

Specialist Committee on Hydrodynamic Modelling of Marine Renewable Energy Devices

Presentation & Discussion at the 28th ITTC Conference

Specialist Committee on Hydrodynamics Modelling of Marine Renewable Energy Devices



Presentation to the 28th ITTC



Committee Members

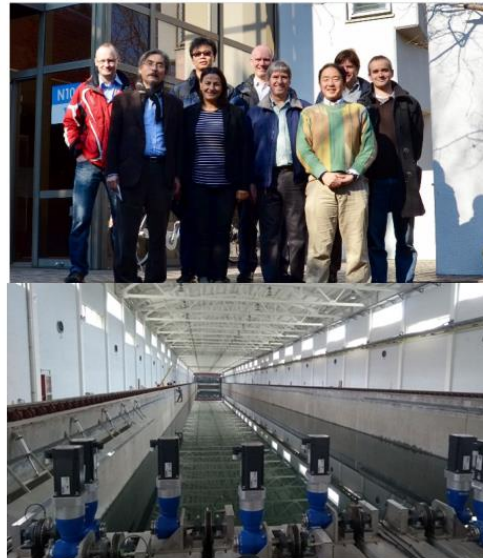
Assoc Prof Irene Penesis (<i>Chair</i>)	<i>Australian Maritime College, Australia</i>
Dr William Batten (<i>Secretary</i>)	<i>QinetiQ, UK</i>
Prof Ye Li	<i>Shanghai Jiaotong University, China</i>
Dr Marek Kraskowski	<i>Centrum Techniki Okrętowej (CTO), Poland</i>
Prof Motohiko Murai	<i>Yokohama National University, Japan</i>
Dr Petter Andreas Berthelsen	<i>SINTEF Ocean (fmr. MARINTEK), Norway</i>
Prof Hyun Kyoung Shin	<i>University of Ulsan, South Korea</i>
*Prof Arnold Fontaine	<i>Pennsylvania State University, USA</i>
*Dr Aurélien Babarit	<i>École Centrale de Nantes, France</i>

Committee Meetings

The committee met four times:

- Yokohama National University, Japan (*February 2015*)
- Australian Maritime College, Australia (*February 2016*)
- SINTEF Ocean, Norway (*July 2016*)
- Centrum Techniki Okrętowej (CTO), Poland (*February 2017*)

*The committee also met prior to the full conference at Shanghai Jiaotong University (SJTU).



Committee's Tasks

1. Guideline development
 - Cooperation with IEC, DNV-GL and major project initiatives
2. Reporting state-of-the-art work related to:
 - Wave energy converters (WEC)
 - Current turbines
 - Offshore wind turbines (OWT)



Guideline Development

- Cooperation with others generating guidelines include:
 - *International Electrotechnical Commission (IEC)*
TC88 (Wind Turbines) & TC114 (Marine Energy)
 - *DNV-GL*
JIP - Coupled Analysis Of Floating Wind Turbines
 - *Research institutes: EMEC, SuperGen, MARINET2,...*
- Other guidelines providing fragmented guidance e.g. WEC PTO modelling and control, extrapolation from model to full-scale and uncertainty analysis.
- Gaps between wave tank and ocean tests – covered by major research & industry collaborative projects



MaRINET2



PerAWa1
Project



Revisions to Existing Guidelines

7.5-02-07-03.7 Wave Energy Converter Model Test Experiments

- Careful consideration of the differences and complexities in testing a device at various TRLs, e.g. PTO system, survivability tests
- Reference new uncertainty procedure 7.5-02-07-03.12
Uncertainty Analysis for a Wave Energy Converter

7.5-02-07-03.8 Model Tests for Offshore Wind Turbines

- Development stage (TRL) better defined
- Updated to include the recent advances in hybrid testing technology

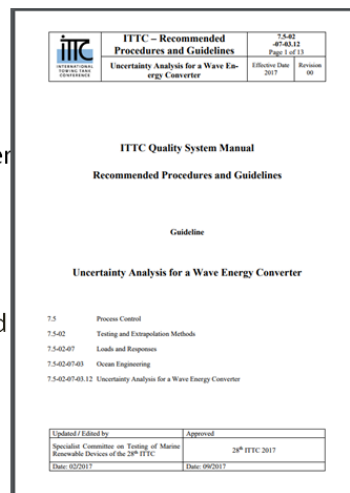
7.5-02-07-03.9 Model Tests for Current Turbines

- Reference new uncertainty procedure 7.5-02-07-03.15
Uncertainty analysis - Example for horizontal axis turbines

Uncertainty Guideline – WEC

7.5-02-07-03.12 Uncertainty Analysis for a Wave Energy Converter

- Guideline complimentary to the ITTC Recommended Procedure, Wave Energy Converter Model Test Experiments (7.5-02-07-03.7).
- Developed based on ISO (1995).
- Focus on TRLs 1-4
- Example of testing an offshore–stationary oscillating water column (OWC) device is provided
- Evaluation of uncertainty in main parameters related to testing environment, and WEC power and efficiency
- 1st and only international guide for uncertainty analysis for WECs



Uncertainty Guideline – Current Turbines

7.5-02-07-03.15 Uncertainty Analysis - Example for Horizontal Axis Turbines

Provides discussion on the sources of uncertainty such as:

- Scaling
- PTO contributions
- Model errors
 - Manufacturing
 - Structural
 - Functional
- Facility issues such as
 - Flow and turbine control
 - Blockage

Provides an example of an uncertainty calculation for 800mm diameter horizontal axis turbine.

ITTC	ITTC – Recommended Guidelines	7.5-02-07-03.15	Page 1 of 13
Uncertainty Analysis - Example for Horizontal Axis Turbines		Effective Date 2017	Revision 00

Table of Contents:

1. PURPOSE OF THE UNCERTAINTY ANALYSIS.....3	4.5. Blockage.....9
2. INTRODUCTION.....3	4.6. Supporting Structures and Instrumentation.....9
3. SUMMARY OF ERROR CONTRIBUTIONS.....3	5. APPLICATION OF UNCERTAINTY ANALYSIS TO A HORIZONTAL AXIS TURBINE MODEL TEST.....9
3.1. Scaling.....3	5.1. Test Data.....9
3.1.1. Superimpose use of Scaling Laws.....3	5.1.1. Precision Limits (Type A Uncertainty).....10
3.1.2. Impact of Re Scaling.....3	5.1.2. Bias Limits (Type B Uncertainty).....10
3.2. PTO Sources of Error.....4	5.1.3. Geometry.....10
3.3. Model Errors.....4	5.1.4. Temperature and Density.....10
3.3.1. Manufacturing.....4	5.1.5. Rotational Speed.....10
3.3.2. Structural.....5	5.1.6. Thrust Speed.....10
3.3.3. Functional.....6	5.1.7. Thrust and Torque.....10
3.4. Standard Sources of Test Errors.....7	5.1.8. Power.....10
4. FACILITY.....7	5.1.9. Tip Speed Ratio Bias.....11
4.1. Flow Quality.....7	5.1.10. Torque Power Coefficient Bias.....11
4.2. Accuracy.....8	5.1.11. Torque Torque Coefficient Bias.....11
4.3. Controllability and Reproducibility.....8	5.1.12. Comments on Total Uncertainty.....12
4.4. Uncertainty.....8	6. REFERENCES.....12

Updated / Edited by	Approved
Specialist Committee on Testing of Marine Renewable Devices of the 28 th ITTC	28 th ITTC 2017
Date: 02/2017	Date: 09/2017

1

Terms of Reference - Wave Energy Converters (WEC)

1. Develop guidelines for uncertainty prediction for WECs.
2. Monitor and report on developments in power take-off (PTO) modelling both for physical and numerical predictions of power capture.
3. Review and report on the progress made on the modelling of WEC arrays.
4. Review and report on challenges associated with the performance of WECs in irregular wave spectra, particularly when they relate to physical modelling.
5. Check willingness of participants for the “round-robin” test campaign before starting work.
6. Review and report on integrated WEC simulation tools based on multi-body solvers which are in development.

