Testing of Wave Energy Converters in Wave Tanks

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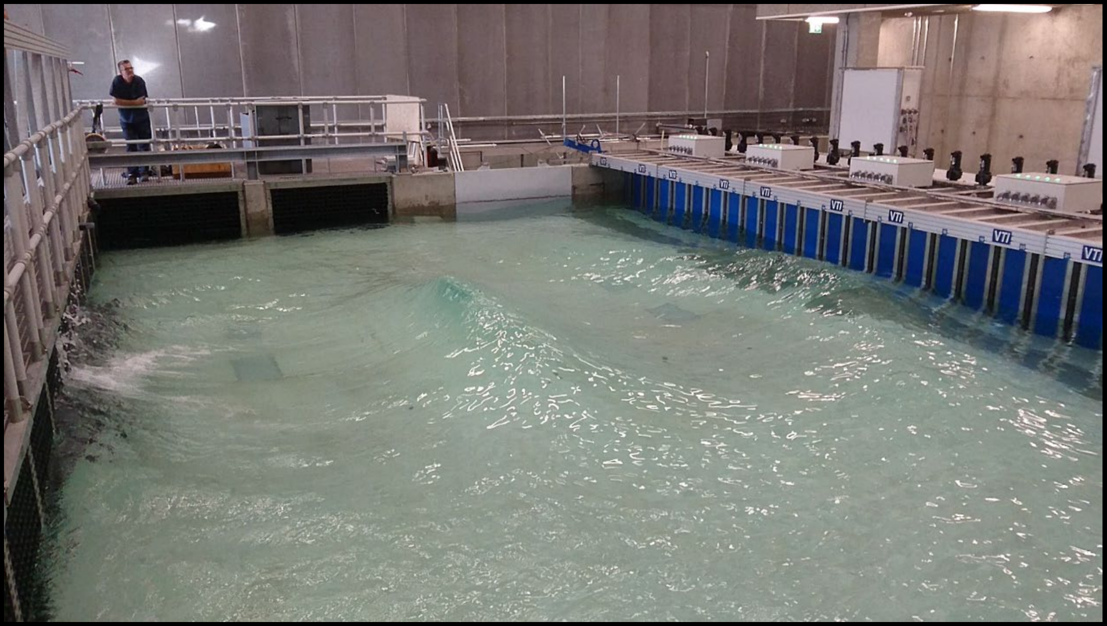
Ocean and Coastal Engineering Laboratory

- Department of Civil Engineering moved into new building at AAU main campus in Sept. 2016
- New Wave Laboratories an important part of the new building
- Greatful for grant from the Obel Family Foundation for new wave maker equipment etc.

DET OBELSKE FAMILIEFOND

Wave Basin

- Wave generator: 13 x 1.5 m (width and height).
- 30 individually controlled wave paddles (snake type configuration) powered by electric motors.
- Accurate generation of 3D waves due to narrow vertically hinged paddles (0.43 m segment width).
- Maximum wave height up to 45 cm (at 3 s period).



Deep pit (+7 m) in middle of basin

- Typical maximum significant wave height in the range of 0.25-0.30 m
- Pumps with a total maximum flow of 3500 m3/h for generation of strong current in the basin (up to 0.15 m/s at 0.5 m water depth). Structures can be tested in combined waves and current (following or opposing).

Wave Energy at Department of the Built Environment

Experimental testing in lab and at sea

Numerical modelling and optimization

Involved in all primary Danish – and numerous international – concept development within the sector

Project driven, based on cooperation with:

Private companies – developers, suppliers, consultants

Danish and international universities and institutions

But also:

