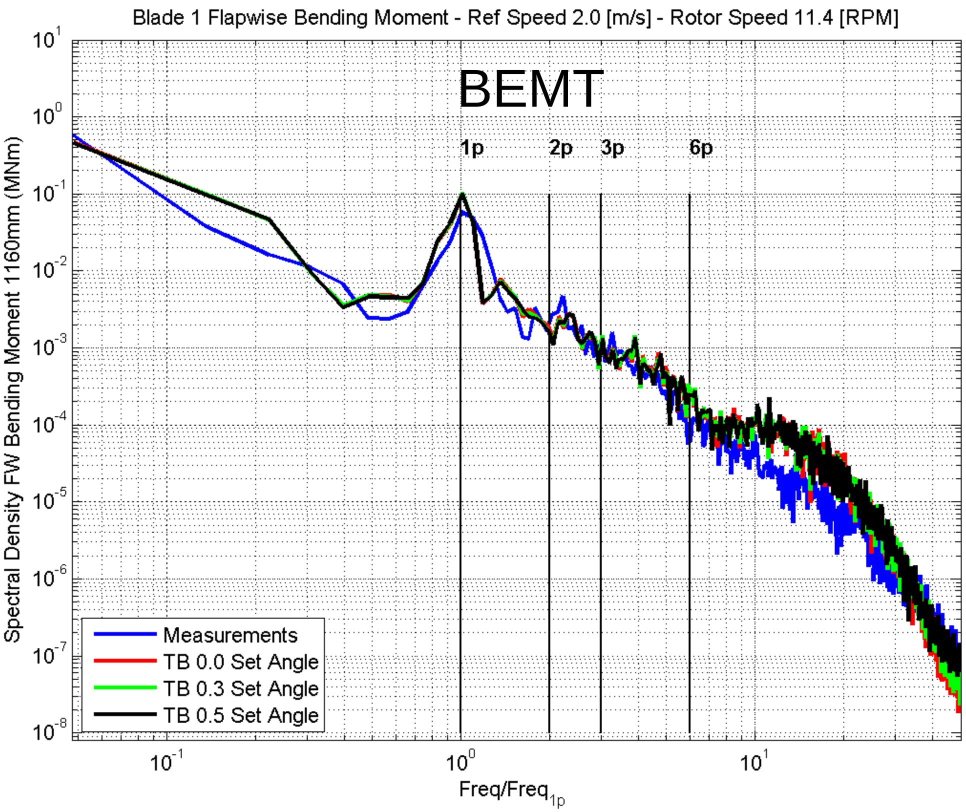
2.8 Verification and Validation

- **Verification** is the process to ensure the model is doing what was intended of it
- **Validation** is the process in determining how accurate the model's results are when applied to real-world applications
  - *Both Tidal Bladed and Code_Saturne were verified in their design process. This is ongoing as new models are developed.*
  - *Validation was performed under ReDAPT with comparison to DEEP-Gen IV running data.*

2.8 Verification and Validation

- Comparison of blade flapwise moment for CFD (left) and BEMT (right)





2.9 Uncertainty Quantification

Numerical uncertainties are present in all modelling methodologies, e.g.:

CFD:

- Mesh definition:
  - Near-wall cell size
  - Growth ratio
  - Cell density
- Inflow characteristics
- Turbulence modelling
- Solver parameters:
  - Time stepping
  - Order of numerical schemes
- Case definition (e.g. forced turbine rotation)

BEMT:

- Environment
- Blade polars
- Hub / tip-loss models
- Rigid / flexible structure definition
- Simplified hydrodynamics for structural loads

2.References

- MD1.1
- MD1.2
- MD1.3
- MD1.4
- MD1.5
- MD3.4
- MD5.1
- MD5.2
- MD6.1
- MD6.2
- MD6.5
- MD6.6

3 Turbine Design

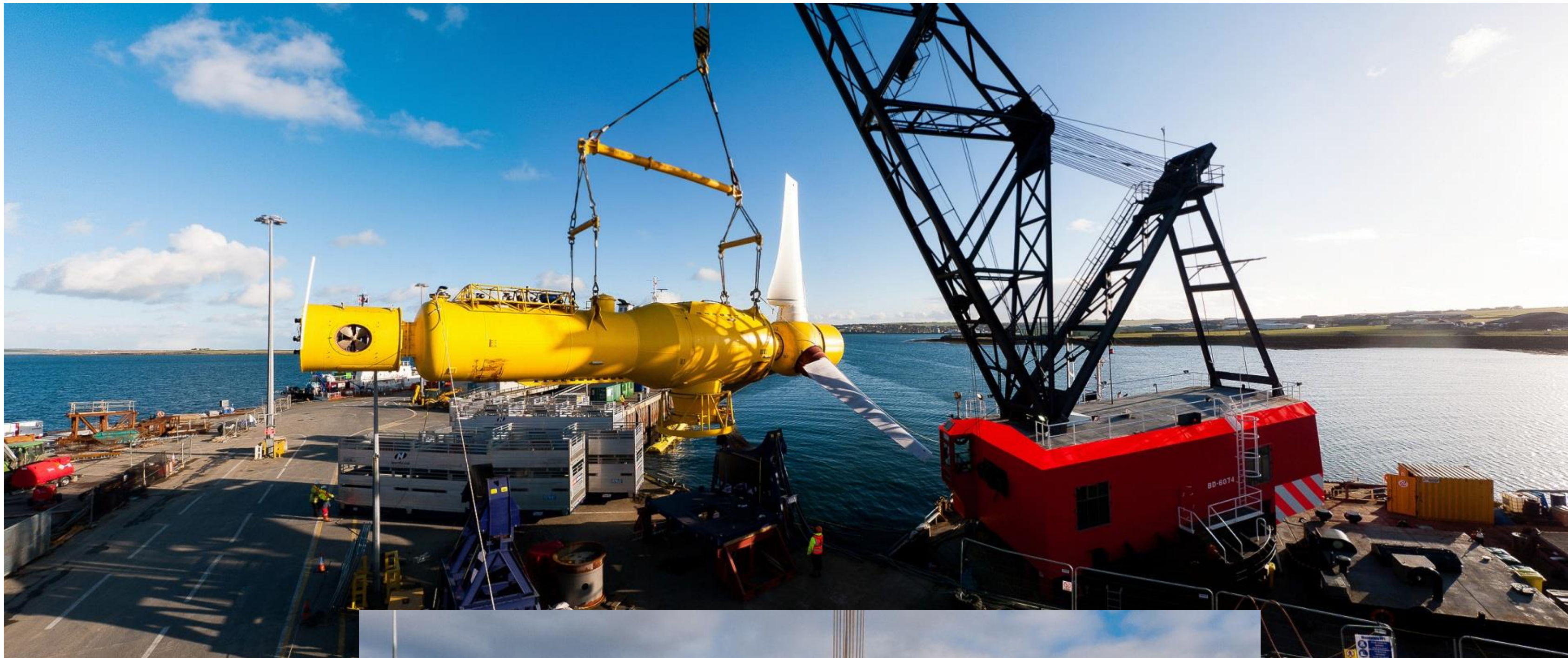
3.1 Design Drivers

3.2 Design for ……….. (DfX)

3.3 Equipment Health Monitoring (EHM)

3.1 Design drivers for a buoyant tidal turbine

- Design of a non-buoyant turbine is relatively simple
  - Each component can be designed in relative isolation
  - A large crane can pick up the machine and place it on a foundation
- Design of a buoyant tidal turbine is a complex iterative procedure, with many possible combinations of solutions
  - The turbine must float level on the surface
  - The turbine must be level when submerged
  - Overall net buoyancy must be within the capability of the winch (<10te)
  - The centre of buoyancy relative to centre of mass must offer pitch and roll stability
  - Each individual component must fulfil its' own requirements
- These requirements are often in conflict with each other.
- For every component in the turbine, the mass or buoyancy and its location(axial, lateral and vertical) is key to a successful design
- It is a complicated 3-dimensional puzzle that keeps changing through the entirety of the design process, manufacture, assembly and commissioning



See front page for details

3.1 The design iterative loop

- The following slide describes the iterative process
- First, define a set of requirements
- Then define a set of assumptions for the tidal bladed model, in order that an initial set of loads can be produced (extreme and fatigue)
- Then decide on the turbine “family strategy” as this will affect mass and buoyancy solutions
- Then, each of the issues around the loop requires some consideration and a baseline solution / conclusion in order to produce a valid turbine design. Inevitably many of the choices will affect other seemingly unrelated items
- Example #1: Increasing the number of signal or power channels to the hub increases the length of the slipring. This pushes the hub forward, pushing buoyancy and the rotor plane further from the tower top, increasing BM on the clamp and moving the centre of buoyancy of the turbine forward
- Example #2: The tallest component on the electrical skid drives the diameter of the rear of the nacelle. Small increases will significantly increase the overall buoyancy. This must be managed either by adding more ballast, adding more buoyancy at the front or increasing the capability of the winch (or both). This can have huge effects very quickly

3.1 The iterative loop

Requirements:
Maintenance on quayside
Buoyant turbine
1.0MW, 1.2MW, 1.4MW
18m, 20m, 23m rotor
Common nacelle for family
Free turbine ascent / winch down
Single pitch control
Tip speed at rated power
Max Installed Depth 60m
>20 Year life
2yr Maintenance

Assumptions:
Turbulence
Distance to waves
Flow distribution
Max wave operation
Crane capability
Pitch system capability
Tripod natural frequency
Hub Strategy
Control strategy

Turbine family options?
Different blade sizes

Hub strategy:

1. Different hub sizes
2. Common hub and blade root PCD
3. Common hub, adaptor flanges for different blade PCD

Calculate loads based upon GB ratio, Gen max speed, Tip Speed Ratio, cavitation speed limit, max pitch rate

If necessary change assumptions

New trim, mass, bcy (floating and submerged) and stability (static and dynamic)

Validation of:

Loads

Marine operations

Performance

LCOE

Turbine Cost

Trim angles

Draft of harbour
Modular design – assembly sequence
Max lifting weight
Winch buoyancy and effect on turbine
Deployment options (no of umbilicals, ROV, weather & tidal window)
Winch pull down load
Road transport capability
Marine ops contingencies (hot stab, umbilical, mechanical intervention)
Lifting solutions (padeye, belly strop, lifting frame)
Deployment options (hip moor, …)

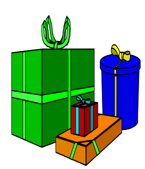
Buoyancy and CoB of components (Blades, hub, nacelle, HV cables, thruster, clamp, winch)
Mass and CoG of components (Gen, TX, FC, GB, thruster, clamp, HPP, hub, pitch, blades, shaft, ballast)
Ballast system capability
Gearbox mount, skirt and nacelle saddle stres
Clamp capability
Blade – flooded vs. foam filled
Clamp operation (ROV, energy backup)
Pitch system speed / torque capability
Shaft bending moment
Battery UPS requirements
Access hatch and back door arrangement – confined space
Thruster / cradle positions

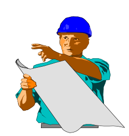
3.2 What is DfX Design Improvement

- A structured approach to improving the design, specifically targetted a number of topics related to the business needs
  - Design for Manufacture (DfM)
  - Design for Assembly (DfA)
  - Design for Cost (DfC)
  - Design for Reliability (DfR)
  - Design for Aftermarket (DfAM)
- A DfX session is held, with representatives from many business functions, in order to get many perspectives on a problem
- A structured approach to ensure all ideas are captured, considered, ranked and pursued if applicable
- Results in outline plans for the top ideas, that can be used immediately. The purpose is not to have hundreds of un-quantified ideas that do not get considered again