Sea Trials & Demonstrations

Seatrivity

- Wave Hub test, UK
- 1:1 scale (~200 kW)
- 10 MW planned
- Point Absorber



Eco Wave Power

- Gibraltar, Spain
- 100 kW
- 5 MW planned
- Point Absorber



Wave Energy Tech.

- Japan
- 1:10 scale
- 1.2 MW planned
- Point Absorber



Carnegie Clean Energy

- WA, Australia
- 1:1 array (250 kW)
- 20 MW planned array
- Point Absorber



Wave Swell Energy

- TAS, Australia
- 1:1 scale (1 MW) planned for 2018
- OWC



Fred Olsen

- US Navy WETS, Hawaii
- 1:1 scale
- Point Absorber



WEC Power Take-off (PTO) Modelling

Physical & Numerical Predictions of Power Capture

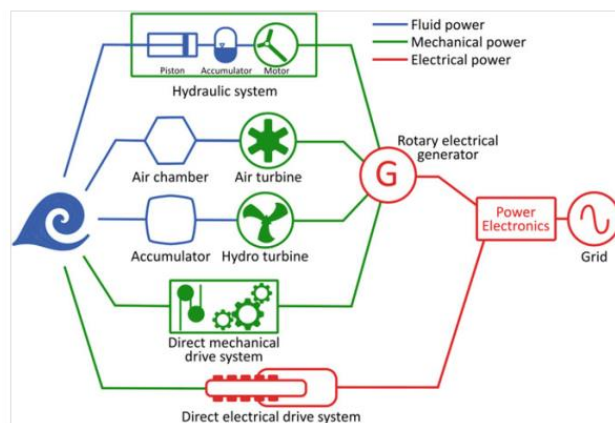
- PTO typically extracts energy from
 - relative motion between the device and the water
 - relative motion between different parts of the device
- Behaviour of PTO influences
 - power capture
 - motions (rigid and/or hydroelastic)
 - hydrodynamic loads
- Appropriate simulation of PTO essential to determine the performance of the system in small-scale model tests



WEC Power Take-off (PTO) Modelling

WEC PTO systems:

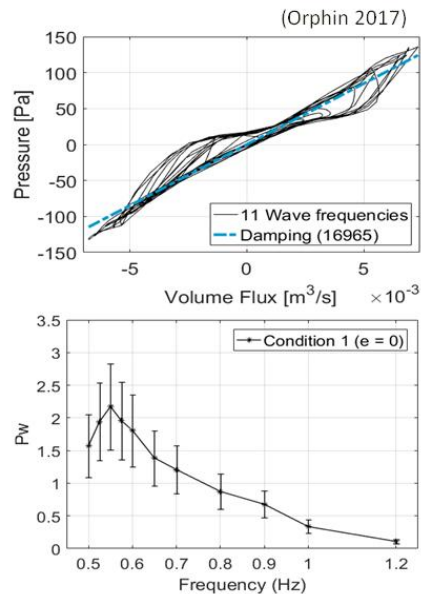
- Air or hydro turbines
- Hydraulics
- Direct electrical or mechanical drive systems
- flexible and/or electrical materials



Different methods for wave energy to electricity conversion
(Handbook of Ocean Wave Energy)

WEC Power Take-off (PTO) Modelling

- At TRLs 1-4 typically use simplified / idealised passive systems
- Typical passive systems:
 - Mesh, orifice plates on OWCs
 - Friction / pneumatic / hydraulic dampers for oscillating bodies
- Power capture determined from
 - pressure & flow rate
(typically OWCs – see right figures)
 - measured force & velocity
(typically oscillating bodies)
 - potential energy of fluid
(overtopping devices)

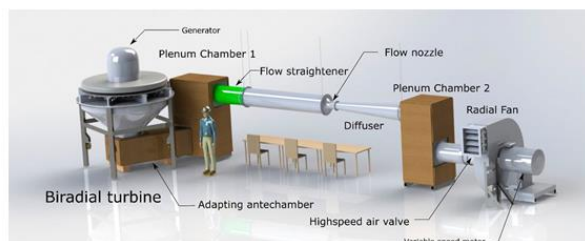


WEC Power Take-off (PTO) Modelling

Example: Use of wave emulators:

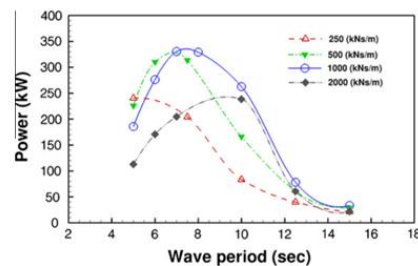
- Capability to simulate realistic sea states often used for scaled experiments to verify numerical models, validate parameters of interest.
- Testing in dry laboratory environments provides easy accessibility, less cost and enables rapid development of PTO

Henriques et al. (2016) present the testing and control of a power take-off system for an oscillating water-column wave energy converter using wave emulators.



WEC PTO Modelling – Numerical Tools

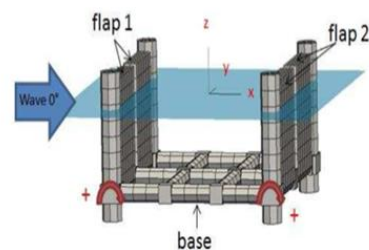
- Limited advanced in WEC PTO modelling tools.
- **Example: PTO-Sim (WEC-Sim)**
 - Sandia National Laboratories (SNL) and National Renewable Energy Laboratory (NREL)
 - Accurately models hydraulic/direct drive PTO systems
- Li and Yu (2013) developed a novel mesh matching method that allows using RANS to accurately describe the two body point absorber's behaviour under complicated sea condition, which was not possible in the past.
 - Significance of the nonlinear effects, including viscous damping and wave overtopping.
 - Showed that the nonlinear effects could significantly decrease the power output and the motion of the FPA system, particularly in larger waves.



Power absorption performance of the FPA system in 4 m waves (Li and Yu (2013)).

WEC Simulation Tools

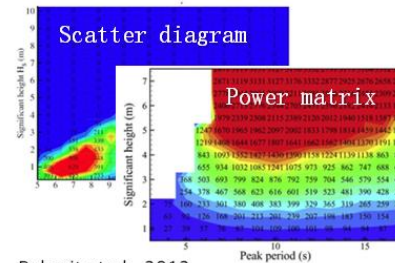
- Several WEC simulation tools are based on multi-body solvers developed.
- Model kinematics/dynamics of WEC body and PTO, and control systems.
- WEC3 Code Comparison project: code-to-code comparison of four numerical tools:
 - *InWave*, *WaveDyn*, *ProteusDS*, *WEC-Sim*
- Participants had different approaches for taking into account viscous effects through corrective terms. It was observed that it lead to differences in numerical predictions that can be significant (Comboureu et al., 2015).
- The next phase of IEA OES Annex IV project will deliver code-to-experiment validation.



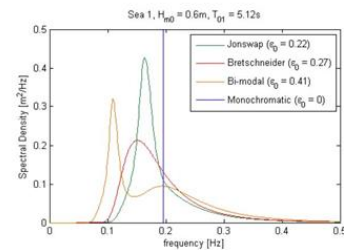
Floating three-body oscillating flap type device (F3OF): WEC code comparison device (Comboureu et al., 2015).