Testsites

PhD courses

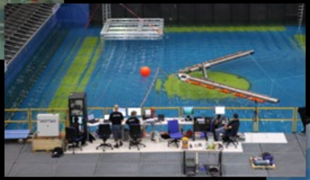
Standardization

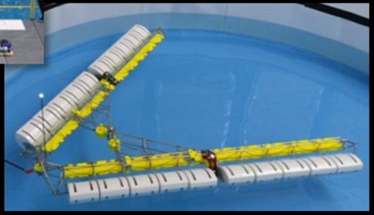
Partnerships

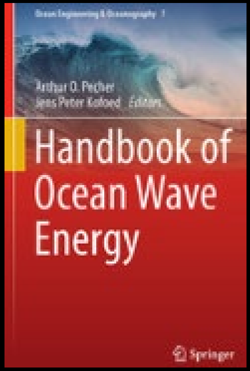
Wave Dragon

Wavestar

WEPTOS





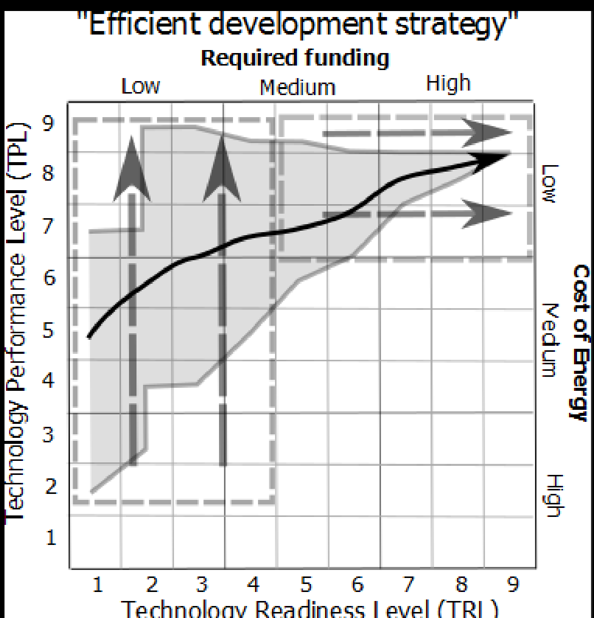


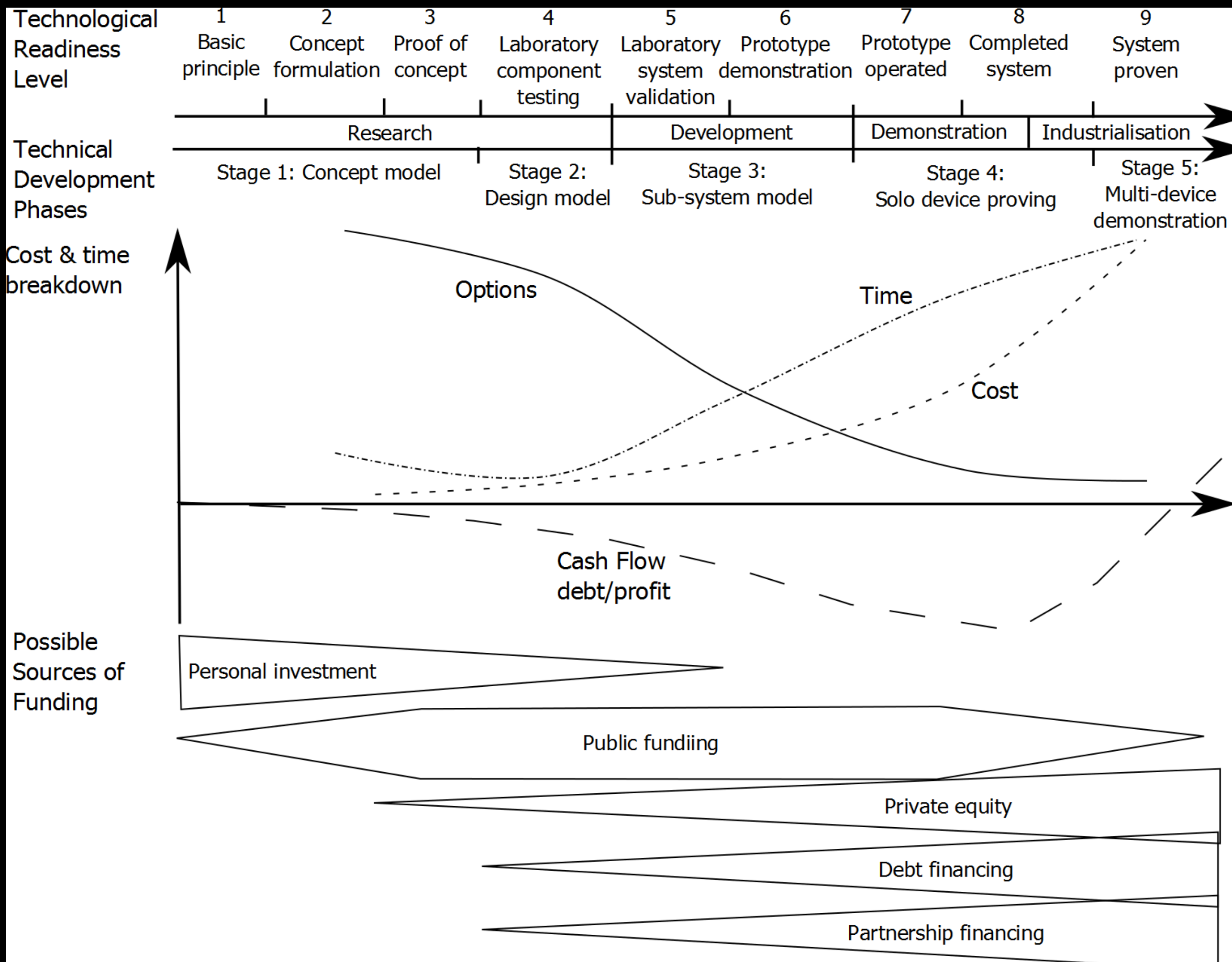
Why model testing?

Most important question is

LCOE

Project costs vs Energy produced
Loads vs Performance





Why model tests?

- Performance
- Loads & motions
- Installation & operations

- Seek qualitative insight
- Obtain measurements to check theoretical results
- Obtain measurements to validate/calibrate numerical results
- Obtain measurements of phenomena too complicated for theoretical/numercal evaluation

How to get performance data?

- The straight way is full scale experience… normally not a reasonable option!

- We need model testing and/or numerical modelling

What is a physical model?

- A physical system reproduced (at reduced size) so dominant forces are represented in the model in correct proportion to the prototype

Principles of similitude – scaling laws

- To ensure similitude between prototype and model, the following requirements must be met:
  - Geometric similarity – ratio between dimensions constant [L]
  - Kinematic similarity – ratio between motions constant [L T]
  - Dynamic similarity – ratio between forces constant [L T M]

- Impossible for ALL forces. Evaluation of violations necessary – these are the scale effects.

Model laws and scaling

Froudes Model law:

- Inertia forces are dominating. These are proportional to the volume/mass of the device.
- Friction forces are neglegible.
- Geometrical similar with full scale device.

Choice of scaling ratio:

- Measuring accuracy ⇒ model size ↑
- Ratio between friction and inertia forces ⇒ model size ↑
- Surface tension ⇒ model size ↑
- Modelling of PTO system ⇒ model size ↑
- Handability ⇒ model size ↓
- Time restrictions ⇒ model size ↓
- Available laboratory size ⇒ model size ↓
- Economics ⇒ model size ↓

Parameter	Model	Full Scale	Example 1:100
Length	1	S	100
Area	1	S^2	10000
Volume	1	S^3	1000000
Time	1	$S^{0.5}$	10
Velocity	1	$S^{0.5}$	10
Force	1	S^3	1000000
Power	1	$S^{3.5}$	10000000

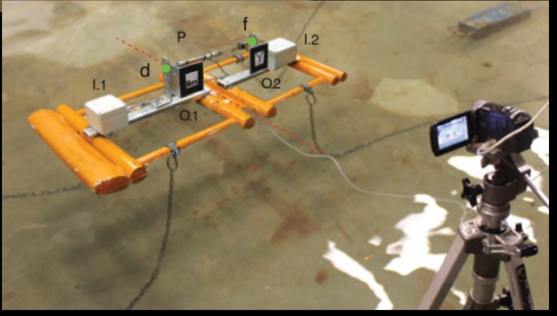
⇒ Scaling ratios of 1:25 – 40 often used in our lab. (1 W ~ 80 – 400 kW !!!)

Measuring techniques – an overview

Measurements of:

- waves (surface elevations)
- pressures
- Forces (strain / stress)
- Motions (displacements / velocity / accelerations)
- Flow
- Torque
- Current velocity
- Dimensions
- ***

Particularly for WECs – PTO!



Modeling the power take-off system

Challenges

- Scaling the PTO normally does not follow the Froud scaling laws. Therefore, a direct model of the full scale PTO can not be used
- The load from the PTO feeds back to the hydraulic behavior of the device, and is normally of paramount importance for the performance of the device. Therefore, the load from the PTO on the system have to be controlable

Solutions

- In smaller scale, ”just” model the loading from the PTO
- Measure the power production early in the power chain

Bevare of where in the chain of power you are measuring!

$$P_{wave} \Rightarrow P_{mech} \Rightarrow P_{hydr} \Rightarrow P_{axle} \Rightarrow P_{gen} \Rightarrow P_{wire} \Rightarrow P_{grid}$$