3.2 Product design has a major effect on component cost

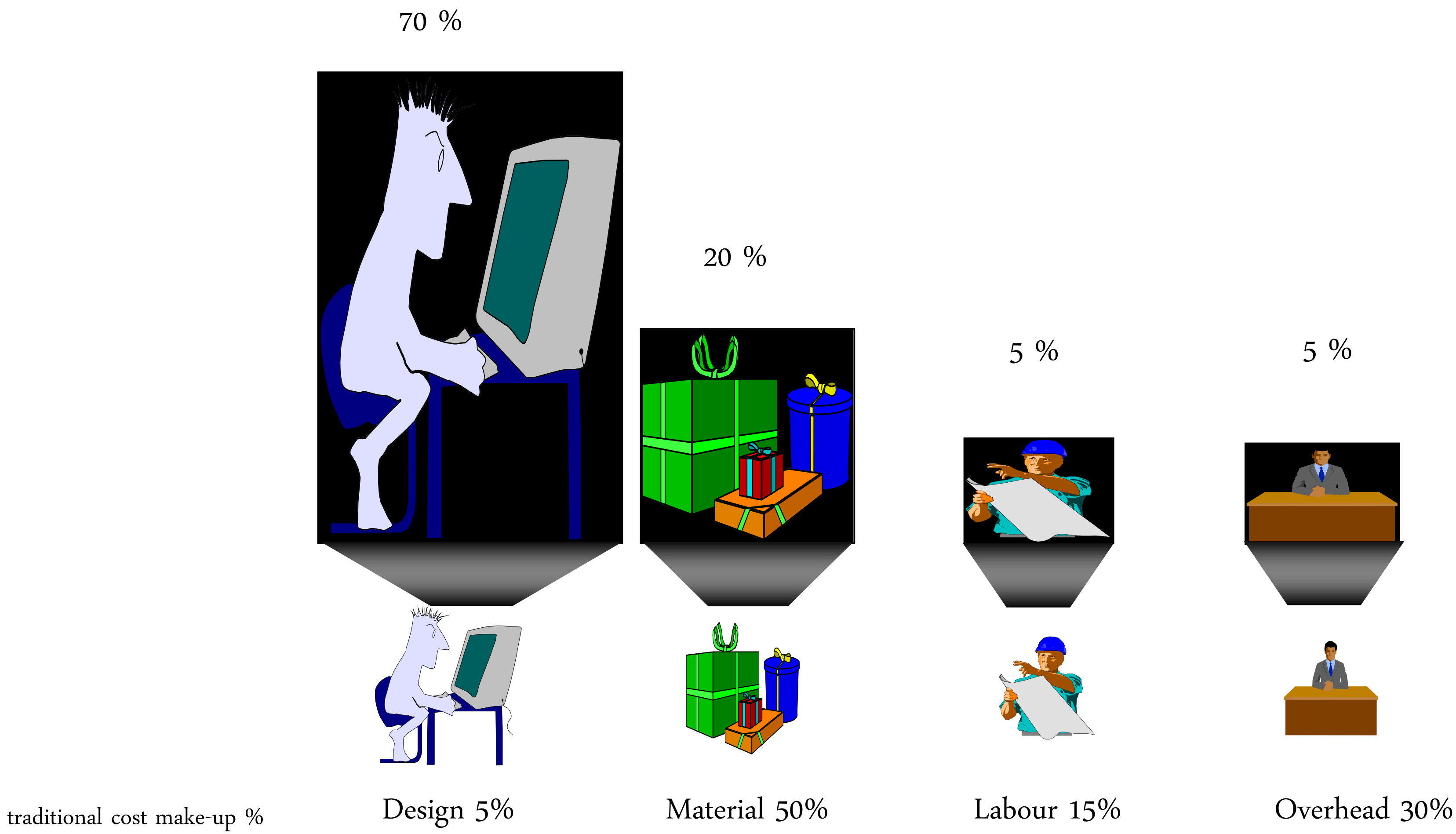
Who casts the biggest shadow on product cost?





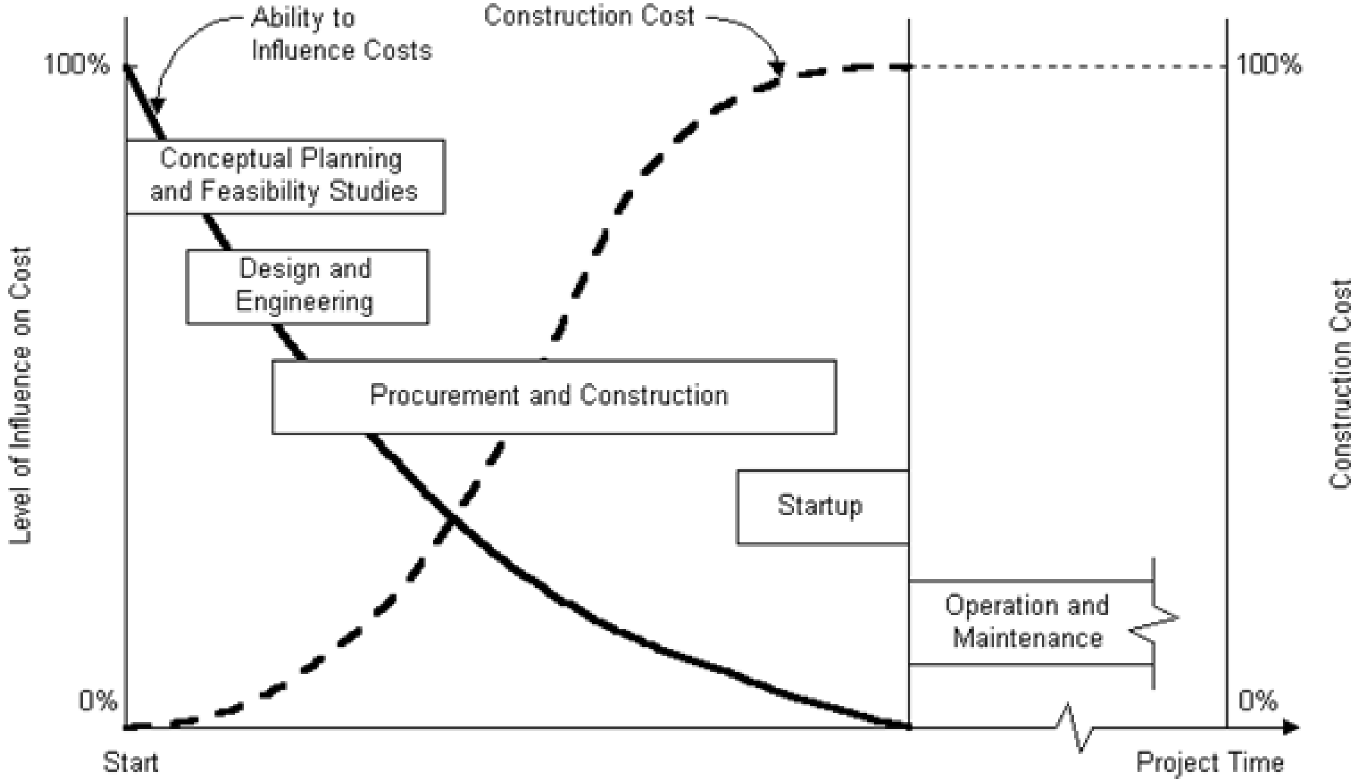
traditional cost make-up % | Design 5% | Material 50% | Labour 15% | Overhead 30%

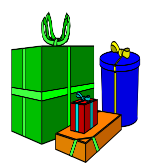
3.2 Product design has a major effect on component cost

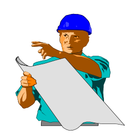


3.2 Product design has a major effect on component cost

The design phase offers the most powerful opportunity to affect the final cost of the product, and the minimum cost to implement those changes







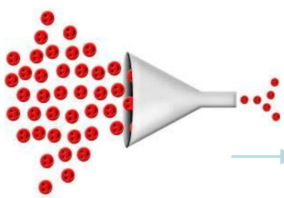
traditional cost make-up % Design 5% Material 50% Labour 15% Overhead 30%

3.2 Outline Of Workshop Structure

Using the tools

- DFA
- DFM
- DFSC
- DF-Aft

Generate as many ideas as possible

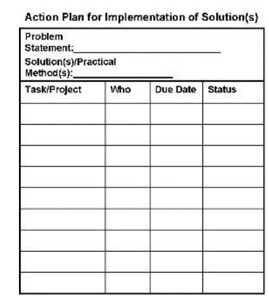


Prioritise circa 30 to 50 Ideas

	Easy	Hard
High	1	2
Low	3	4

Select circa 12 Ideas to implement via business case

Combined action plan to deliver bottom line saving


Action Plan for Implementation of Solution(s)

Problem Statement:____________

Solution(s)/Practical Method(s):____________

Task/Project	Who	Due Date	Status

Interrogate each feature of the design.
Why must that tolerance be so small, what would happen if it is larger?
Why are those components separate – can they be combined?
Can threaded holes be changed to through holes?
Can the weld position be changed to improve access?
Can the shape be modified to allow standard material sourcing?
If requirements are driving the design, can we question the requirements?

3.2 Outline Of Workshop Structure

Using the tools

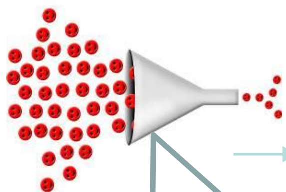
DFA

DFM

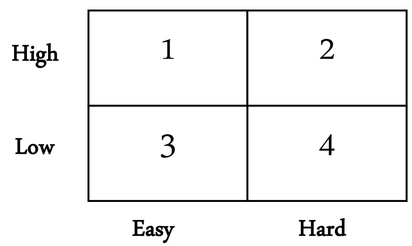
DFSC

DF-Aft

Generate as many ideas as possible



Prioritise circa 30 to 50 Ideas

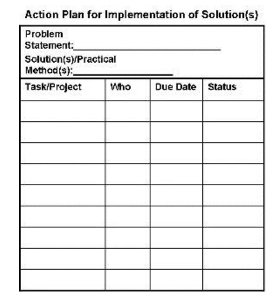


Select circa 12 Ideas to implement via business case

Cost

Benefit

Combined action plan to deliver bottom line saving



Action Plan for Implementation of Solution(s)

Problem Statement:

Solution(s)/Practical Method(s):

Task/Project	Who	Due Date	Status

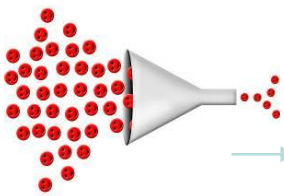
During the discussion, write any ideas down on a card (one idea per card)
Do not discuss the idea, just record it (this is not a design meeting)
Do not discount an idea – it might trigger another, better one
Everyone should be generating ideas and suggestions

3.2 Outline Of Workshop Structure

Using the tools

- DFA
- DFM
- DFSC
- DF-Aft

→ **Generate as many ideas as possible**



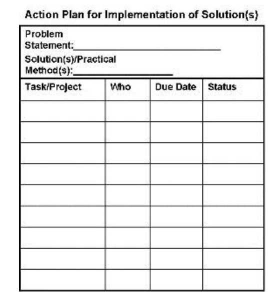
→ **Prioritise circa 30 to 50 Ideas**

	Easy	Hard
High	1	2
Low	3	4

→ **Select circa 12 Ideas to implement via business case**

Cost | Benefit

→ **Combined action plan to deliver bottom line saving**



Using group experience, rank the ideas according to:

- cost saving (high = >2% of total product cost or low = <2%)
- difficulty to implement (easy = been done before) or hard = never been done before).

Do not discuss each idea in detail, as you may have several hundred ideas!

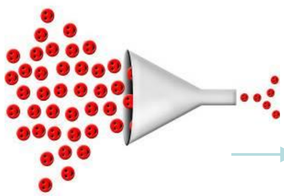
3.2 Outline Of Workshop Structure

Using the tools

- DFA
- DFM
- DFSC
- DF-Aft

→

Generate as many ideas as possible



→

Prioritise circa 30 to 50 Ideas

	Easy	Hard
High	1	2
Low	3	4

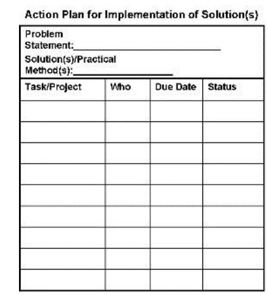
→

Select circa 12 Ideas to implement via business case

Cost Benefit

→

Combined action plan to deliver bottom line saving



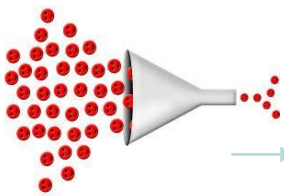
Select the top ideas from category 1 and 2 (major cost saving potential)
Reject all ideas that are ranked 4
All ideas ranked 3 are kept for later reviews
Reject all duplicate ideas,
Highlight if local processes need to be updated or if an issue needs to be escalated

3.2 Outline Of Workshop Structure

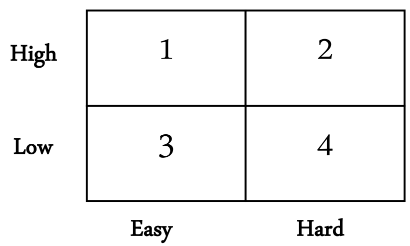
Using the tools

- DFA
- DFM
- DFSC
- DF-Aft

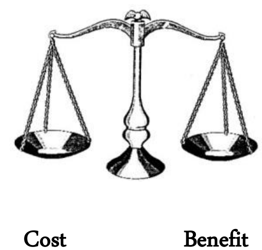
Generate as many ideas as possible



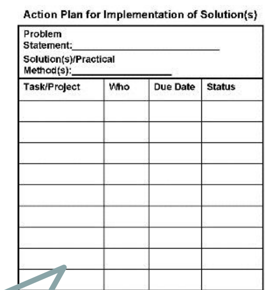
Prioritise circa 30 to 50 Ideas



Select circa 12 Ideas to implement via business case



Combined action plan to deliver bottom line saving



Before the end of the session, each of the top ranked ideas needs an action plan.
In small groups, agree advantages, disadvantages, cost to implement, time to implement, assumptions and an overall confidence that idea will be implemented in full.
This becomes the basis of the action plan and can be assigened to an owner