Performance of WECs in Irregular Waves

- Irregular wave tests are crucial for predicting performance of prototype
- Performance assessment requires resource characterisation and determining power matrix
 - performance matrix (H_s , T_e/T_p) – spectral distribution and directional spreading are also important*
- Important to use site-specific hindcast data in wave tank tests at TRL > 3 but simplifications using polychromatic waves can be used at early TRLs
- Challenges for survivability tests: numerical models being developed by SNL/NREL to address this



Babarit et al., 2012



Effect of spectral distribution on resonant WEC (Clabby et al., 2012)

Modelling of WEC Arrays

- To date, most large scale deployments have been single WECs, but its necessary to expand these to arrays or farms.
- Requires a thorough understanding of WEC arrays:
 - Interaction, performance (intra-array effects), and
 - Downstream effects (environmental effects, *aka* extra-array effects)
- Essential to predicting energy yield and cost of energy.
- Provide understanding of using WEC arrays for coastal defence.



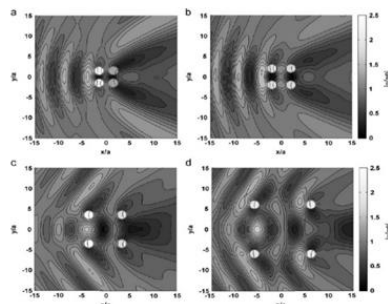


WEC Arrays – Numerical Modelling

Folley, M., 2016, Ed., “Numerical Modelling of Wave Energy Converters: State-of-the-Art Techniques for Single Devices and Arrays”, Academic Press.

Multiple DoF models

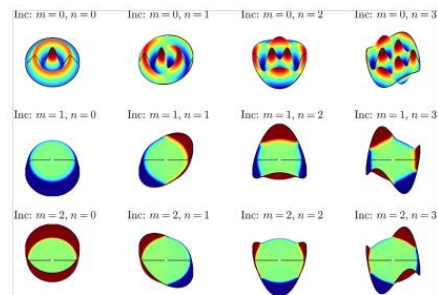
- Extends modelling of single WECs
- Freq.-domain models (BEM, FEM)
- Time-domain models (nonlinear)
- Limited CFD studies



FEM model of OWC array (Nader, 2012)

Semi-analytical models

- Point absorber method
- Plane wave method
- Multiple scattering method
- Direct matrix method



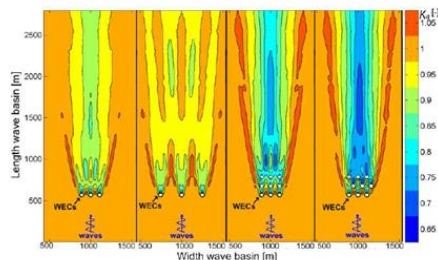
Wave pattern around WEC array (Folley, 2015)



WEC Arrays – Numerical Modelling

Phase-resolving wave propagation models

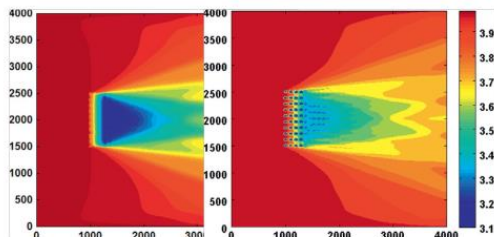
- Effect of WECs on environment
- MILDwave (mild slope equations)
- WECs modelled at sponge layers
- Can model large domains



Phase-resolved WEC wakes (Folley, 2015)

Phase-averaging wave propagation models

- Spectral wave models
- WECs either supragrid or subgrid
- Require another model for WEC response

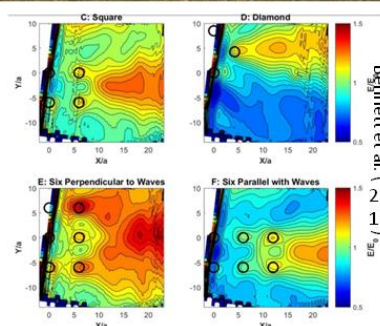


Supragrid and subgrid models (Folley, 2015)

WEC Arrays – Physical Modelling

- Limited physical experiments of WEC arrays
...due to cost, size of test facilities, and complexity
- Difficulties in measuring WEC kinematics/dynamics, and WEC array effects (near- and far-field)
- Model the radiation and diffraction forces separately -> sum to obtain q-factor (Nader et al., 2017; Bennett et al., 2017)
- Very few array floating WEC (with moorings) experiments
- **Provides urgently needed experimental validation for numerical models**

WEC array with 25 heaving buoys from the WECwakes project (taken from Troch et al., 2014)



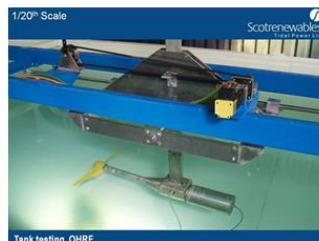
Terms of References – Current Turbines

1. Develop specific uncertainty analysis guidelines / example for horizontal axis turbines.
2. Report on developments in physical and numerical techniques for prediction of performance of current turbines, with particular emphasis on unsteady flows, off-axis conditions, and other phenomena which offer particular challenges to current devices.
3. Report on the progress made on the modelling of arrays.
4. Report on progress in testing at full-scale and moderate scale in-sea test sites.



<http://tidalenergytoday.com/2017/09/13/orkney-isles-light-up-with-scotrenewables-tidal-power/>

SCOTRENEWABLES – Scales tested



- 1/40th
- 1/20th
- 1/16th
- 1/7th
- 1/5th
- 250kW prototype leading to 2MW full scale

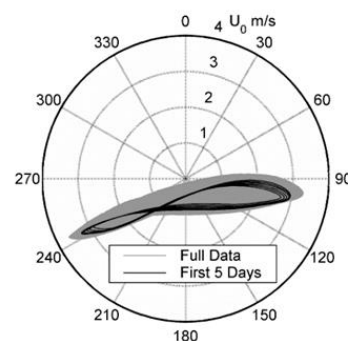


Physical and numerical modelling challenges

- Shear layer
- Turbulence
- Waves
- Off axis flow
- Motion of tethered device

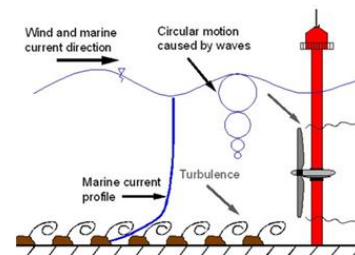


Ifremer, Boulogne-sur-Mer

Portland Bill, English Channel,
Blunden (2006)

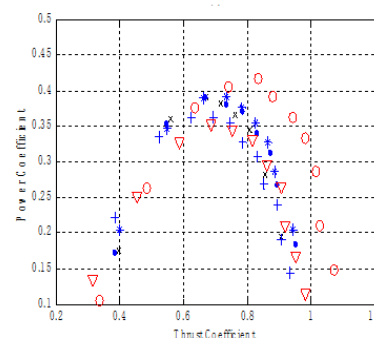
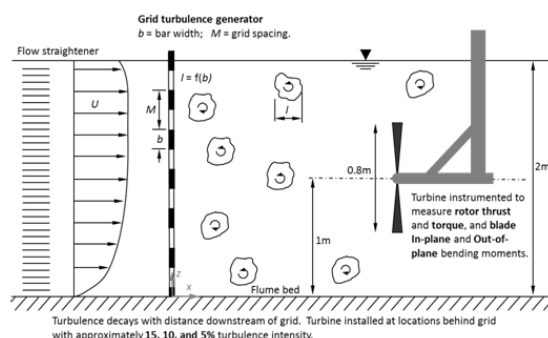
Modelling Challenges – Terrain blockage and Scour