$P_{overtop}$ $P_{reservoir}$

$P_{chamber}$ P_{pneu}

Some examples – weights lifted by rotating axle

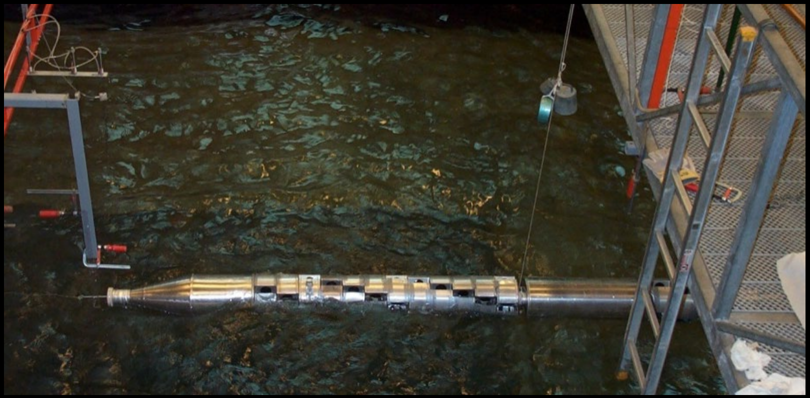
Power measured through weight, axle diameter, displacement and time

Pros

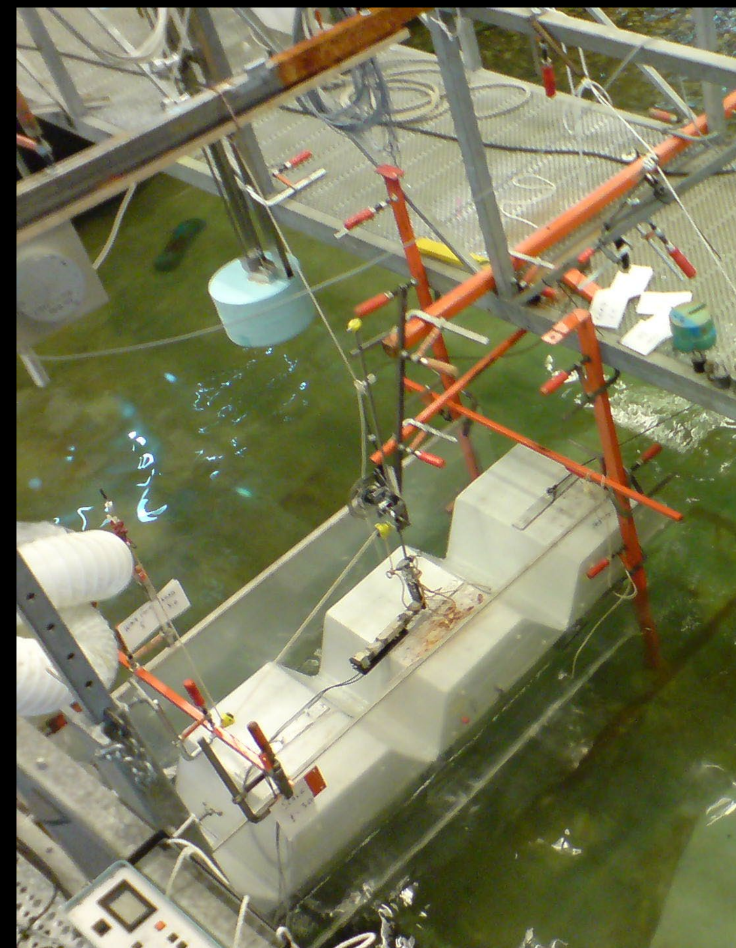
- Very simple and direct measurement. Easy to change loading – weights and/or axle diameter

Cons

- Limited test durations – need large heights for long tests. Therefore best for regular wave tests
- Not possible to change loading ”on the fly”
- Gives a constant torque on axle – not realistic loading charateristic of a generator



Some examples – friction force and velocity



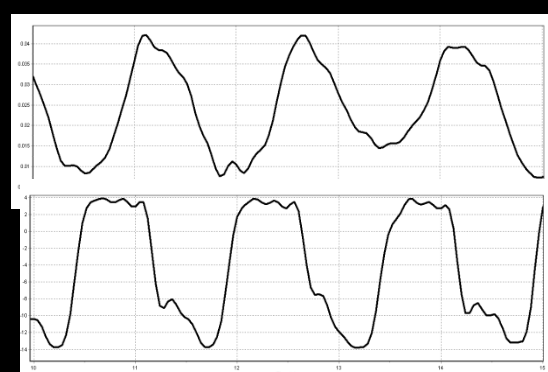
Power measured through force and displacement time series

Pros

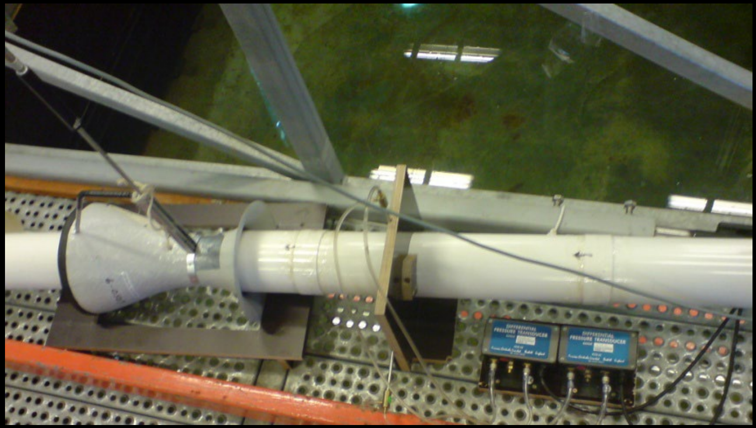
- No limitations on test duration
- Loading can in principle be changed ”on the fly”

Cons

- Risk of changing load characteristics due to heating of brakes
- Sometimes hard to get little enough friction for small waves



Some examples – air flow



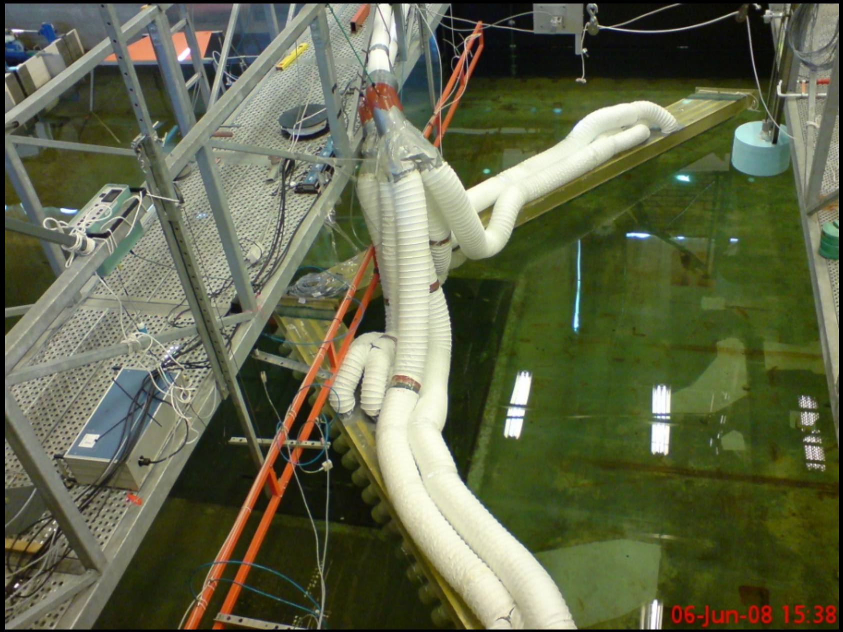
Power measured through flow and pressure time series