3.2 Outputs from the DfX Workshop

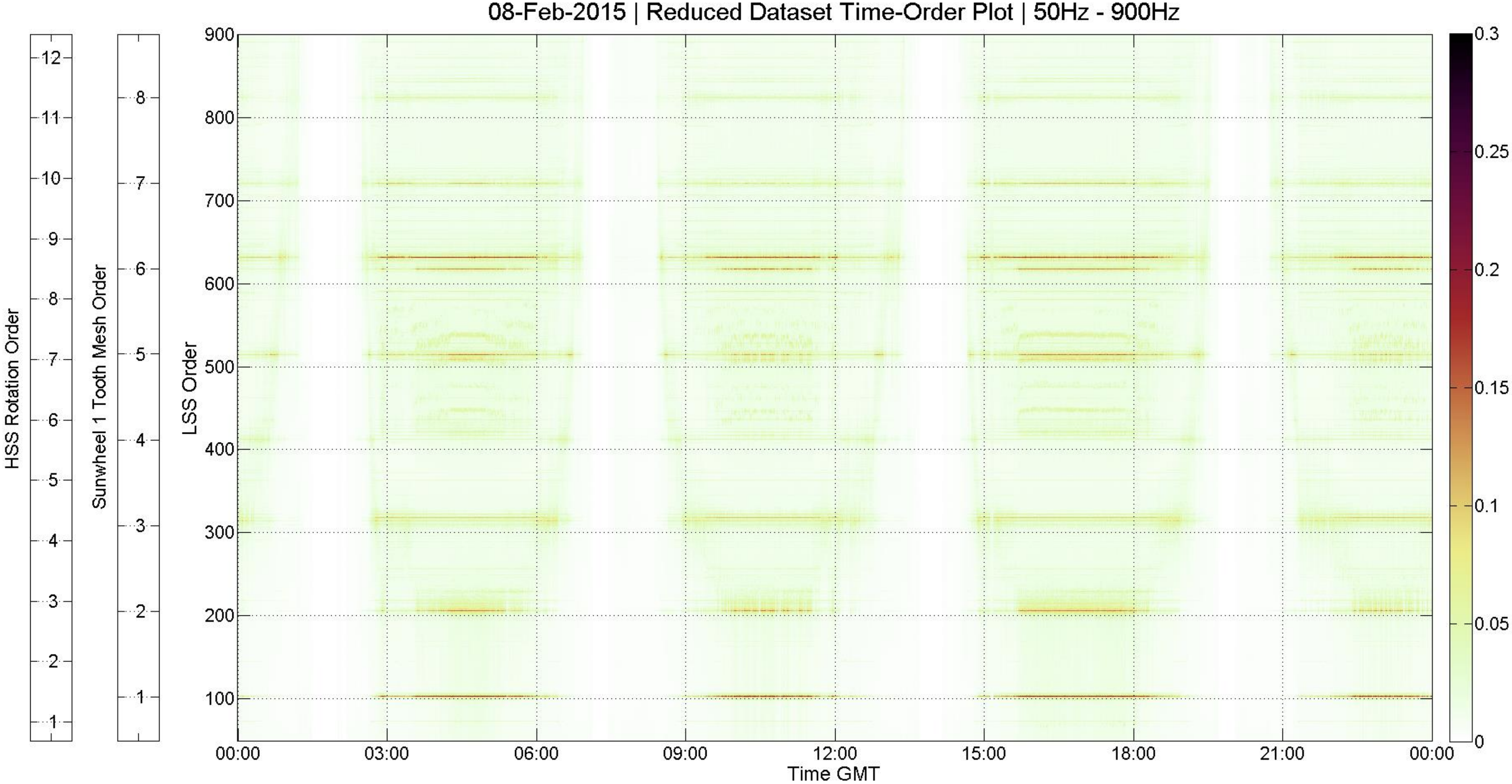
- The structured process ensures that the results are:
  - Quantified
    - everyone understands which ideas should be pursued and why and what the potential benefits are
  - Planned
    - The best ideas have an action plan before the meeting ends. This way ideas do not get forgotten or lost, due to other time pressures back in the office
  - Recorded
    - There is a record of all suggestions (even the hard to implement / low cost saving ideas). This can often trigger further ideas at a later date that can be assessed and planned as required

3.3 EHM

- DEEP-Gen IV was fitted with accelerometers on the Gearbox recorded at 140kHz to provide vibration data that could be processed to understand the condition of the gear teeth and bearings.
- The low speed shaft position was also recorded and was used to convert the vibration data from the time domain to the order domain.
  - This allows us to see vibrations produced by parts of the gearbox based on their ratio to the low speed shaft speed.
  - Removes the smearing caused by a variable speed gearbox.
- Advanced analysis techniques were used to analyse the data such as:
  - Time-Order Analyses, Enveloping, Side lobe ratio analysis, Cepstrum, Spectral Kurtosis.
- Analysis can detect deteriorations is gear teeth and bearings to enable predictive maintenance plananing and avoid catastrophic failure.

3.3 EHM

- Example Time-Order plot over one day showing vibration peaks at the Sunwheel meshing frequency, it’s harmonics and some side bands.



4 Electrical Design

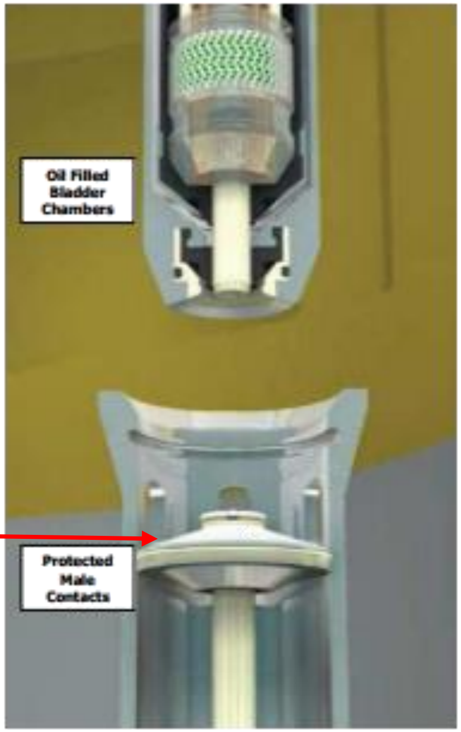
4.1 Connector requirement

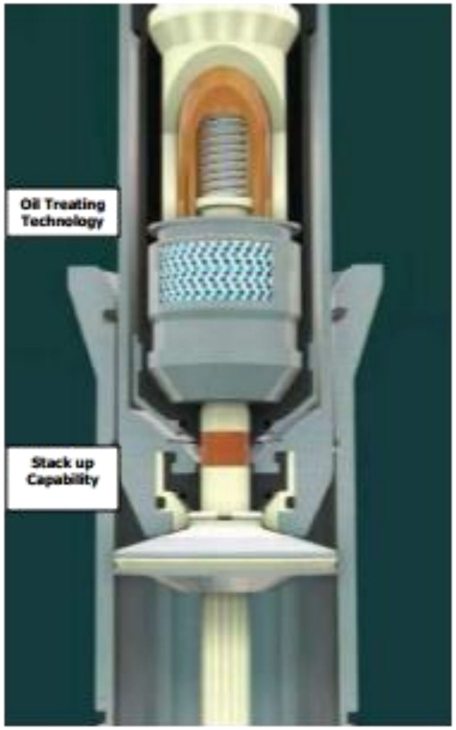
- Electrical and optical wet-mate connector - What differs compared to standard (oil & gas) practice ?
  - Several mate / De-mate in the connector lifetime
  - We want to avoid connector capping with ROV, when the connector is left unmated subsea (twice a year – 14 days)
  - In tidal, the connectors are used at shallower depth (lighter and warmer water)
    -> this helps the development of bio-fouling

4.1 Connector requirement - Tidal Industry Requirements

- Avoid use of ROV capping – Need to have intrinsic protection on the connector (shuttle to protect electrical pins for example)
- Define reasonable period of time where the connector can be left un-matted subsea

Example of shuttle to protect the male electrical contact





4.2 Cable Testing

Transformer box at EMEC substation

- Cable testing can be performed according to various standards. There is no definitive standard for testing of submarine cables
- Generally DC tests or AC VLF (Very Low Frequency testing) is applied
- Test levels must be agreed based on type of test (production, installation, periodic).
- Typical standards are from IEC 60502 range or IEEE400

4.3 Best Practice for safe working

- EMEC safety rules based upon current industry best practice
- Roles defined
  - Senior Authorised Person
  - Authorised Person
  - Competent Person
  - Keyholder
- Standard permits and certificates used
  - Permit to Work, Sanction For Test, Isolation Certificate

- Some flexibility required to account for marine operations. Signing off Permit to Work and Isolation Certificate possible when work leader is remotely located using radio comms.

5 Test

5.1 Risk assessment of performance tests

5.2 Verification

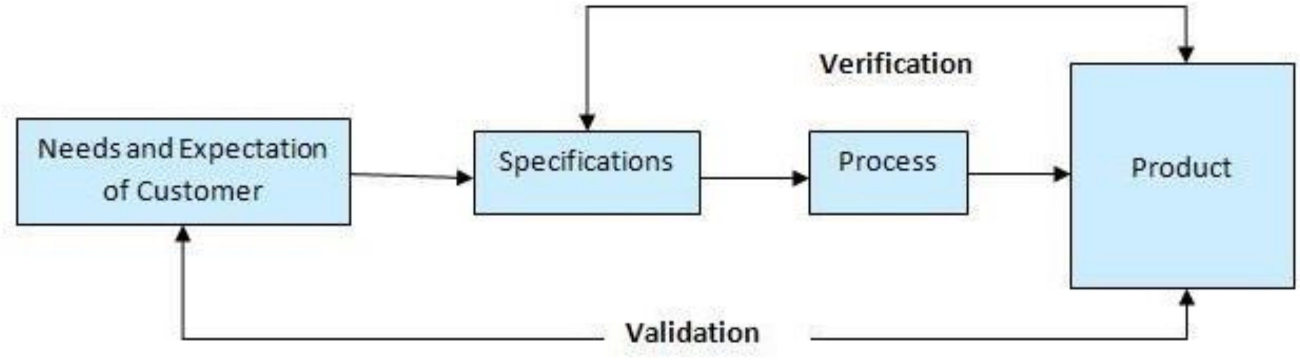
5.3 Technology Readiness

5.2 Validation and Verification

The definitions of validation and verification are given below:

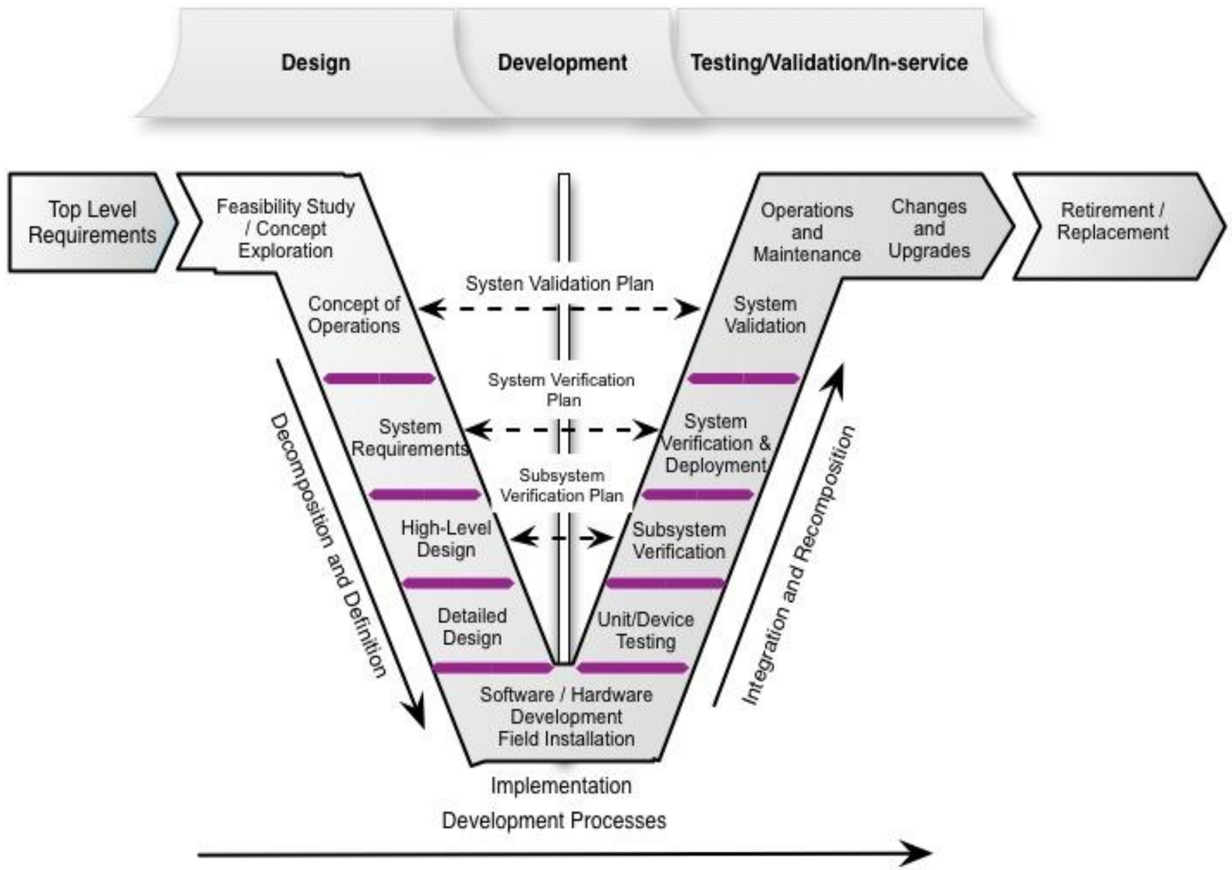
- **Validation** The assurance that a product, service, or system meets the needs of the customer and other identified stakeholders. It often involves acceptance and suitability with external customers. *Validation: Are we building the right system?*