- **Terrain blockage** (proximity to bed-floor and free surface)
 - Optimal performance is dependent on proper vertical placement
 - Performance decreases with proximity to bed-floor or free-surface
 - Bedform topology can adversely impact performance with amplified turbine-bedform interactions and downstream scour
- **Scour**
 - Scour patterns could impact downstream turbine performance
 - Turbine array energy extraction in a tidal bay can impact sediment transport and deposition in the bay



Example: Physical Modelling Turbulence

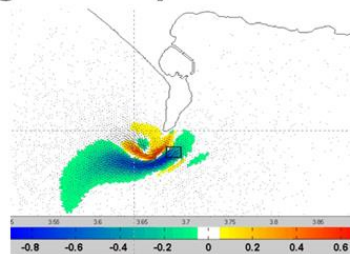
- Influence of grid generated turbulence in 0.8m/s circulating water channel, CWC Ifremer
- The turbine was instrumented to measure overall rotor thrust and torque, and flap-wise and edgewise blade root bending moments.



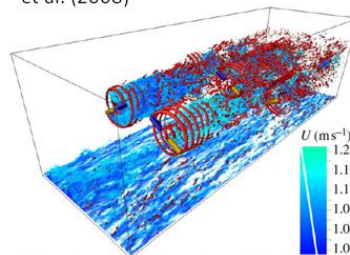
Blackmore, et al. (2015)

Numerical Modelling of Arrays

- Solvers:
 - Shallow Water Equation Solvers
 - RANS
 - LES
- Turbine modeling
 - Added drag / momentum sink
 - Immersed body force
 - Actuator disc
 - BEM Disk
 - Rotating actuator lines
 - Full turbine modeling with rotation
- Types of simulation
 - Size of the array/farm
 - Array configuration
 - *In-line*
 - *Side by side*
 - *Staggered*



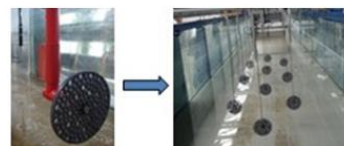
Shallow water – added drag Blunden et al. (2008)



LES + Actuator Line Churchfield, et al. (2013)

Experimental Modelling of Arrays

- Environmental conditions
 - Matched Froude number results in low tank speeds
 - Bed roughness to simulate the velocity profile needs to be suitably scaled
- Scaled turbine models
 - Small scale porous disks
 - Redesigned turbine to match thrust at correct rotational speed
- Support Structure
 - Normally mounted from above due to ease of measurements
 - *not scaled*
- Measurements required
 - Device performance
 - Velocity and turbulence field
 - Head differences



Daley et al. (2013)



Stallard et al. (2013)

Modelling Arrays - Key Findings

In-line

- Lower power production on downstream turbine
- Upstream turbine wakes persisted for > 6 turbine diameters (D_T)

Staggered

- In small arrays (2 or 3 turbines) downstream staggering with lateral spacing of $> 1.5D$ show minimal impact on downstream turbine

Turbine wake flow development – Array impact

- Low ambient turbulence environment
 - Longitudinal spacing in a staggered array configuration has small impact on wake recovery
 - Lateral spacing of middle row turbines impacted wake position and recovery
- High ambient turbulence ($\sim 15\%$) reduces turbine downstream wake
- Counter-rotating consecutive rows indicated small benefit

Moderate scale testing - Device concept testing

- Towed by vessel/tug
- A floating pontoon pulled/pushed on a lake
- Mounted below a floating pontoon moored in a tidal site in a sheltered estuary
- Mounted in rivers near constrictions such as sluice gates



SCHOTTEL HYDRO GmbH



Tocardo Tidal Turbines



Jeffcoate et al. (2016)

Large scale in-sea test sites

- EMEC Fall of Warress, Orkney Islands, Scotland
- FORCE, Minas Passage, Bay of Fundy, Nova Scotia, Canada
- Paimpol-Bréhat, Normandy, France
- Nagasaki Asia Marine Energy Centre in Japan
 - Aims to go online in 2018
- There are a few other sites being considered to become test centres these include :
 - Morlaris Demonstration zone
 - Zhoushan Islands China

Full list provided in Tables 6 and 7.



Alstom's 1MW turbine: Hatston Quay

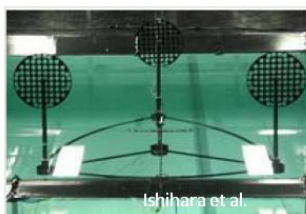


Terms of Reference – Offshore Wind Turbines (OWT)

1. Report and review on wind field modelling including Froude/ Reynolds scaling challenges for the turbine in cooperation with the Specialist Committee on Modelling of Environmental Conditions.
2. Report on the impact of control strategies and other features on full-scale devices on global response to allow improved understanding of the impact of simplifications adopted in model tests.
3. Report on integrated tools for the simulation of floating wind turbines including platform, mooring, turbine and control system.
4. Report on developments in full-scale demonstrators of floating wind turbines.

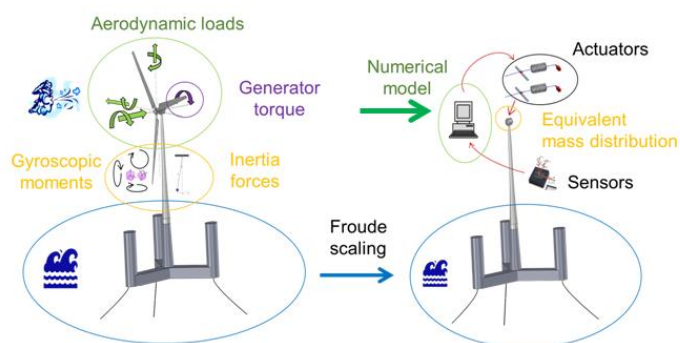
Traditional Methods for Modelling Wind Turbines

- Solid or perforated discs
- Geometric scaling
- Performance scaling



New Methods for Modelling Wind Turbines

Combine experiments with real-time simulations

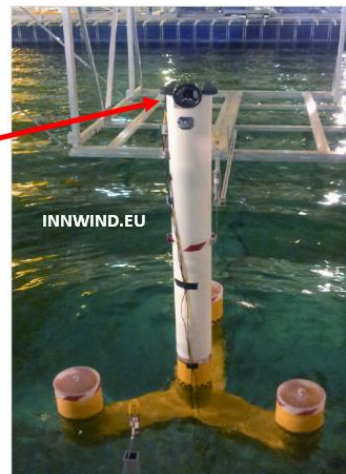


New Methods for Modelling Wind Turbines

Example: Innwind.EU

Rotor is replaced by a fan

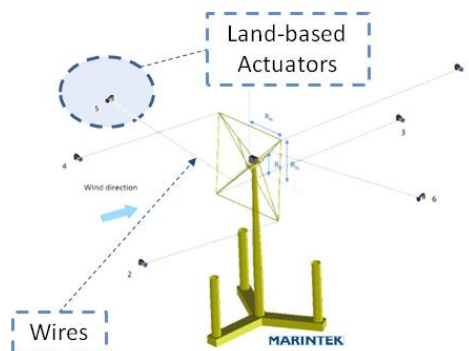
- No wind generation required
- No scaling issue from rotor blades
- Limited to thrust force only



Azcona et al. (2014)