Pros

- Most appropriate for OWCs to get power measurements as early in the power chain as possible

Cons

- Difficulties in measuring fluctuating air flows



Some examples – overtopping flow

Power production measured through crest height and overtopping flow time series

Pros

- Simple and direct measurement
- Easy to change loading – crest height
- Power obtained very early in the power chain

Cons

- Resolution of flow in time
- Not possible to change loading ”on the fly”
- Power obtained very early in the power chain

Some examples – Controllable force and velocity

Power production measured through force and velocity time series

Pros

- Full control – can be run in force or displacement control mode

Cons

- Cost
- Complexity

Some examples – Controllable torque and rotational speed

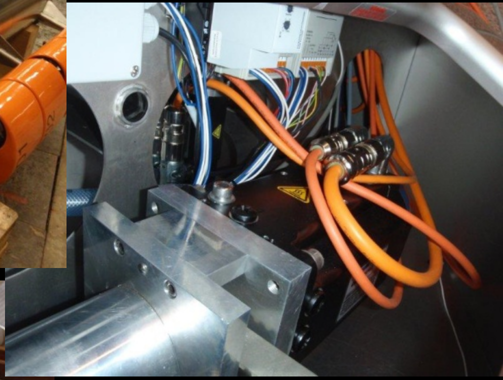
Power production measured through torque and rotational velocity time series

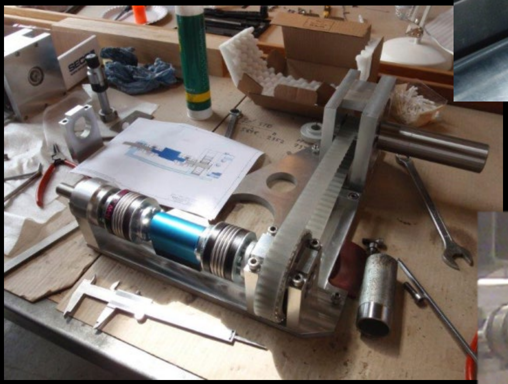
Pros

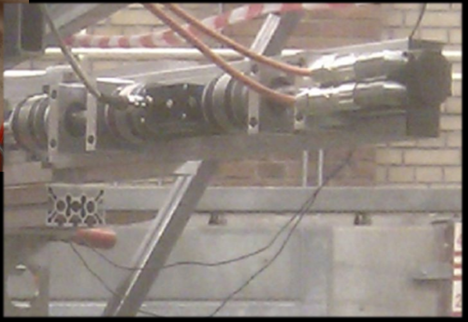
- Full control – relation between torque and rotational velocity can be specified

Cons

- Cost
- Complexity







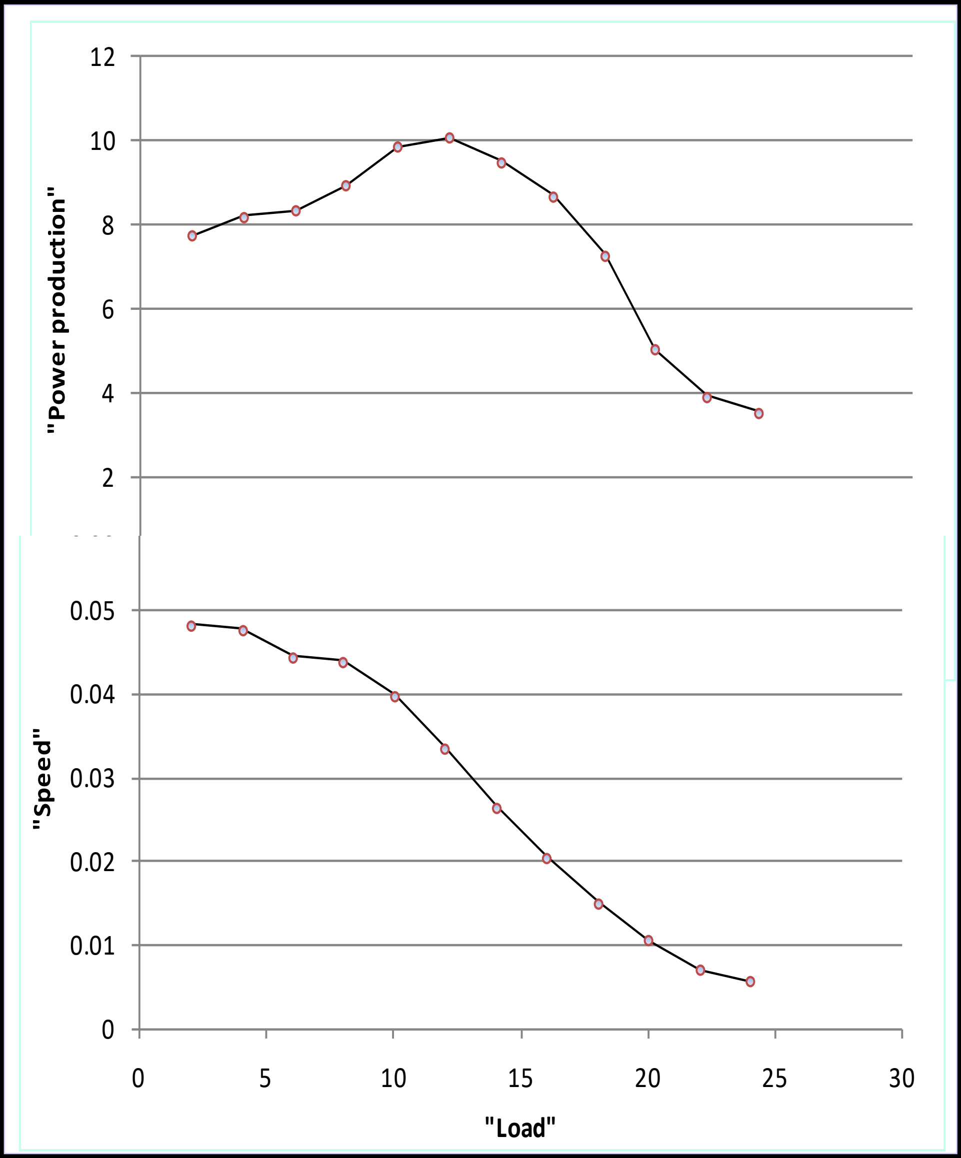
Load optimization

Often load optimized using regular waves (maintaining energy contents)