- **Verification** The evaluation of whether or not a product, service, or system complies with a regulation, requirement, specification, or imposed condition. It is often an internal process. *Verification: Are we building the system right?*



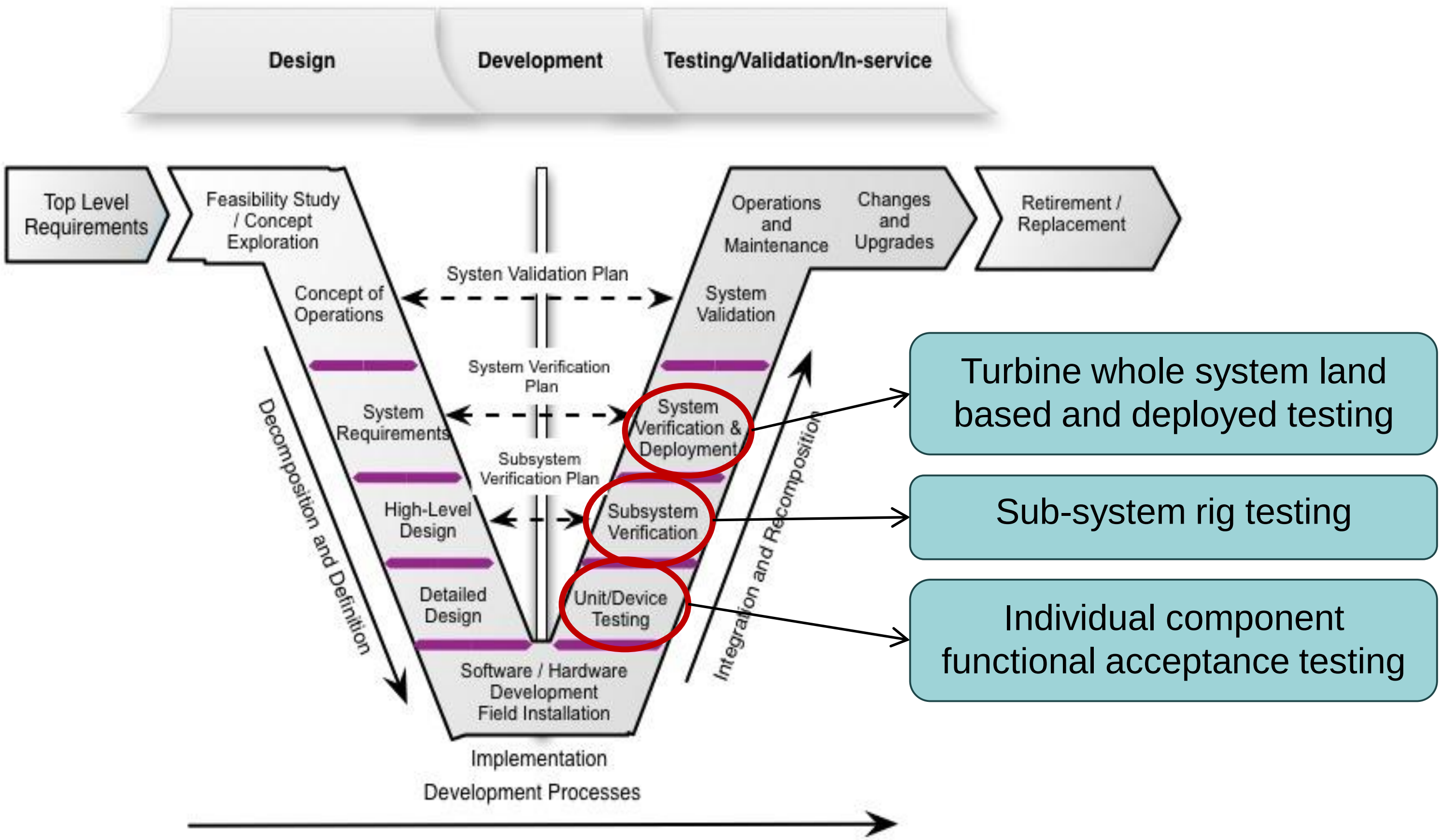
5.2 Validation and Verification

The Verification "V" shows process from initial requirements to retirement.



5.2 Validation and Verification

The component and turbine testing fits into the process as shown.



5.2 Validation and Verification

Example of component functional acceptance testing – Clamp FAT.

FAT
- Component tested at OEM factory.
- Verifies basic component functions in isolation from rest of system.
- Carried out by OEM, sometimes with customer present.

Clamp FAT
- Tested hydraulic system for leaks.
- Confirmed operation of clamp through full travel.

5.2 Validation and Verification

Example of sub-system rig testing – Yaw Load Testing.

Sub-System Testing

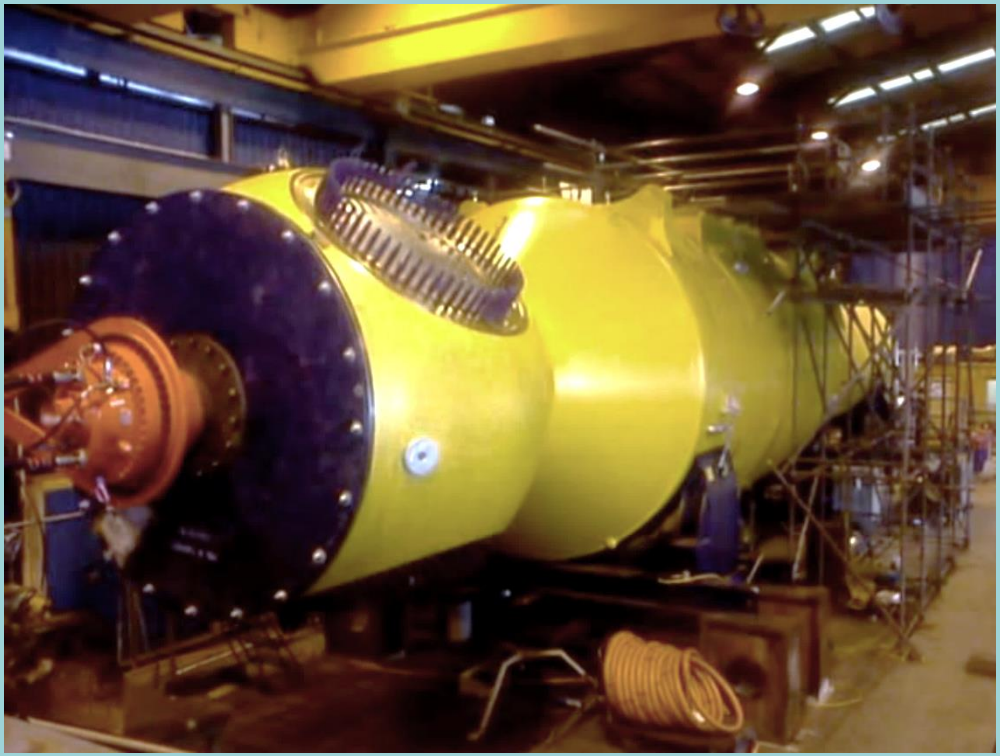
- Verifies sub-system functions and performance.
- Can be undertaken in isolation or as part of a rig with representative boundary conditions.

Yaw System Rig Test

- Tested clamp performance (max yaw load reaction capability).
- Confirmed operation of clamp through at full load.

5.2 Validation and Verification

Example of turbine whole system land based testing – Rotational Test.



Whole System Testing (land-based)

- Verifies system-wide functions and performance.
- Verifies functional interfaces between sub-systems.
- Does not represent all "deployed operation" conditions.

Turbine Rotational Test

- Tested function of drivetrain (motoring via turbine generator).
- Tested function of electrical power conversion (generating via hydraulic motor on hub – picture on left).
- Verified sub-system functional interactions (control system, cooling systems, pitch system).

5.2 Validation and Verification

Example of turbine whole system deployed testing – Dunk Test.

Whole System "Wet" Testing (water-based)

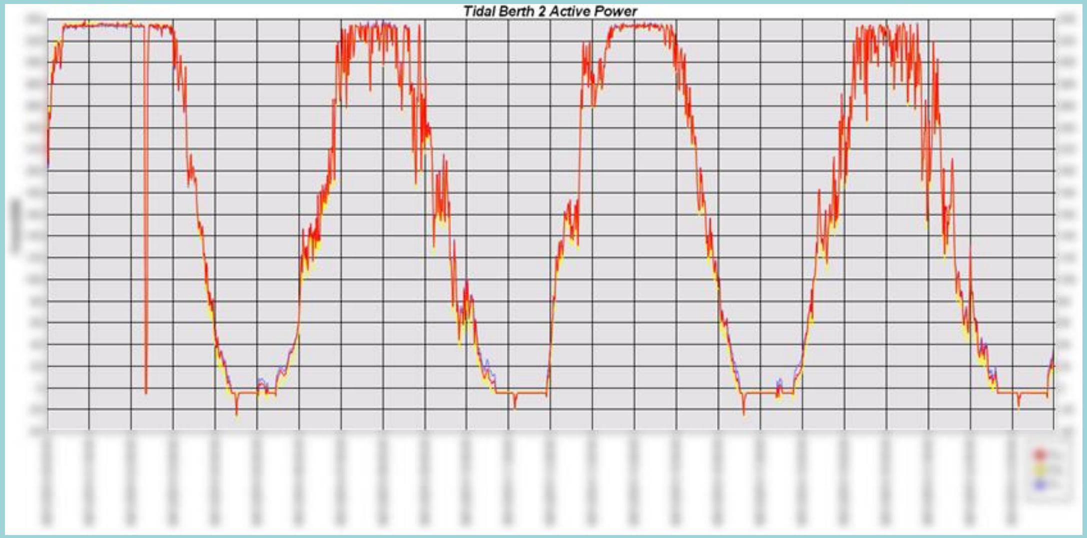
- Verifies functional interfaces between turbine and other systems (lifting, handling, deployment systems etc).
- Verifies marine operations methods.
- Provides evidence to validate buoyancy model.

Turbine Dunk Test

- Verified sealing capability of turbine under controlled conditions.
- Verified interfaces with crane, support vessel, winch and tower-top.
- Verified deployment and retrieval methods, including contingencies, in benign environment.
- Verified trim and buoyancy of turbine.
- Verified towing capability (picture on left).

5.2 Validation and Verification

Example of turbine whole system operation – Deployed Operation.



Whole System Operation

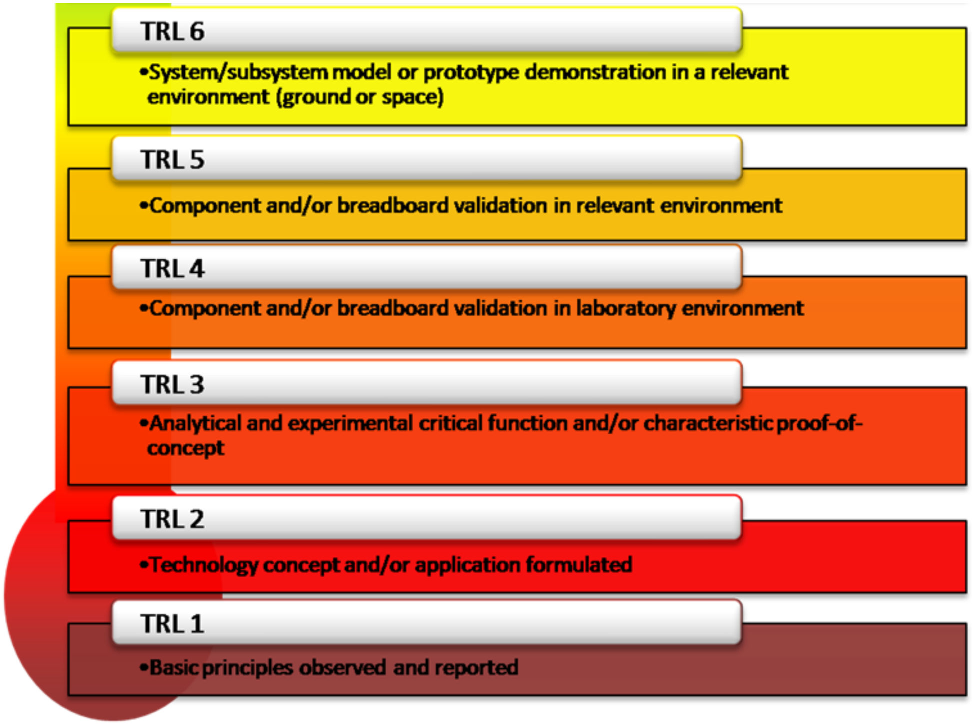
- Verifies function and performance of turbine wider system (tower-top, sub-sea cable, interface with grid etc).
- Validates turbine concept.