New Methods for Modelling Wind Turbines

Example: ReaTHMTM testing



ReaTHMTM - Real-Time Hybrid Model testing



Sauder et al. (2016)

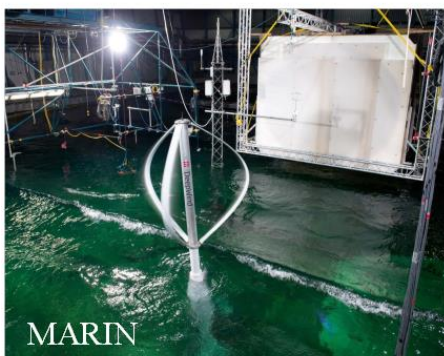
Bachynski et al. (2016)

Wind Field Modelling Challenges

- Testing the wind turbines requires high quality wind over large area
 - ❖ Development of dedicated facilities
- Geometric similarity of the model does not provide correct response to Froude-scaled wind field; performance-matched rotor design is preferred
 - ❖ Development of performance-matched blade design methods

Wind Field Modelling Challenges

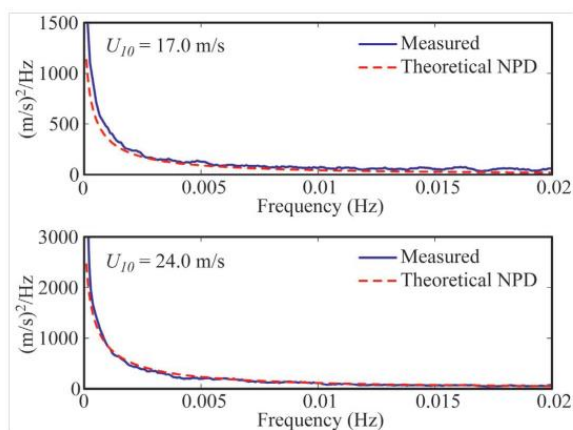
Examples of dedicated facilities (multiple fans, direction of rotation varying in checkerboard pattern, honeycombs, screens)



Wind Field Modelling Challenges

Features of dedicated facilities:

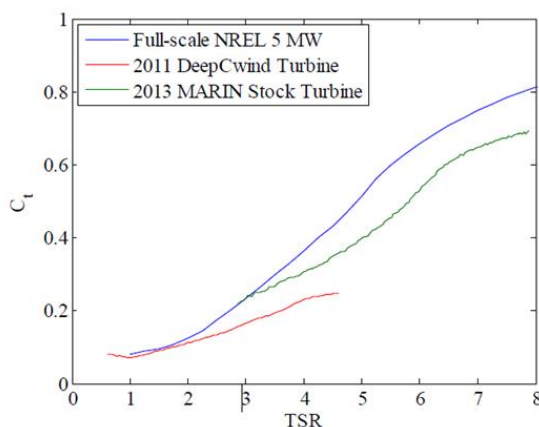
- Uniform velocity field over large area
- Modelling the turbulence spectrum



Comparison between measured and theoretical dynamic wind spectra (Goupee et al., 2012)

Wind Field Modelling Challenges

Correct response to Froude-scaled wind field: performance-matched blade design



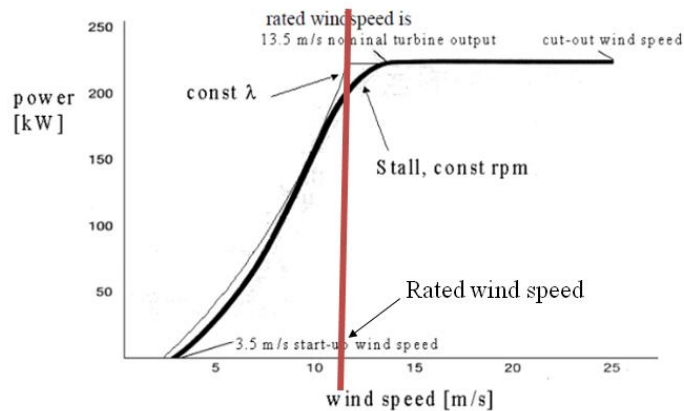
(Goupee et al., 2014)

Thrust coefficient vs. tip speed ratio curves for geosim model and performance-matched model

Impact of Control Strategies on OWT Global Response

Blade pitch control goals:

- maximize power in below-rated wind
- prevent overload in over-rated wind



Control type for OWTs – pitch-to-feather blade pitch control

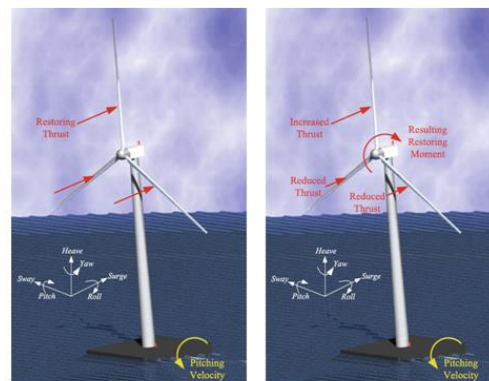
(Van Kuik and Bierbooms, 2002)

Impact of Control Strategies on OWT Global Response

Problem: negative damping effect (how to minimize motion when preventing overloads)

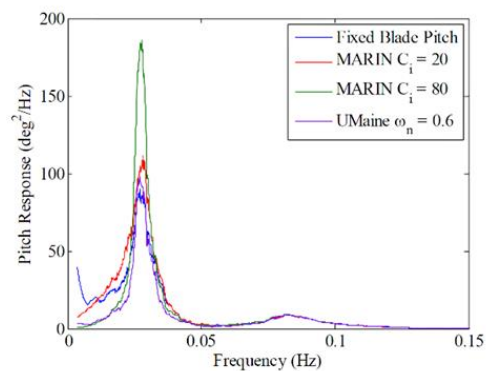
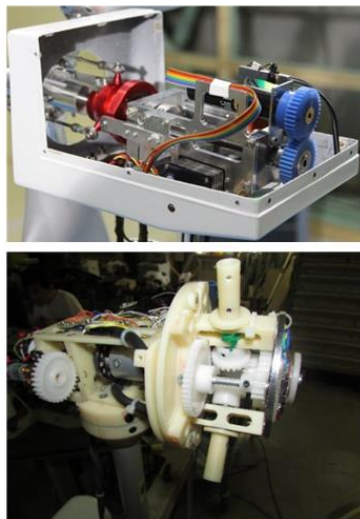
Development:

- Optimization of control algorithms for collective blade pitch control
- Application of individual blade pitch control
- Application of other devices reducing the motion, e.g. liquid mass dampers



Impact of Control Strategies on OWT Global Response

Direct modelling of blade pitch control system at model scale

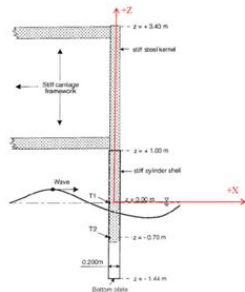


Response spectra for fixed pitch and for different control strategies (Goupee et al. (2014))

Alternative to direct modelling of wind field and blade pitch control system: hybrid testing



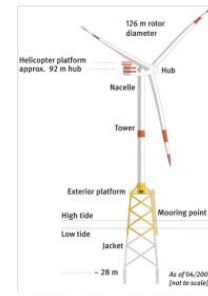
Numerical Simulation Tools



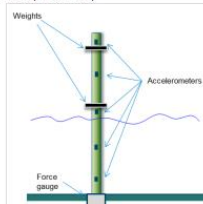
Fixed cylinder test configuration performed at MARINTEK (Phase Ia)



Instrumented OC5-DeepCwind model in MARIN (Phase II)