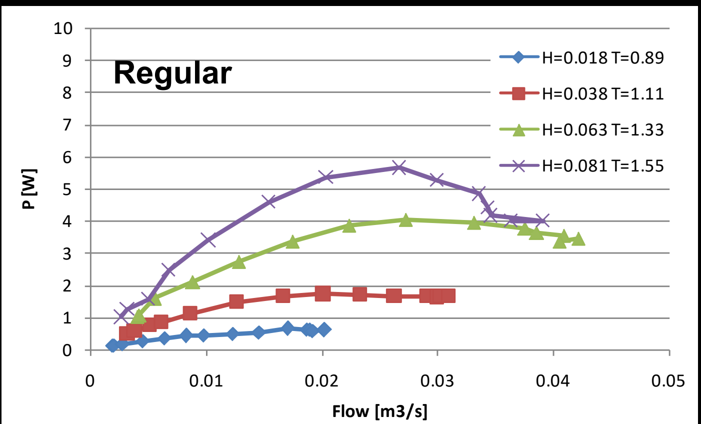
- $H = H_{m0}/sqrt(2)$
- $T = T_p$

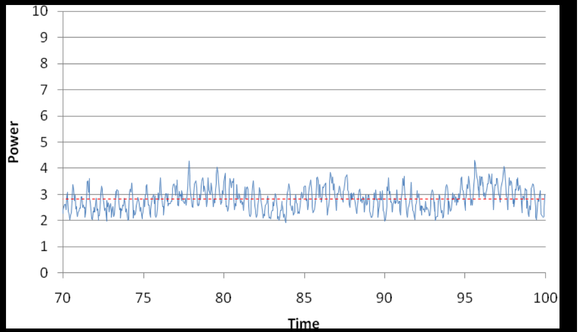
Optimization for each wave condition

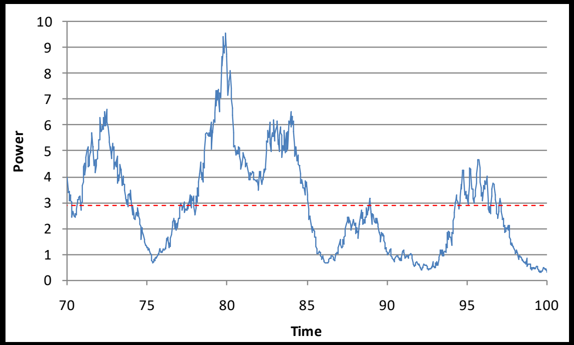
Power production measured in irregular waves using found optimal load setting (plus check runs on either sides)