Turbine Deployed Operation

- Verified operation of turbine in deployed environment.
- Verified interfaces with tower-top, sub-sea cable and grid.
- Verified deployment and retrieval methods in tidal environment.

5.3 Technology Readiness Levels (TRL)

- TRLs define the level of maturity of a given technology based on "hard" evidence.
- Developed by NASA they are a recognised metric to assess any technology.
- TRLs enable consistent, uniform, discussions of maturity across different technologies.



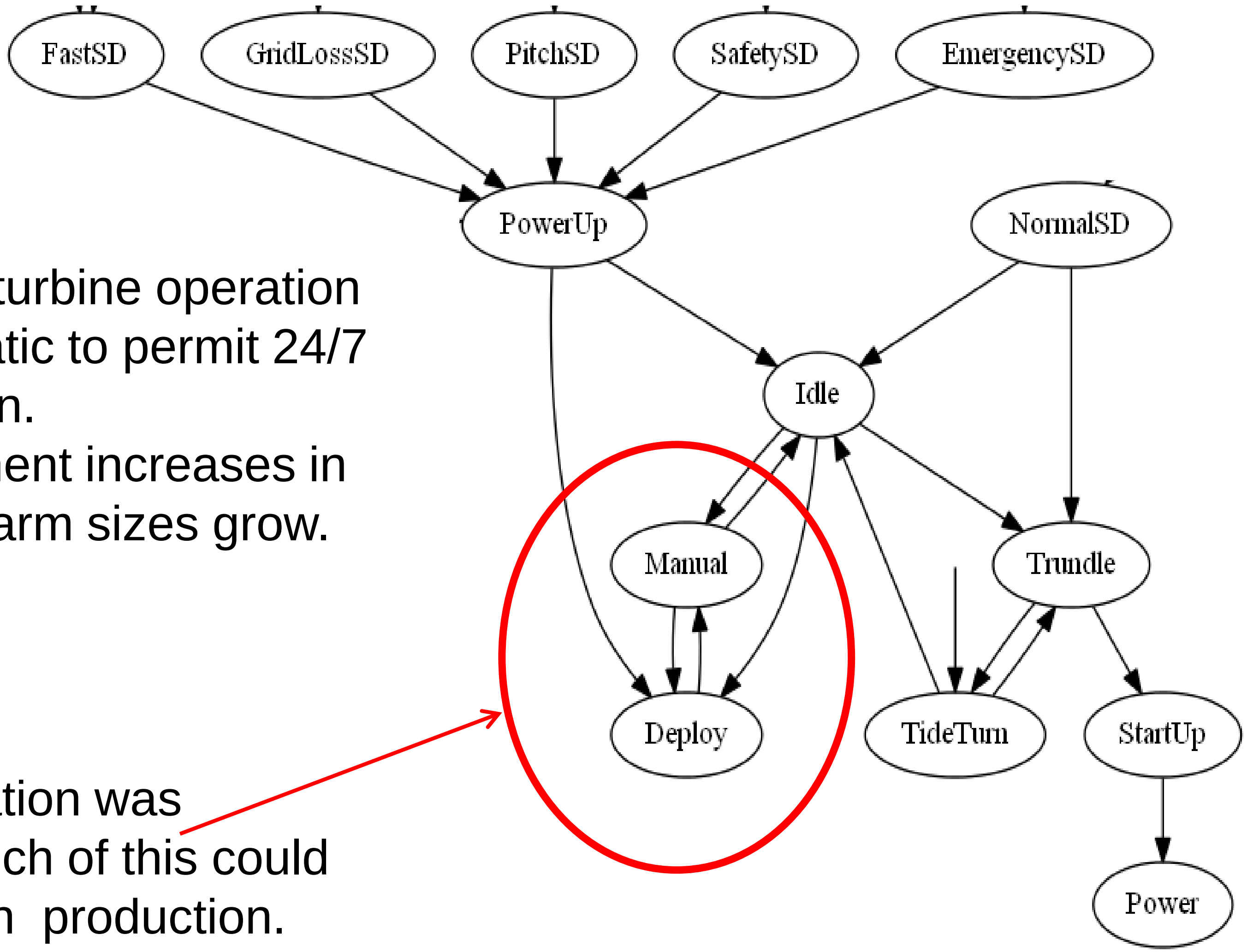
- Prior to DEEP-Gen III & DEEP-Gen IV (ReDAPT) was TRL3.
- Following these turbine deployments the technology to developed to TRL6.

6 Operation

6.1 Manual Operation

- Manual operation is not normally used for turbine control. It is typically reserved for quayside maintenance or turbine assessments.

6.2 Automatic Operation



The majority of turbine operation must be automatic to permit 24/7 turbine operation.
This is requirement increases in importance as farm sizes grow.

Very little operation was manual and much of this could be automated in production.

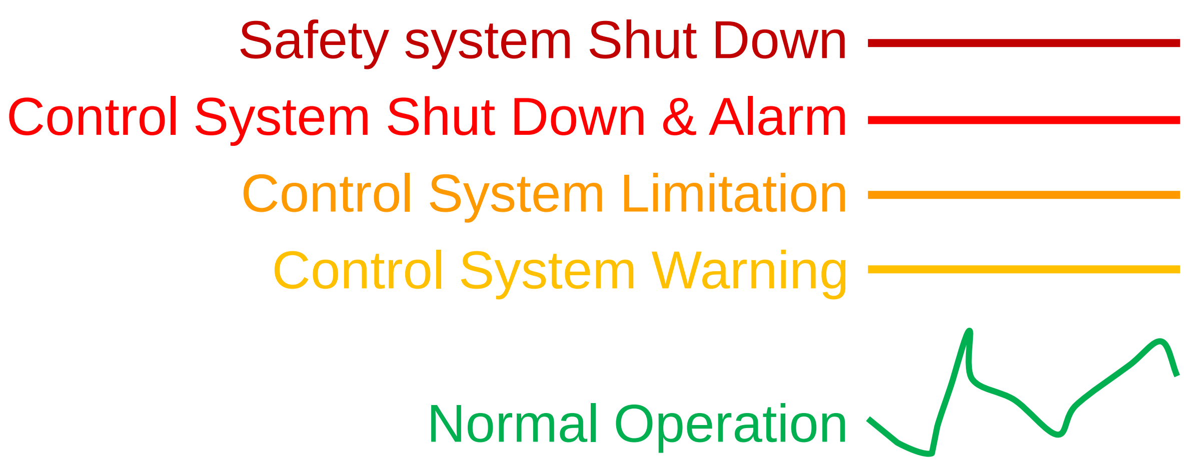
6.3 Grid Compliance

- Grid compliance measured at EMEC point of connection and not at turbine output

Criteria	Description	Pass Criteria
Voltage step changes	Largest changes due to onshore transformer energisation and turbine shutdown from full power	Engineering recommendation P28 3% max. voltage step change
Flicker	Voltage variation due to unsteady turbine output and load switching	Engineering Recommendation P28 Pst < 1, Plt <0.8
Power Factor (Real and Reactive Power)	Power factor must be within given range	Compliance with EMEC grid connection agreement
Voltage Unbalance (at point of connection)	Voltage unbalance at point of connection due to unbalanced turbine output	Engineering Recommendation P29 Voltage unbalance < 2% over 1 minute
Harmonic distortion (at point of connection)	Voltage harmonic distortion at point of connection due to unbalanced turbine output	Engineering Recommendation G5/4

6.4 Safety System Considerations

- The safety system is present to protect the turbine if the control system does no detect, or act on, measurements indicating a potential failure.
- The system must be reliable so is typically SIL level 3 or above.
- The safety system is dependent on the turbine design but usually includes action on
  - rotator overspeed,
  - watch dogs and
  - vibration.
- The Safety System protection us always set above the control system.



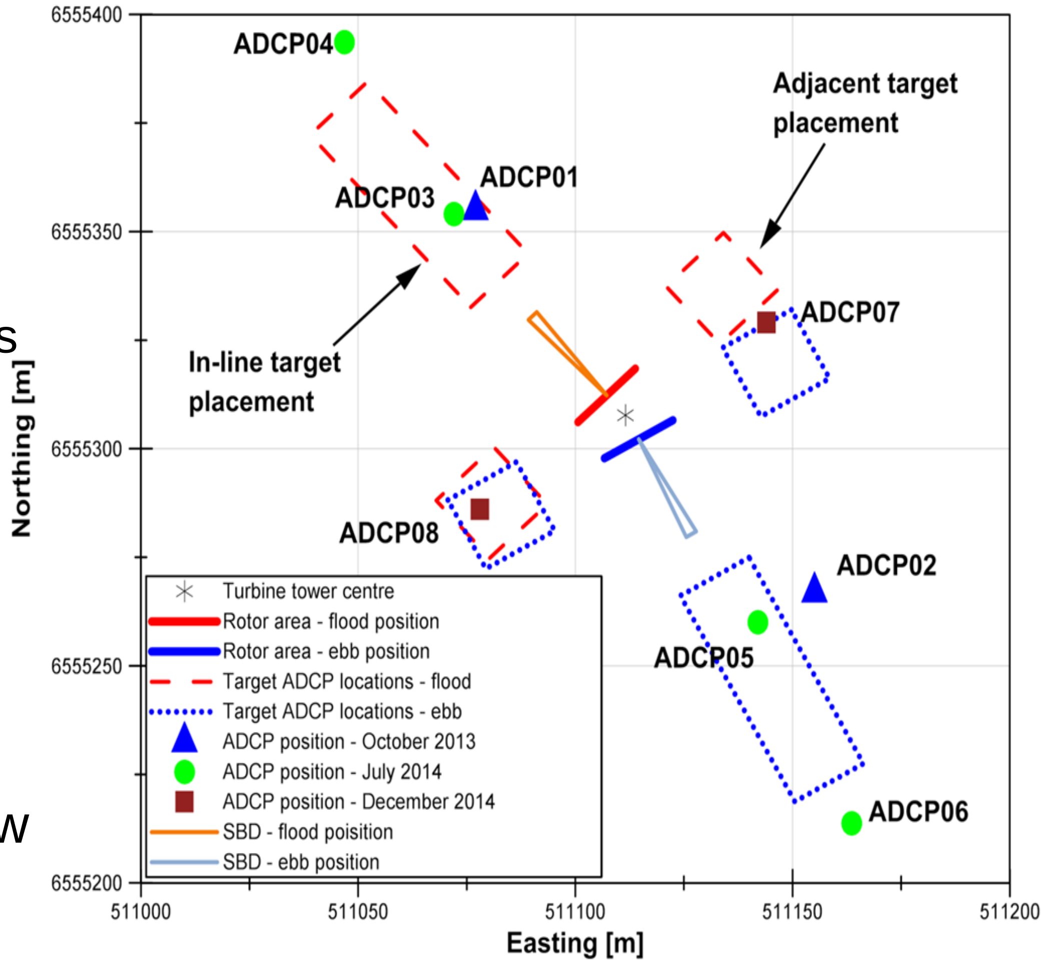
6.5 Supervisory Control and Data Acquisition (SCADA)

The prime purposes of the SCADA system was:

1. To provide real-time visualisation of device status
2. To collate, store and make available information gathered from other sources
3. To produce key performance indicators
4. To allow a user of the system to report on and trend collected data