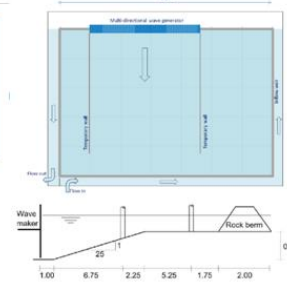


REpower 5M turbine with OWEC quattropod (Phase III)



Flexible cylinder test configuration performed at DHI (Phase Ib)

- Model:**
- Force gauge x,y,z
 - Model Height ~200 cm
 - Accelerometer 1: 25 cm
 - Accelerometer 2: 60 cm
 - Accelerometer 3: 95 cm
 - Accelerometer 4: 130 cm
 - Accelerometer 5: 165 cm
 - Weight 1 (1.788kg): 160.75 cm above seabed
 - Weight 2 (1.784kg): 108.75 cm above seabed



Codes used in numerical simulations of Wind Turbines

Participant	Code	Aerodynamics	Wave Kinematics (Regular Waves)	Wave Kinematics (Irreg. Waves)	Hydro Model (Reg/Irr)	Wave Elevation (Reg/Irr)	Wave Surface	Mooring
Codes used in Phase II, OC5 Project of IEA Wind Task30 (2015-2016), Robertson, et al., 2017								
4Subsea	OrcaFlex-FAST8	AeroDyn - Bolles/ Dynamic wake	2nd order stream function	Linear Airy	1st order FF+ME	Computed	IW	Dynamic
CENER	FAST v6 + OTEAS	AeroDyn - Bolles/ Equil. inflow	Linear Airy	Linear Airy (JONSWAP)	1st order FF + 1st/2nd order damping	Computed	None	Dynamic
CENTEC	FAST8	AeroDyn15 Steady	2nd Order Stokes	Linear Airy (JONSWAP)	2nd Order FF	Computed	None	Dynamic
DNV GL/ DNV GL DM	Bladed 4.7	Glaierman/Bolles/Dye Dynamic wake	Linear Airy	Linear Airy	1st order FF + 1 st order damping	Comp./Meas.	None	Quasi-static/Dynamic
DTU	HAWC2	BEM/Bolles/Dynamic Wake	Linear Airy	Linear Airy (JONSWAP)	ME	Computed	IWW	Dynamic
ECN-MARIN	aN51M/FHATA5 v16	BEM + Dynamic stall	Linear Airy	Linear Airy	2 nd Order FF	Comp./Meas.	None	Dynamic
EPRI	DeepWind VSR2	BEM + Dynamic stall	Airy + Wheeler stretching	Airy + Wheeler stretching	1 st order FF + ME	Computed	IW	Dynamic
NREL	FAST v8	AeroDyn14 - Bolles/Dynamic wake	2 nd Order Airy/ 1 st Order Airy	Linear Airy	2 nd Order FF/ 2 nd Order FF (Hif only)	1 st Order BEM/ No Elbowing	None	Dynamic
FOLIMI	FAST v8.15	DYNIN + BEDDOES	Linear Airy	Linear Airy	2 nd Order FF + SS + ME/FF	Computed	None	Dynamic
Siemens FLM	Saved Wind Turbines	BEM + Dynamic Stall	Linear Airy	Linear Airy (JONSWAP)	ME	Computed	IWW	Dynamic, hydro, SE contact
Tecalia T70	FAST7+OrcaFlex 9.7b	AeroDyn13 - Bolles/ Dynamic wake	Linear Airy	Linear Airy (JONSWAP)	FF + 1 st order damping	Computed	IWW	Dynamic
Tecalia T8	FAST v8.12	AeroDyn14 - Bolles/ Dynamic wake	Linear Airy	Linear Airy (JONSWAP)	FF+ME	Computed	No	Dynamic
UC-IBC	Sesun	BEM + Dynamic Stall	Linear Airy	Linear Airy (JONSWAP)	FF+ME+MD	Computed/Measured	IW	Dynamic
UC-IBC	IC-WAVE2WIRE	BEM + Dynamic Stall	Linear Airy	Linear Airy (JONSWAP)	FF+MD	Computed/Measured	IW	Dynamic
UOU	UOU + FAST8	AeroDyn14	Linear Airy	Linear Airy (JONSWAP)	FF+ME	Computed	None	Dynamic (MeorDyn)
Utoyo	NKUTWind(AeroDyn)		Linear Airy	Linear Airy	ME	Computed	IWW	Dynamic
WaveEC_FAST	FAST8	AeroDyn - Bolles/Dynamic wake	Linear Airy	Linear Airy	1st Order FF	Measured/no filtering	None	Quasi-static
WaveEC_FTZW	FTZW		Linear Airy	Linear Airy	1st Order FF	Measured/no filtering	None	Quasi-static
Other codes								
Bayen & Heinz GmbH	Vortexje	Unsteady 2D panel method						No
WMC	FOCUS6	BEM or Vortex wake model						No
Tech. U. of Berlin	Qblade	BEM						No
Chonank National U.	UBEM	Unsteady BEM, Shovel yaw model						No
DTU	Bes5	BEM						No
SINTEF Ocean (for MARINTEK)	STMA	Unsteady BEM + Dynamic stall	Linear Airy 2 nd and 1 st order Stokes	Linear Airy and 2 nd order	1 st and 2 nd order FF + ME	Computed + measured	IWW/ IWW	Quasi Static / Dynamic

* BEM : Blade Element Momentum / DYNIN : Generalized Dynamic Wake / PF : Potential Flow / ME or MD : Morison equation(Damping)

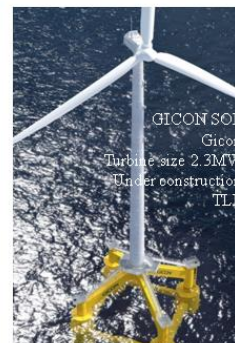
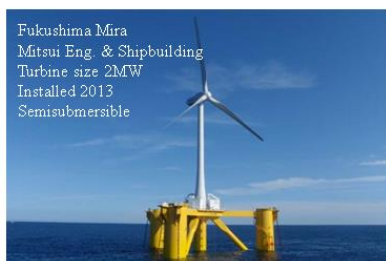
* IW : Instantaneous Water level / IWW : Instantaneous Water level(Wheeler) / IWW : Instantaneous Water level(Vertical Stretching) SS : State-Spac

Recent Developments in Full-Scale Demonstrators

- Number of demonstrators deployed or planned has steadily increased the past few years
- A trend towards larger turbines (5 to 7MW)
- So far only spar and semi substructures; however, barge and TLP substructures are under construction
- First floating pilot park deployed 2017 (Hywind Scotland)
- More floating parks under planning



Recent Developments in Full-Scale Demonstrators





Closing Comments/Recommendations

Necessary to have feedback from full/moderate scale tests and check how these can be used for validating and informing model scale tests.

Wave Energy Converters:

- Modelling of PTO systems both physically and numerically is challenging due to the difficulty in accounting for coupling between PTO systems and loads, the influence of scaling effects.
- Difficult in modelling array interactions even at moderate scales in test tanks.

Current Turbines:

- Significant limitations in replicating environmental conditions in test facilities.
- Full-scale environment conditions at the turbine site → difficult to simulate realistic turbulence and vibration levels at model scale in test facilities.
- Interactions between current turbines within small and large scale arrays.

Offshore Wind Turbines:

- Continue model testing methodology with respect to Froude/Reynolds scaling issues and incorporating the control system strategies.
- A guideline for uncertainty analysis for model testing of offshore wind turbines.



Thanks for your attention!