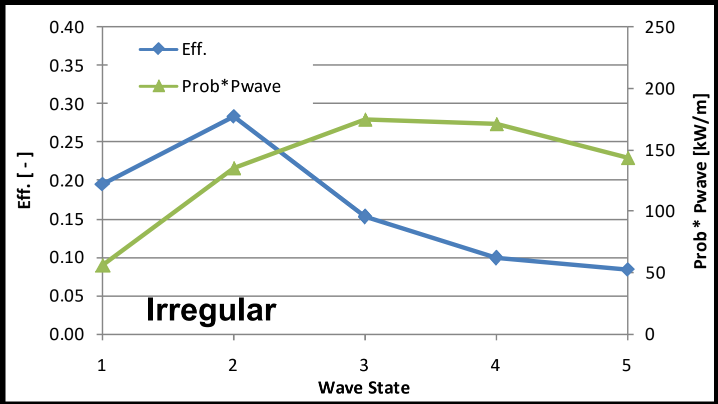
Estimation of yearly power production



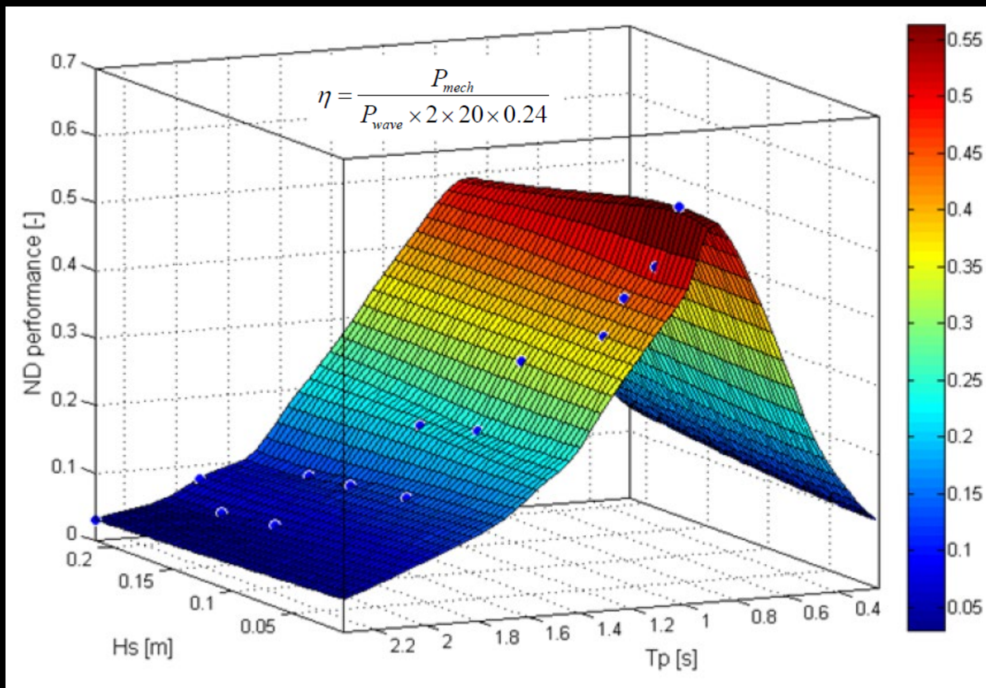


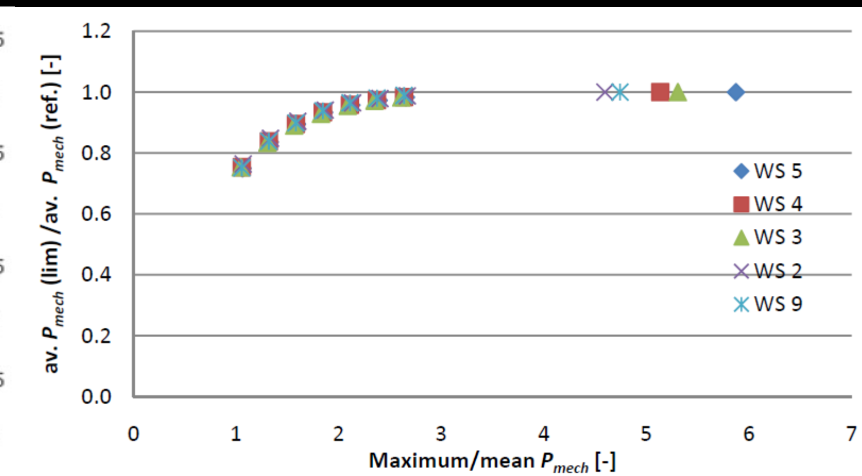


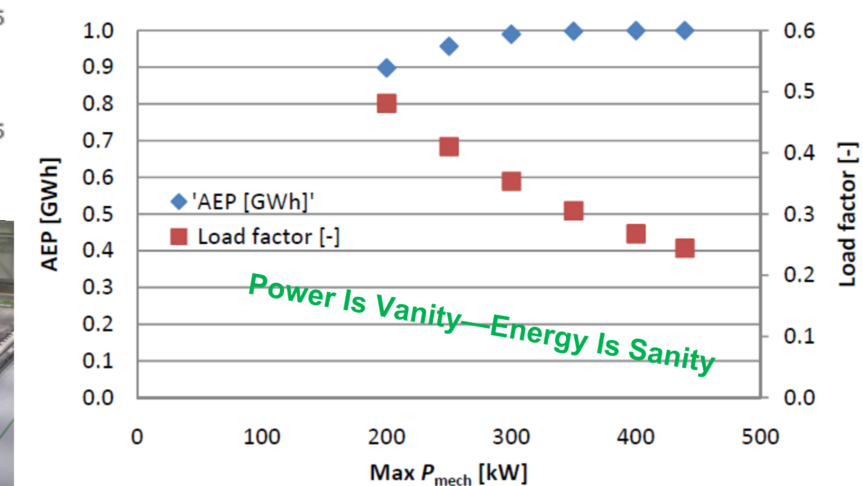
Wave State	Pwave [kW]	Prob [%]	Prob*Pwave [kW]	Eff. [-]	Energy prod. [kW]	Pgen [kW]
1	120	0.468	56	0.195	11	23
2	598	0.226	135	0.284	38	170
3	1616	0.108	175	0.152	27	246
4	3351	0.051	171	0.098	17	330
5	5985	0.024	144	0.084	12	505
Yearly average [kW]			680		105	
Overall eff. [-]					0.154	
Yearly prod. [MWh/y]					919	
Max. Pgen [MW]						0.505
Load factor [-]						0.21