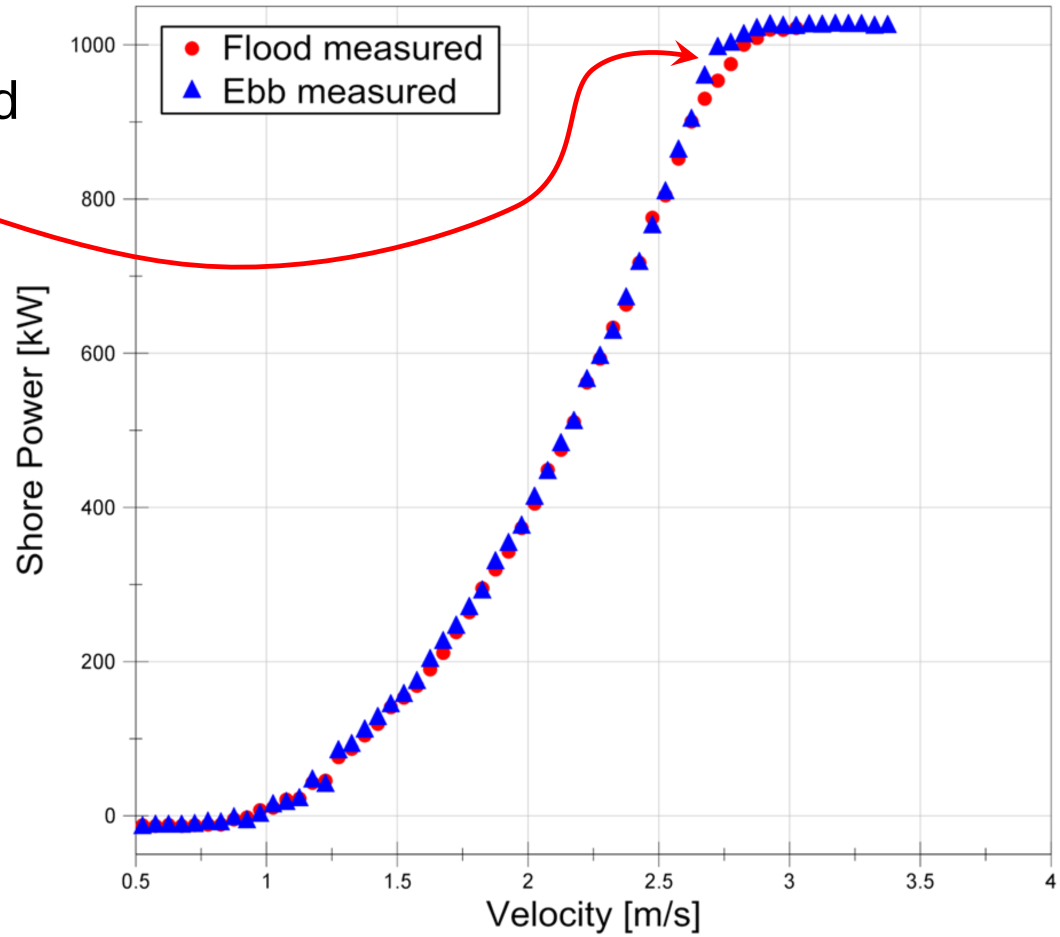
6.6 Performance Measurements and Predictions

- Prediction
  - Made using BEM tool such as Tidal Bladed
  - Site specific environment:
    - Custom shear profiles
    - Mean turbulence intensities
    - Wave scatter diagram
- Measurement
  - Measurements conducted under IEC/TS 62600-200
  - Power measured from turbine or shore measurements and tidal flow from seabed ADCPs

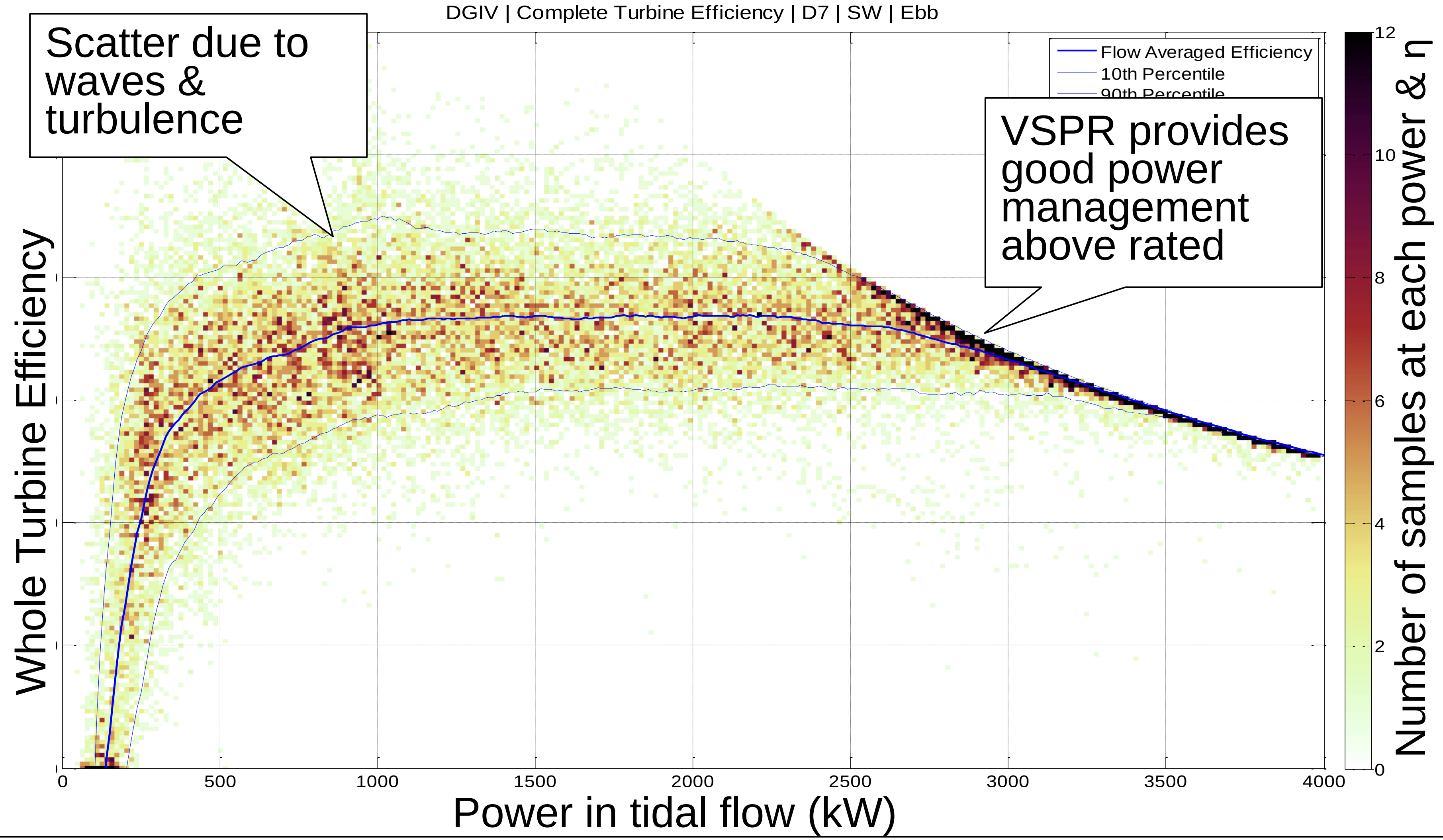


6.6 Performance Measurements

- Power curves are generally similar for both tides
- Transition into rated influenced by tide specifics:
  - Wave climate
  - Turbulence

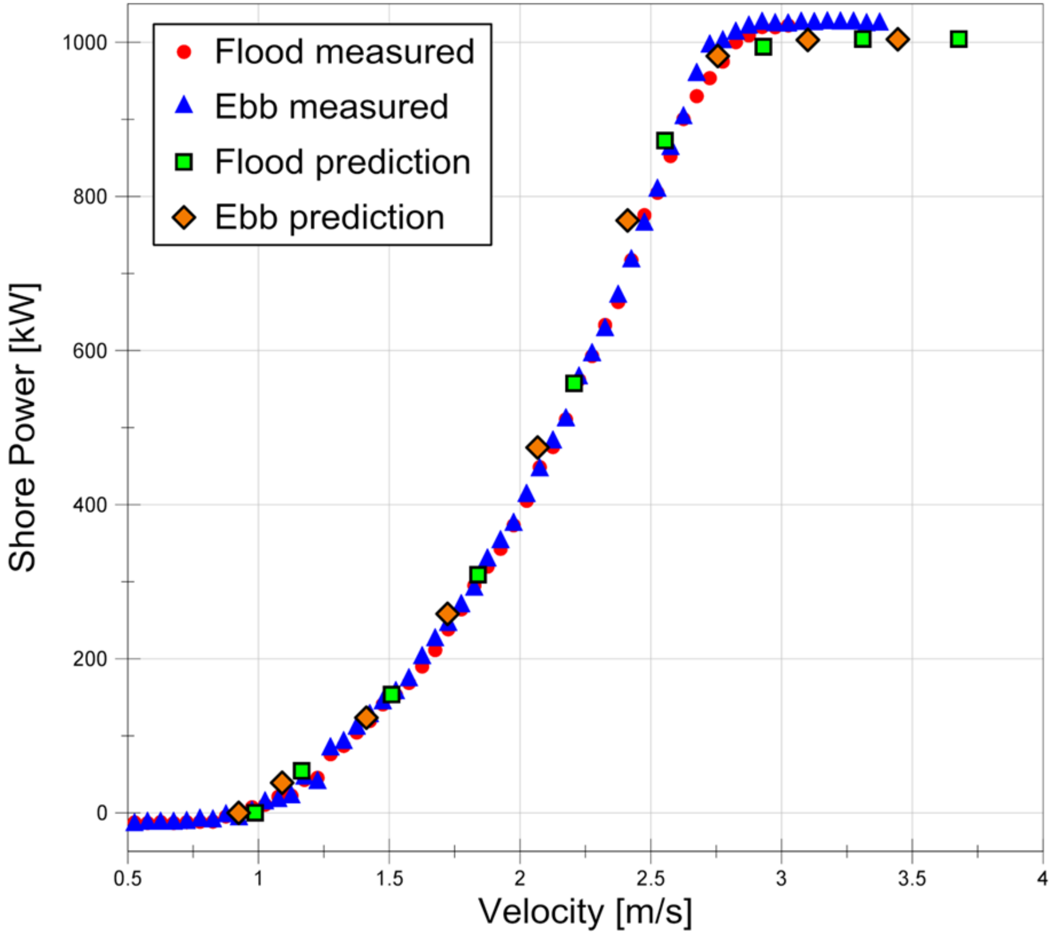


6.6 Performance Measurements



6.6 Performance Measurements and Predictions

- Numerical prediction shows good agreement



6.6 References

- MC7.1
- MD6.5
- IEC/TS 62600-200

7 Maintenance / Site Working

8 Marine Operations

8.1 Contracting
8.2 Weather, Risk and Planning
8.3 HIRA process
8.4 Vessel types, experience & selection
8.5 ROVs – specifications, suitability, limitations, lessons
8.6 Slack water prediction
8.7 Stability
8.8 Buoyant Recovery

8.1 Contracting

- Offshore contact structures are completely different from standard corporate supplier terms & conditions
- The LOGIC Offshore Services and Construction terms (link) are often used as these have been developed after year of experience in the Oil & Gas sector BUT there is a need to understand how they are intended to work (e.g. knock-for-knock basis) and how they are interpreted.
- The BIMCO GENTIME Charter (link) which tends to be used for chartering vessels (e.g. for delivery services) and BIMCO TOWCON Charter (link) which is used for towing operations: both carry a different range of liabilities for the charterer compared to the LOGIC contract.

8.1 Contracting on ReDAPT

- For the ReDAPT programme:
  - The BIMCO contract worked for the crane hire
  - The LOGIC format worked for the services on the crane and the installation vessel Seven Sea
  - The tiered call-off (Low day rate = long term standby, Medium day rate = short term standby, Operational day rate) was sufficiently flexible to cope with the weather and tidal windows
  - A dedicated crew meant continuity and learning, lowering the risk for failed operations and other operational issues

8.1 Contracting on ReDAPT

- The "luxury" of a long-term charter for ReDAPT gave flexibility but came at a significant financial cost. However, a more flexible charter (e.g. allowing the vessel to go to other places to find work) would have meant much longer mobilisation call-off periods which would have delayed the test programme.
  - Going forward, there is a balance between having a vessel and crew dedicated to the project (high cost, but rapid response = better availability) and having a limited range of vessels on a more "sport market" or long call-off rate (= lower availability and potentially inexperienced crews = higher risk)
- The "luxury" of a crane charter provided lifting logistics but came at a cost.
  - Lifting services should have been supplied by the local authority as part of the port infrastructure.

8.1 Contracting – Lessons Learned

- Get some specialist help in offshore contact structure – the marine contractor will understand it better than you!
- Work in a spirit of partnership with the marine contractor and take advantage of their specialist marine knowledge
- Recognise that the skipper is the boss and has the final say over operations for the safety of his crew, his vessel and lastly your asset!
- Ensure enough of your own staff are offshore-survival trained to allow flexibility to work offshore and that the vessel has sufficient "passenger" space to permit your own staff to witness the offshore process (you want to make sure you see that the marine contractor is fulfilling his contractual obligations and you may be needed to sign off aspects of the work as completed, acting as the client expert witness)

8.1 Contracting – Lessons Learned

- As with any contract, agreement on the scope, interfaces and payment terms are key focal points
  - Understand who takes what risk and ensure a risk mitigation plan is produced to manage risk e.g. weather delays, mobilisation delays, pollution, risk of loss (to vessel, assets, 3rd party assets etc.)
  - Understand what is included in contract and what is not and who is responsible for the items not included
  - Ensure that interfaces are fully understood and appropriate insurance put in place to mitigate third party risks e.g. cable damage
  - Spend the time up-front clarifying scope, roles & responsibilities and planning for contingency. Do as much engineering work up front, including testing of systems and contingency operations, to avoid costly delays later
  - Ensure payment clauses are detailed so that all parties understand what they will and will not be paid for.
  - Clearly define the invoice process to ensure prompt payment.
  - Agree any contract amendment/additional work in a formal manner to avoid misunderstanding and dispute at a later date – there is a temptation to agree things verbally in what is often a dynamic and time pressured environment, but if this agreement is not captured there will be dispute over scope, cost and risk allocation!