We will be happy to discuss any questions...



Recommendations For Future Work: WECs

- Continue to monitor developments in PTO modelling both for physical and numerical prediction of power capture.
- Review challenges associated with numerical prediction of performance of WECs in irregular wave spectra.
- Review and report on integrated WEC simulation tools based on multi-body solvers which are in development, such as WaveDyn (GL-GH), WECsim (NREL), InWave (Innosea).
- Review and report on the progress made on the modelling of arrays.
- Consider developing a “round-robin” test campaign for a simple WEC device (e.g. oscillating water column) in order to explore facility bias issues (or identify and build on an existing programme).
- Develop guidelines for physical modelling of WEC arrays elaborating on uncertainty analysis required for WEC arrays.
- Develop guidelines for numerical modelling of WECs.



Recommendations For Future Work: Current Turbines

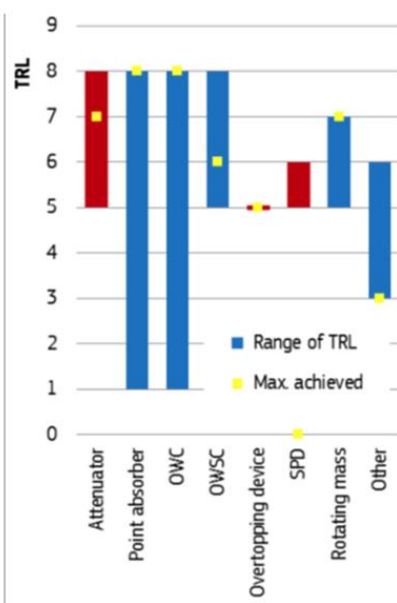
- Continue to monitor development in physical and numerical techniques for prediction of performance of current turbines, with particular emphasis on unsteady flows, off-axis conditions, and other phenomena which offer particular challenges to current devices.
- Review and report on progress in testing at full-scale and moderate scale in-sea test sites. Develop cooperation with medium/large test centres.
- Review and report on the progress made on the modelling of arrays elaborating on uncertainty analysis specific for device arrays.
- Review and report on limitations in replicating environmental conditions in test facilities.

Recommendations For Future Work: Offshore Wind Turbines

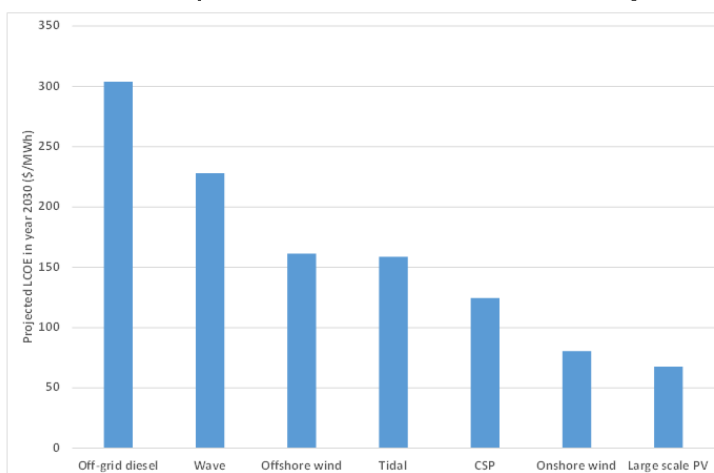
- Monitor and report on recent research related to model tests of bottom-fixed offshore wind turbines including modelling the influence of structure stiffness and soil stiffness.
- Report on other existing regulations related to model tests of FOWT (e.g. IEC, classification societies, DoE). Interact with these bodies to get the guidelines aligned with each other.
- Collect the feedback from full/moderate scale tests and check how these can be used for validating model scale tests.
- Continue monitoring the development in model testing methodology with respect to Froude/Reynolds scaling issues and incorporating the control system strategies.
- Consider the possibility of elaborating a separate guideline for uncertainty analysis for model testing of offshore wind turbines.

Proposed Tests For Round-Robin Campaign

Test	Objective	Measurement technique and reporting
Motion response	Determine the response amplitude operators (RAOs) of relevant performance indicators (e.g. kinematic and dynamics)	• Free decay tests for relevant DoF's (free-floating body and full system) • RAO curves for regular and irregular waves
Absorbed power	Determine the WEC absorbed power	• Based on the measurements of kinematics and dynamics (e.g. velocity/force, flow/pressure) • Reported as capture width for regular waves • Power matrix for irregular waves
Wave tank characterisation	Characterisation of the wave field at the location of the device	• Characterisation carried out following either three methodologies: • Calibration of incident waves without WEC • From suitable wave specifications • Measuring wave field during tests, separating into incident, reflected and radiated components in post-processing • Performance indicators to report for regular waves: height and period • Performance indicators to report for irregular waves: significant wave height, zero up-crossing period, energy period, peak period, repeat time, and spectral shape.

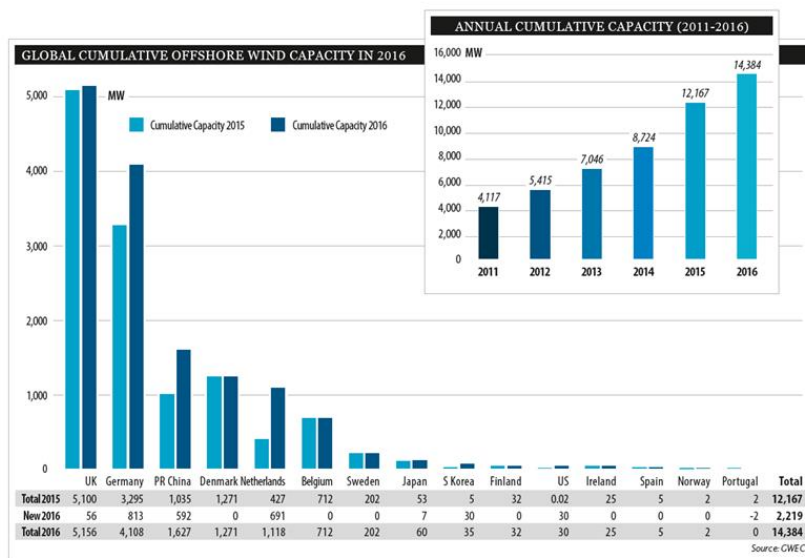


Tidal LCOE comparable with offshore wind by 2030

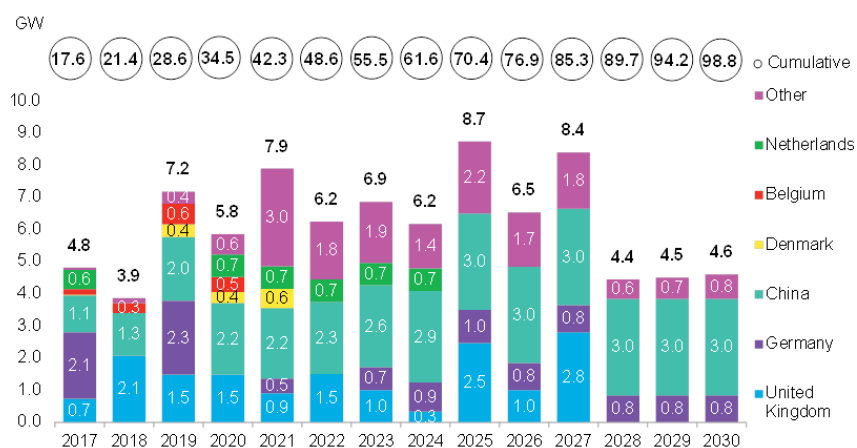


- Tidal has added advantage that highly predictable
- Tidal has half the LCOE of off-grid diesel and can work in a hybrid power system