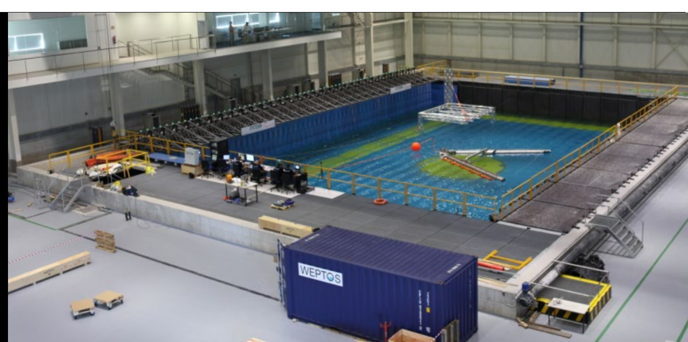
Power production measurements



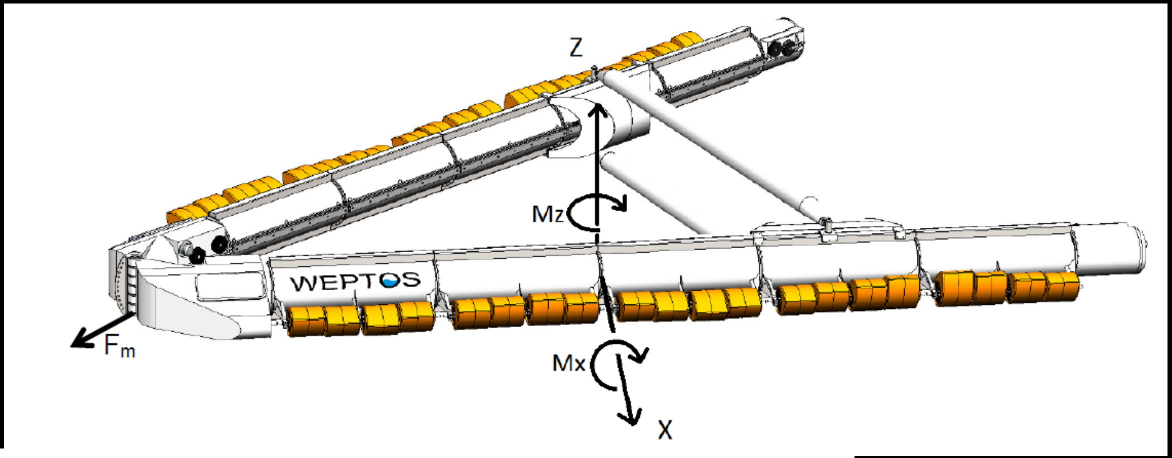


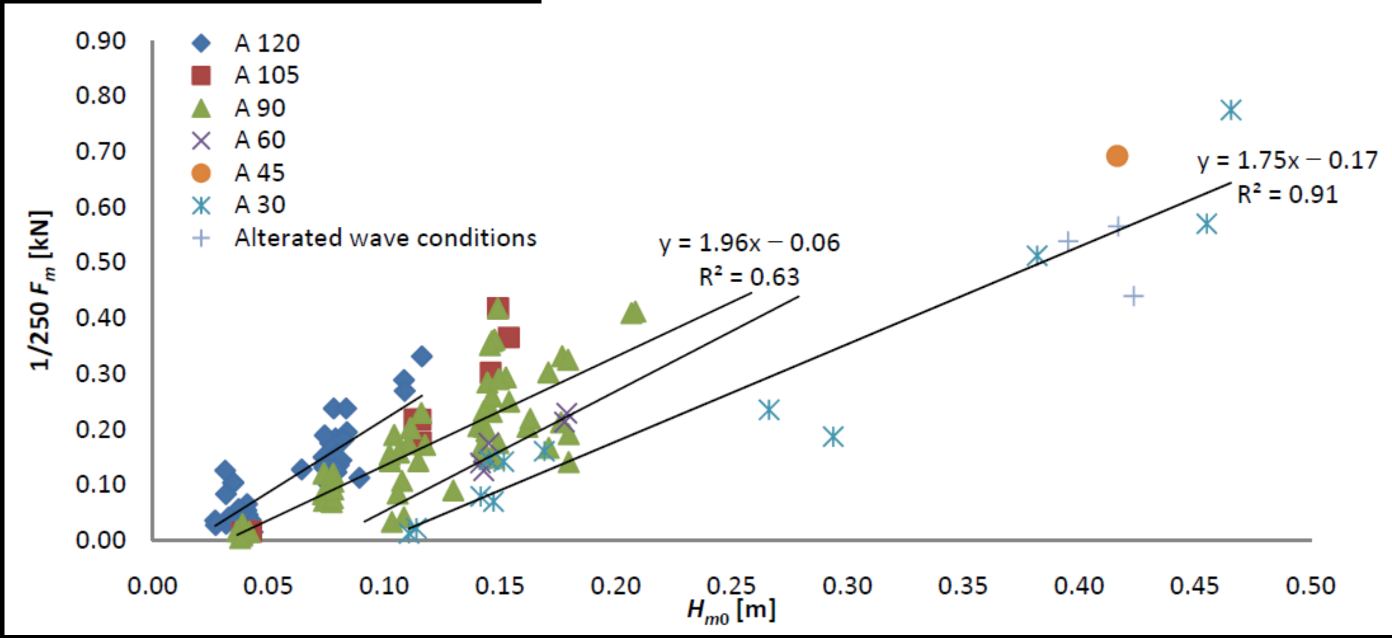


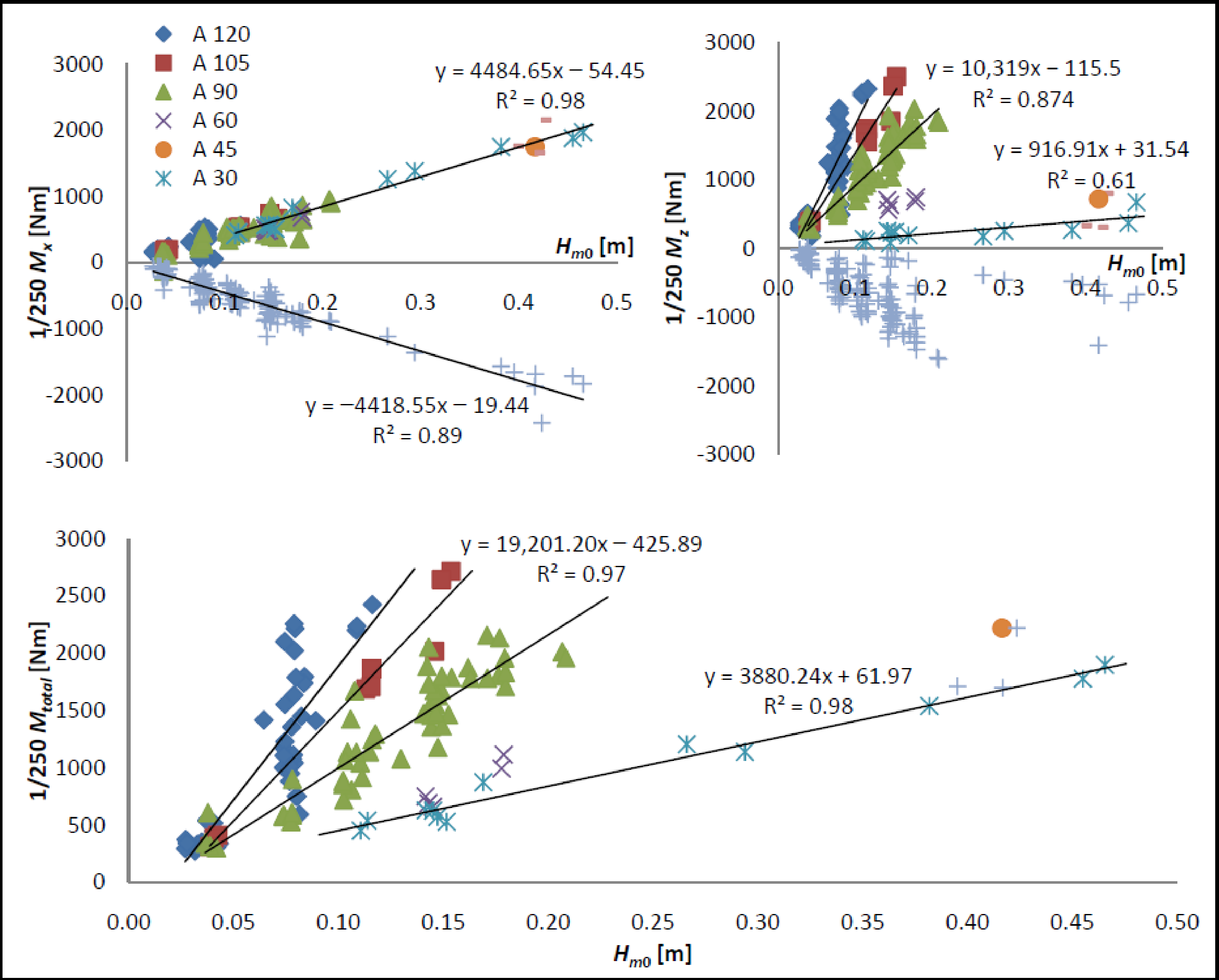
Weptos



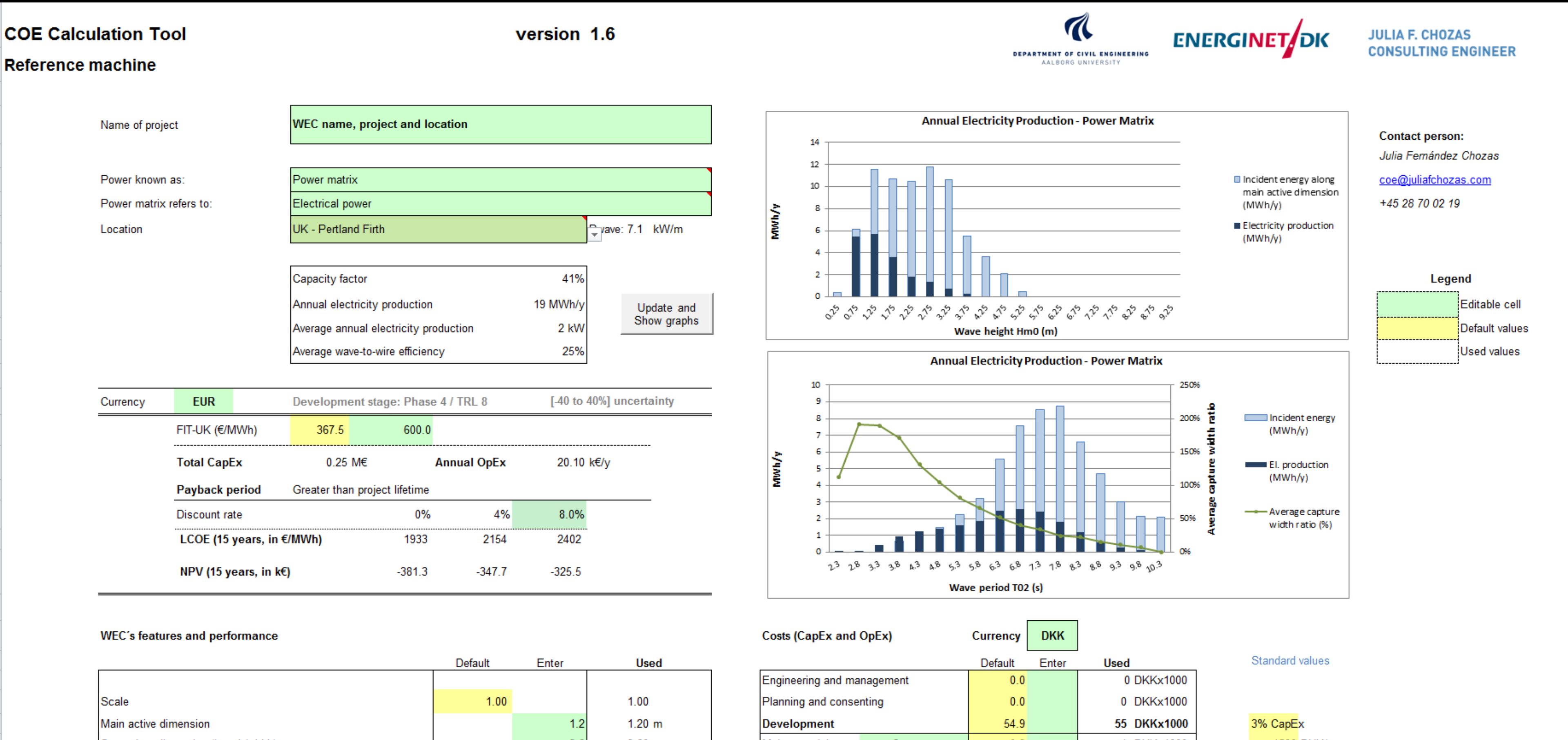
Loadings


Z
Mz
WEPTOS
Fm
Mx
X


A 120
A 105
A 90
A 60
A 45
A 30
Alterated wave conditions
y = 1.96x – 0.06
R² = 0.63
y = 1.75x – 0.17
R² = 0.91
1/250 Fm [kN]
Hm0 [m]
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
0.05
0.15
0.25
0.35
0.45


A 120
A 105
A 90
A 60
A 45
A 30
y = 4484.65x − 54.45
R² = 0.98