8.1 Contracting – Lessons Learned

- Offshore the marine contractor and the skipper are in charge, an important interface is the where the marine contractor interacts with your own EHS procedures and work site (i.e. onshore):
  - Ensure EHS interfaces between offshore and onshore work are clearly defined and control mechanisms put in place
  - Ensure marine contractor understands what EHS rules have to be followed when working on shore and who is responsible for administering them e.g. PPE, lock out and tag out (LOTO) procedures, performing risk assessments, attending tool-box talks etc.
  - Ensure the interfaces between the marine contractor and local harbour authority are understood and that the risks are defined
  - Ensure any marine contractor lay-down areas are managed by the marine contractor to the appropriate standards

8.2 Weather, risks and planning

- Pre-defined weather limits were observed throughout operations onshore and offshore.
- Issues which occurred due to poor weather
  - Barge / quayside damage – storm conditions
  - Severn Sea damage – storm conditions
  - Moorings parted during hip mooring operations. The operations remained safe but it proved that hip mooring in this manner isn't suitable in poorer seastates
- Forecasting and project planning
  - Many forecasts are available (Orkney Harbours, XC weather, Magic seaweed, etc).
  - Confidence can only be gained 3 day in advance of a target date.
  - Call up of marine contractors on a 'closing window' contract proved to be useful as operations could be postponed if the forecast was poor. Target dates for operations were planned around the weather forecasts.

8.2 Weather, risks and planning

- Quayside operations
  - The maintenance site on Hatston quay was very exposed. Operations had to be suspended on many occasions due to high winds (particularly lifting operations).
  - Good storage of equipment was important as high wind regularly had the potential to cause damage or blow items away.
  - Maintenance activities had to be planned around weather forecasts.

- **Conclusions**
  - Orkney is susceptible to high winds and as such careful planning is required around weather forecasts.
  - Operations should be designed to reduce weather sensitive activities to avoid down time and cost. E.g. reducing crane operations where possible
  - The deployment process is weather sensitive in exposed sites.
  - An exposed maintenance site restricts operations as poor weather can significantly hamper operations.
  - Summer operations are much less susceptible to down time due to poor weather, as opposed to winter operations. An obvious but important point!

Poor weather after a deployment (note that turbine deployment & retrieval operations were not conducted in these conditions)

8.3 HIRA Process

- **HIRA definition – “Hazard Identification and Risk Assessment”.**
- HIRAs were conducted for all standard and contingency operations for turbine deployment and retrieval, involving key operation personnel in the assessment.
- HIRAs were also conducted for the onshore maintenance tasks, also involving the engineers involved with the tasks.
- HIRAs should always accompany method statements for the tasks to be conducted.
- The HIRA process proved useful during the planning of standard and contingency operations to mitigate all risks to acceptable levels or ALARP (As Low As Reasonably Practicable).
- The HIRA process should be used on future projects in a similar manner to ReDAPT.

8.3 HIRA Process

Process / task	Hazard		Probable Causes	Hazardous effect	People at risk	Likelihood (1-5)	Severity (1-5)	Risk	Main Type of Control	Control measures	Likelihood (1-5)	Severity (1-5)	Risk
4 point Mooring Installation		See risk assessment for mooring installation						0					0
	Marine	Proximity of moorings to subsea cables	Unaware of subsea cable positions	damage to cables		3	4	12	Engineering control	Confirmation with EMEC and Alstom of cable and ADCP positions Calibration checks on GPS survey system on board Good vessel station keeping Good weather	2	4	8
								0		pre-installation seabed surveys with ROV			0
Mooring installation on turbine	Marine	Mooring line entanglement (with blades)	tidal current during peak flow	Damage to blade Damage to mooring line		4	2	8	Administrative control	Mooring line buoyed off as short as possible. Diver to disentangle mooring line. 4 point mooring gives sufficient station keeping without relying solely on the mooring on the turbine.	3	2	6
								0					0
Hotstab dummy removal and water ingress check	Mechanical	Water ingress observed	failure of check valve	water ingress into turbine		2	4	8	Engineering control	Re-install hotstab dummies immediately Diver to remain next to hotstab receptacles for 2 minutes during tests	1	4	4
	Mechanical	Diver cannot re-install hotstab dummies, and leak IS present	fouling on hotstab dummies or receptacles Diver cannot remain next to clamp	Cannot prevent water ingress to turbine		2	4	8	Engineering control	Hotstabs attached to clamp with chains Sufficient dive time allowance Good slack water period Second diver to complete task ROV to attempt to install hotstab dummies De-isolate turbine and pump the bilge	1	4	4
	Mechanical	Diver cannot re-install hotstab dummies, and leak is NOT present	fouling on hotstab dummies or receptacles Diver cannot remain next to clamp	Increased risk of water ingress between dives		2	2	4	Engineering control	Continue with operation Second diver to complete task if deemed necessary	1	2	2

Example of HIRA for contingency turbine recovery

8.4 Vessel types, experience and selection

Vessel selection criteria	Solution for ReDAPT	Lessons Learned
Cost (day rates)	Circa £7 for operational day rates.	Day rates acceptable to the project, but it is recognised that day rates are a significant driving factor in the maintenance costs and should be kept to a minimum. Competitors day rates are significantly higher.
Size	30m	Suitable to hip moor turbine Suitable to accommodate all deck equipment, but tight access in some areas.
Propulsion, towing and station keeping capabilities	Stern azimuths A bow thruster was added during the project as the marine contractor upgraded the vessel as they recognised a need for increased performance.	The vessel was suitable for towing and station keeping, however project specific upgrades increased the performance overall. Station keeping in high currents and poor weather is a demanding requirement for work vessels. Several marine contractors are considering DP (Dynamic Positioning) for small vessels and bespoke propulsion systems to accommodate for this requirement.
Accommodation capacity	15 people	
Stability	Work boat – traditional boat shaped hull.	The vessel roll was reasonably significant. Other types of vessels with better stability should be considered in the future (e.g. multicats).
Cranage and deck equipment	Upgrades were made to mobilise for the project.	Cranes were suitable in good weather, but it is recognised that more advance Launch and Recovery Systems may be required when operating in poorer conditions.
Contract frame work	Tiered day rate, scheduled around the tidal cycle: • Low day rate, long term standby. • Medium day rate, short term standby. • Operational day rate.	Proved to be effective and economic compared to other options. Close management of call up periods was required to optimise schedules around weather windows and potential uncertainties in turbine readiness.
Marine contractors familiarity to working in tidal sites	KML had previous experience of working in tidal sites prior to ReDAPT. Efforts were made to have consistency in the crew to keep familiarity levels high.	The vagaries of working in the tidal environment require significant previous experience. Learning on the job is a costly way to gain experience.
Safety	Upgrades made to improve safety equipment and methods. No serios incidents or accidents occurred durign the course of the ReDAPT project.	Continual improvement on safety is always a requirement in a dynamic environment. Improvements could be made by arranging better deck layouts (potentially larger deck area required), better communication systems, automised mechanical handling, etc.

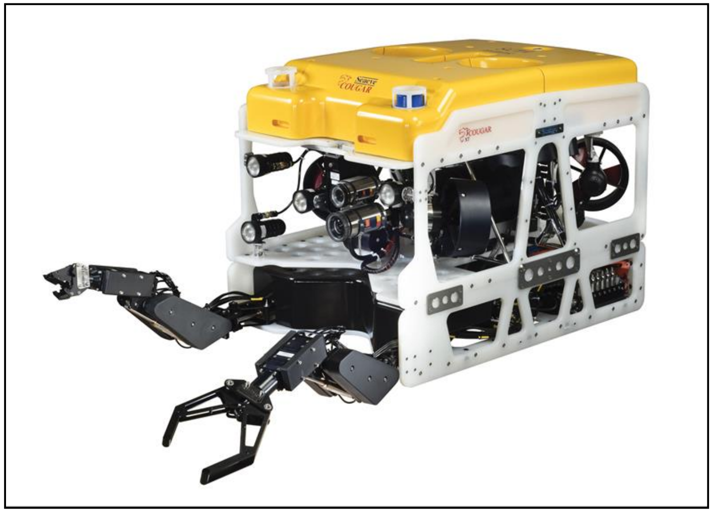
8.4 Vessel types, experience and selection

KML's Severn Sea

- Vessel upgrades for ReDAPT
  - Towing winch
  - Crane for winch Launch and Recovery
  - Cougar ROV (including Launch and Recovery System and workshop)
  - Fender arrangement on hull for hip-mooring
  - Bow thruster (DP 1)

8.5 ROVs – specifications, suitability, limitations

- A Seaeye Cougar was selected for the ReDAPT project.
- This was an upgrade from previous projects (Seaeye Falcon) as it was recognised that increased ROV performance was required.
- A cougar gives a high power to size ratio and low day rates.
- The limits of tidal current were in the region of 1 knot, but 1.5 knots were achievable.
- This gave typical operating windows of up to one hour, which was acceptable for the deployment operations.
- ROV operations are generally difficult and hazardous in tidal sites. The duration of a specific operation can vary considerably.
- Pilot skill, experience and understanding of the tide is of critical importance.
- Attaching / detaching the winch rope was problematic and lots improvement can be made to this in the future.
- If shorter windows and higher current is required in the future, higher performance ROVs would be required.



Seaeye Cougar ROV

8.5 ROVs – specifications, suitability, limitations

- Bespoke tooling was developed for the control umbilical stab / de-stab
- This was due to the lack of capability in the standard Cougar performance
- Many faults were found with this tool and lots of improvement is planned for the future
- A bespoke tool was also developed to release the rope coupling. This worked reasonably well, but can be eliminated in the future through better design
- The contingency operation for inserting hotstabs to open the turbine clamp was deemed to be not possible with the ROV due to lack of performance and dexterity. Divers were used in this instance.

ROV Launch

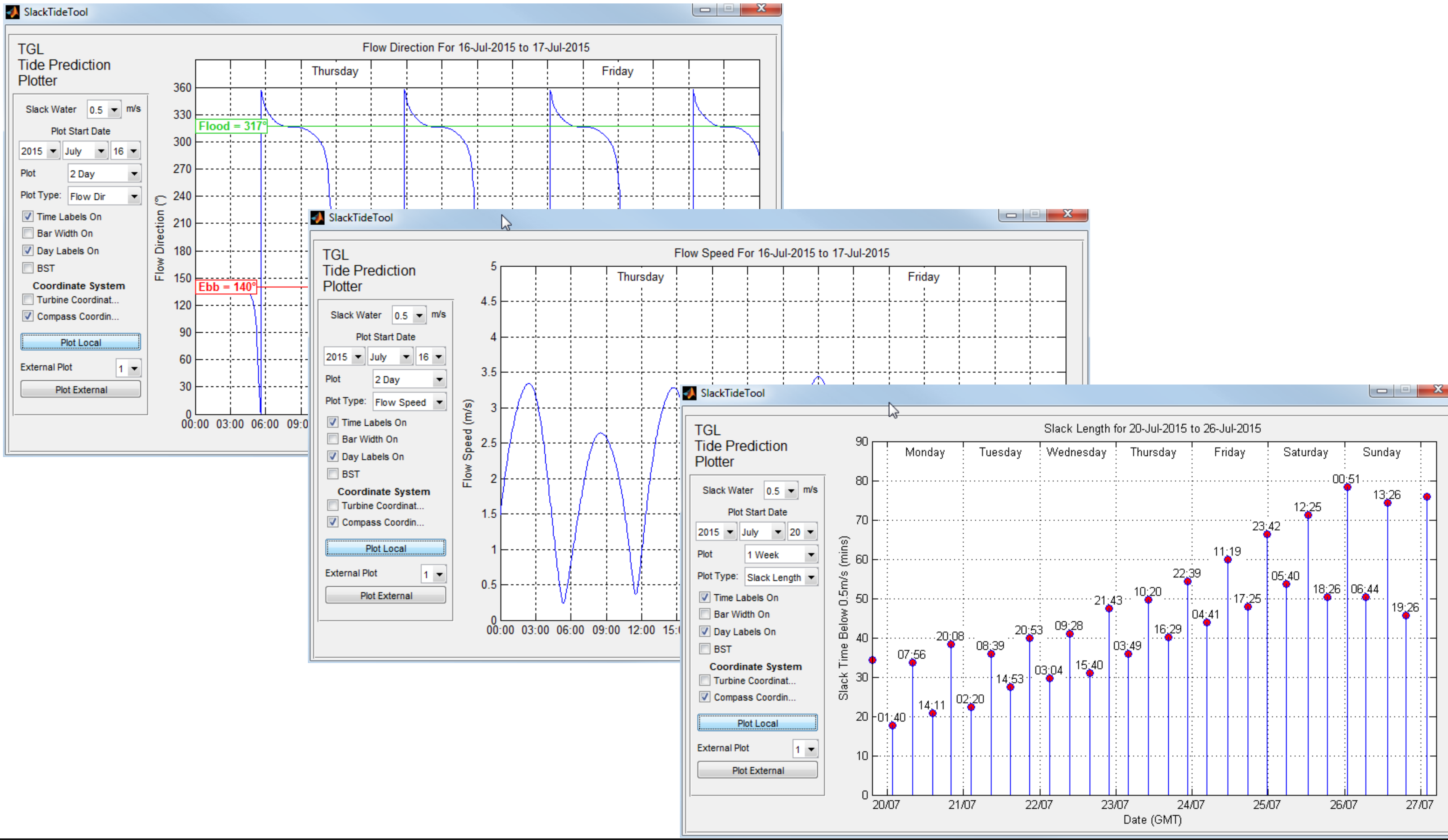
Conclusions

- ROV operations should be designed out where possible as ROV operations are a weak point when operating in tide
- Where ROV operations are essential, robust design should ensure operations have a limited number of steps, and each step should be easy, quick and repeatable.