Offshore Wind Turbine Capacity



- Global offshore wind forecast



Source: Bloomberg New Energy Finance. Note: "Other" includes France, Ireland, Italy, Japan, Korea, Poland, Sweden, Taiwan and US

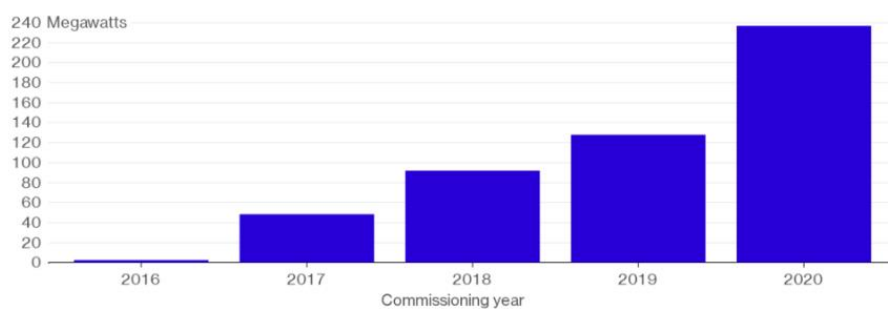


Vision of Floating Offshore Wind Turbines

Floating Pipeline

Global installations of floating offshore wind farms could reach 237 megawatts by 2020

■ Cumulative capacity

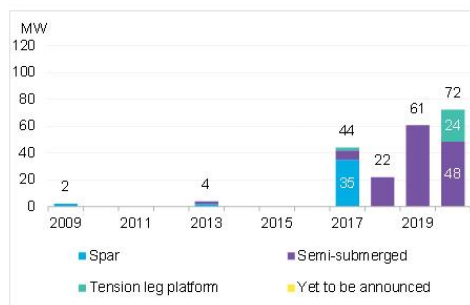


Source: Bloomberg New Energy Finance
(03. 2017)

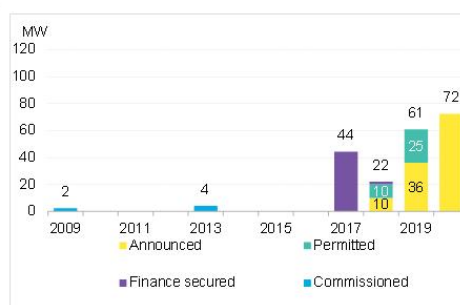
Bloomberg

Vision of Floating Offshore Wind Turbines

Foundation type



Status

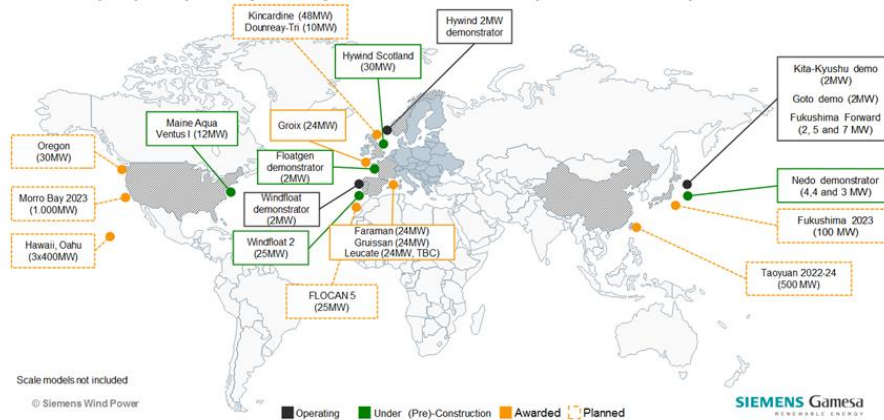


Source: Bloomberg New Energy Finance, Offshore Wind Energy 2017 (June. 07)

- Development of full scale demonstrators for floating offshore wind turbines

Current market situation

The majority of operating floating wind farms is currently located in Europe



Negative damping issue

- the rigid-body platform-pitch mode as a single DOF

$$(I_{Mass} + A_{Radiation})\ddot{\xi} + (B_{Radiation} + B_{Viscous})\dot{\xi} + (C_{Hydrostatic} + C_{Lines})\xi = L_{HH}T$$

- For small pitch angles, translational displacement of hub, x , is linearly related to the platform-pitch angle

$$x = L_{HH}\xi$$

- Considering variations in rotor thrust only with hub speed, a first-order Taylor series expansion

$$T = T_0 - \frac{\partial T}{\partial V}\dot{x}$$

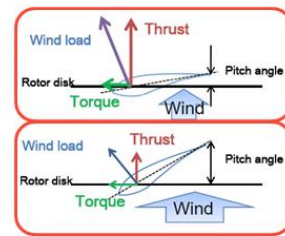
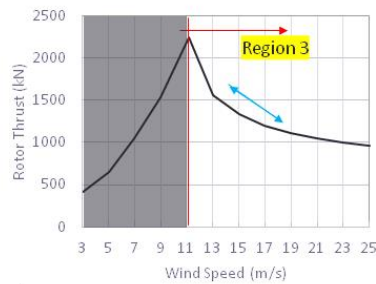
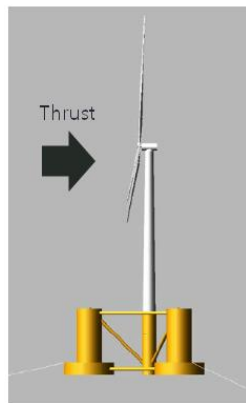
- the equation of the platform-pitch mode stated in terms of the translational motion of the hub

$$\underbrace{\left(\frac{I_{Mass} + A_{Radiation}}{L_{HH}^2}\right)}_{M_x}\ddot{x} + \underbrace{\left(\frac{B_{Radiation} + B_{Viscous}}{L_{HH}^2} + \frac{\partial T}{\partial V}\right)}_{C_x}\dot{x} + \underbrace{\left(\frac{C_{Hydrostatic} + C_{Lines}}{L_{HH}^2}\right)}_{K_x}x = T_0$$

Negative damping issue

In Region 3,

1. tilt downwind $\rightarrow$ relative wind speed $\downarrow$ $\rightarrow$ blade pitch $\downarrow$ $\rightarrow$ thrust $\uparrow$ $\rightarrow$ tilt more
2. tilt upwind $\rightarrow$ relative wind speed $\uparrow$ $\rightarrow$ blade pitch $\uparrow$ $\rightarrow$ thrust $\downarrow$ $\rightarrow$ tilt more



To avoid negative damping issue,

- Natural frequency of controller is modified
"0.6 rad/s $\rightarrow$ 0.2 rad/s"
- Constant Torque in region III

Source: A. Robertson, J. Jonkman et al, 2014, "Definition of the Semisubmersible Floating System for Phase II of OC4", NREL/TP-5000-60601

Discusser:Yin Lu (Julie) Young

Affiliation:University of Michigan

Comments/Question(s):

In addition to the hydrodynamics, the structural performance is also important. There has been several reported field and laboratory tests of marine current turbines that suffered from structural failure to the blades. The spatial variation in the inflow and the high density of water make the dynamic blade load variation much more significant than wind turbines. Unsteady flow induced vibration can also significantly affect the dynamic loads, power variations, stability and feature response of many marine renewable energy harvest devices, includes marine current turbines. Hence, it is important to consider the hydroelastic response and structural performance of marine renewable energy devices, and properly scale the flow, structure and material in model-scale response.

Response by Committee:

Verbal responses by Committee at conference, but written response not available after conference.