8.6 Slack Water Prediction

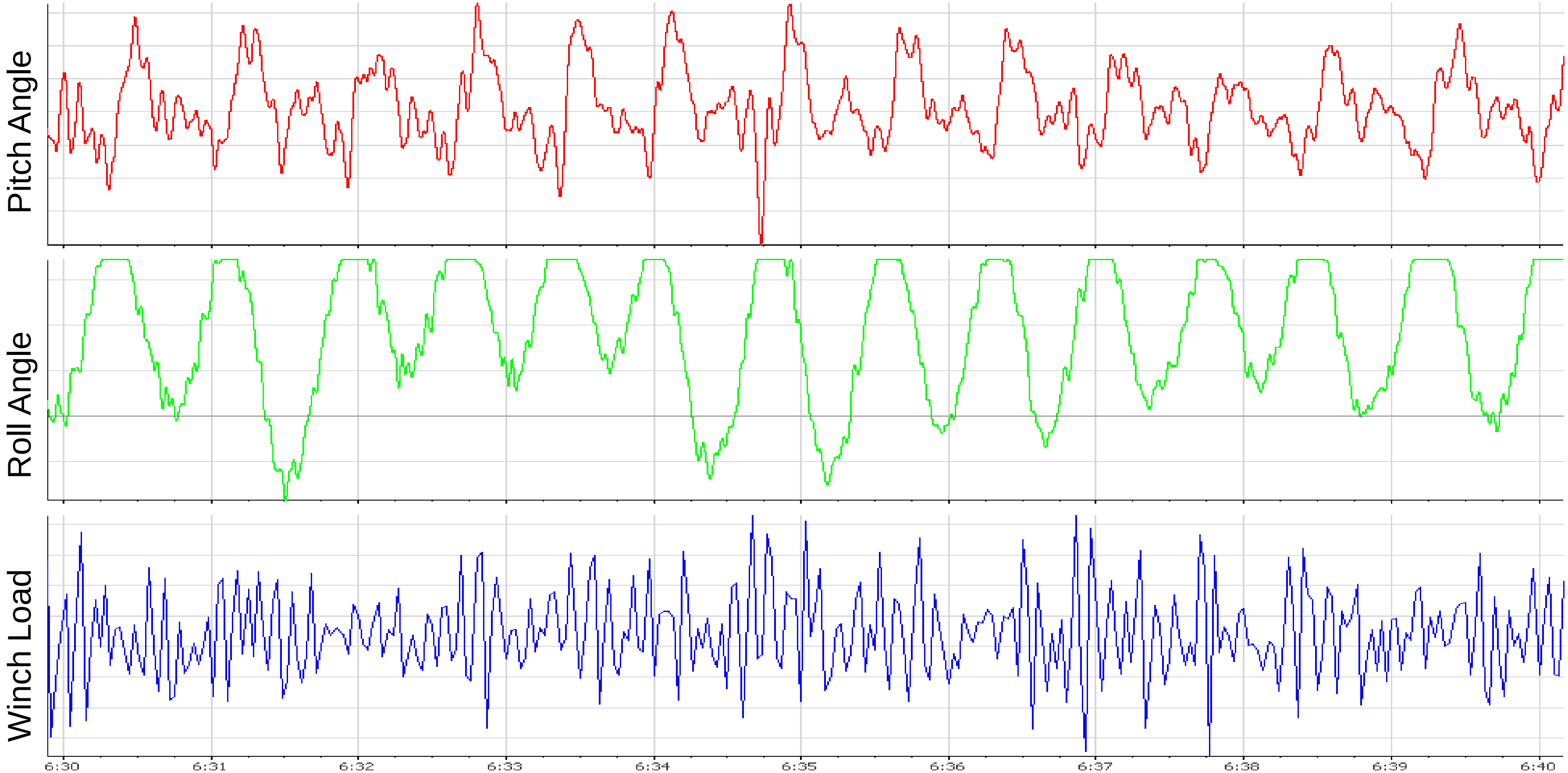
- Tidal flow prediction as described in section 1.9 only predicts flow along the axis of the turbine.
- At slack water the flow can come from any direction and so this prediction is unsuitable.
- Solution is to perform tidal harmonic analysis in two axes perpendicular to one another and then combine the predictions of both to get a flow magnitude and direction.
- With a desired maximum flow speed configurable, then possible to calculate when the slack tide centre and length.
- Can't take account for weather effects which can shift the tide ±30mins

8.6 Slack Water Prediction



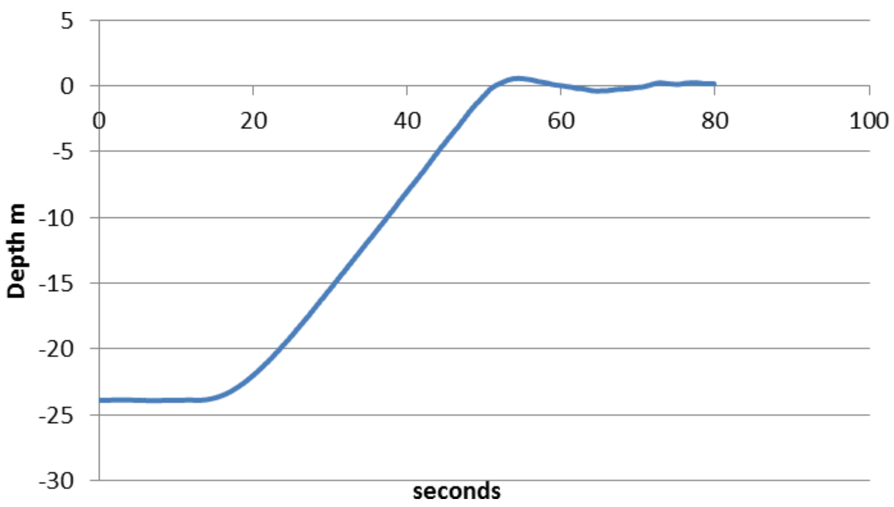
8.7 Stability

- DEEP-Gen IV was a buoyant turbine therefore towing and winching stability was important so monitored with strain gauges, video, inclinometers and load cells.
- For towing the behaviour could be modified with blade pitch angle



8.8 Buoyant Recovery

- The turbine floats.
- So why not just release it from the foundation and let it float to the surface?
- Calculations estimated turbine behaviour and free retrieval trialled on DGIII
- Now baseline for reliable recovery
  - Removes ROV operations
  - Increases recovery sea state
- Health and safety needs managing, as with all marine operations

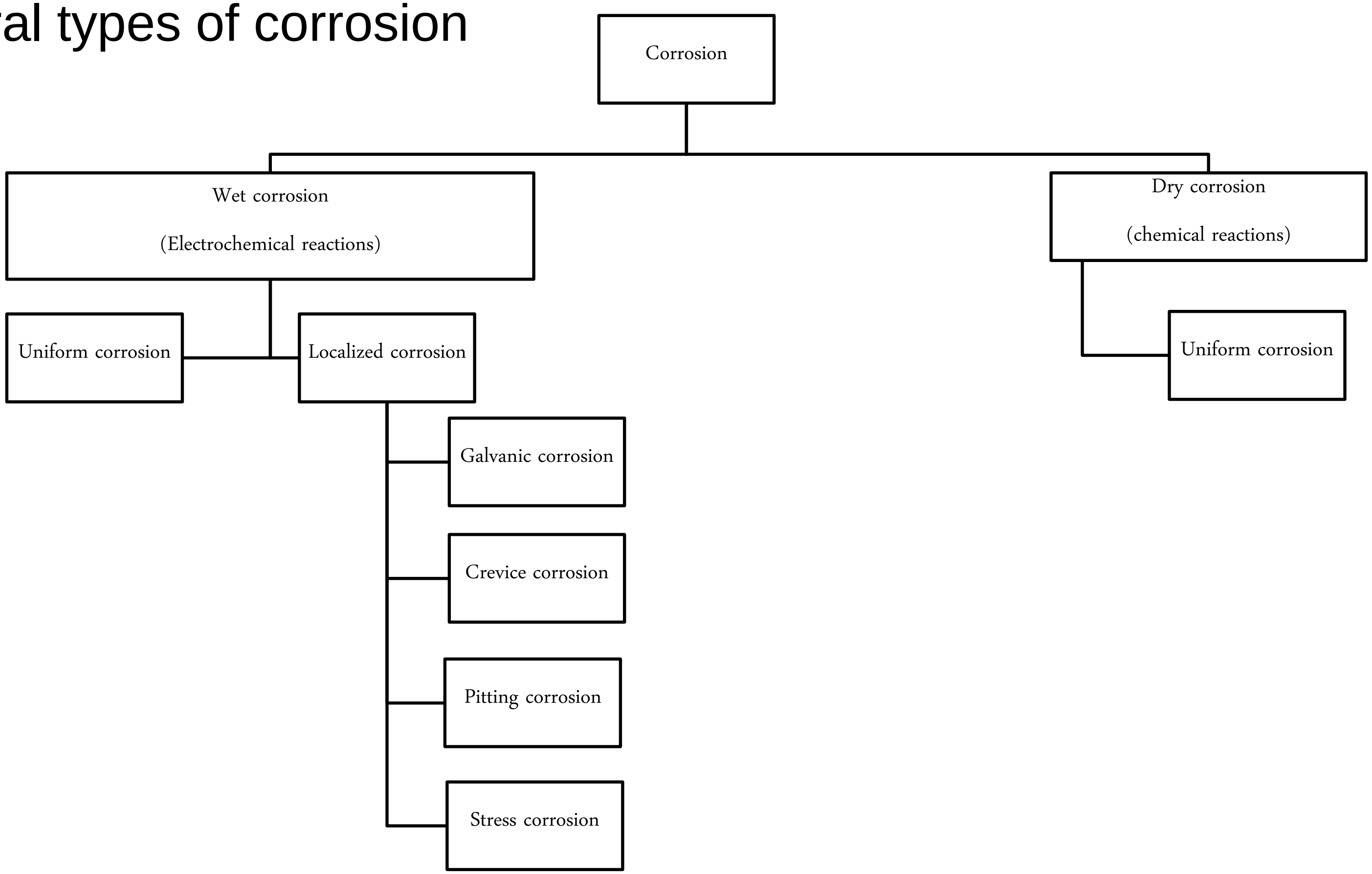


9 Marine Environment

- 9.1 Corrosion
- 9.2 Cathodic Protection
- 9.3 Biofouling
- 9.4 Anti-fouling
- 9.5 Coatings
- 9.6 Calcareous Deposit
- 9.7 Material Selection
- 9.8 Mammal Monitoring

9.1 Marine Environment: Corrosion

Several types of corrosion



9.1 Marine Environment: Corrosion

On DEEP-Gen IV corrosion protection was by :

Paints :

•Interzone (yellow paint)

•Different anti-fouling on the 3 blades

Cathodic protection :

•Aluminium-based sacrificial anodes

Paints and cathodic protection system both provided an efficient corrosion protection.

9.2 Marine Environment: Cathodic Protection

Cathodic protection was provided by Aluminium-based sacrificial anodes

The weight and distribution of these anodes must be sufficient to give protection for at least one turbine deployment.

9.3 Marine Environment: Biofouling

Biofouling

9.4 Marine Environment: Anti-fouling

Anti-fouling

9.5 Marine Environment: Coatings

Coatings

9.6 Marine Environment: Calcareous Deposit

Calcareous Deposit

9.7 Marine Environment: Material Selection

Material Selection

9.8 Mammal Monitoring

- DEEP-Gen IV turbine had the potential to monitor for any potential mammal interactions.
- Monitoring system built upon an initial system that was developed on DEEP-Gen III turbine.
- Due to the lack of success using cameras in the turbid marine environment this system was built on the use of strain gauge measurements for absolute bending moments and rates of change.
- Strain gauges in the shaft and the blades were used to identify any potential interaction.
- An algorithm was developed to monitor spikes in the signals from these strain gauges.
- Threshold values of monitoring parameters were established based on mammal dimensional data for mammals appropriate to that area.

9.8 Mammal Monitoring

- The algorithm was run for longer continuous periods as well as targeted dates based on mammal observation information available.
- Throughout all these tests no evidence of mammal interaction was identified.
- Sample data for a specific tide shown below, both rates of change and bending moments were well below limits in normal operation.