y = −4418.55x − 19.44
R² = 0.89
1/250 Mx [Nm]
Hm0 [m]
3000
2000
1000
0
-1000
-2000
-3000
0.0
0.1
0.2
0.3
0.4
0.5
y = 10,319x − 115.5
R² = 0.874
y = 916.91x + 31.54
R² = 0.61
1/250 Mz [Nm]
Hm0 [m]
y = 19,201.20x − 425.89
R² = 0.97
y = 3880.24x + 61.97
R² = 0.98
1/250 Mtotal [Nm]
3000
2500
2000
1500
1000
500
0
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.50
Hm0 [m]

COE Calculation spreadsheet

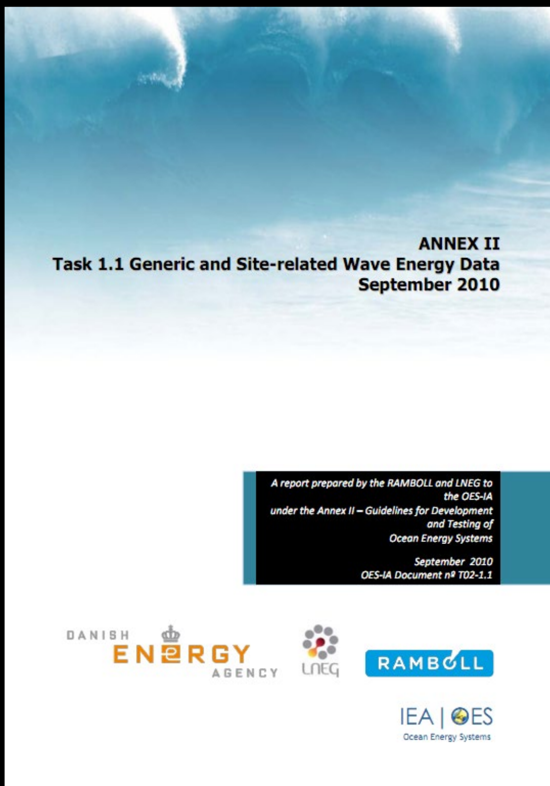


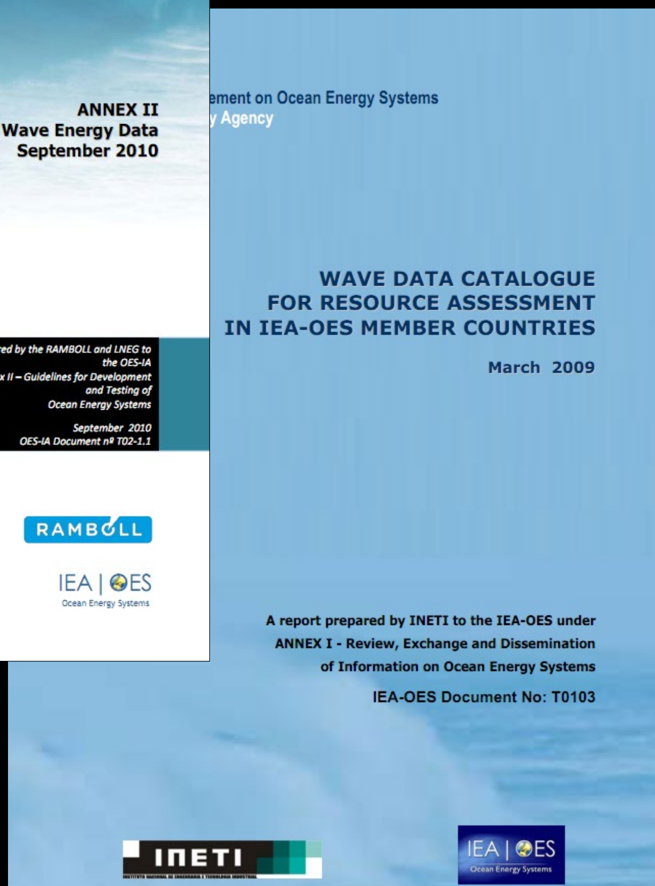
COE sheet

http://vbn.aau.dk/en/publications/user-gui½de--coe-calculation-tool-for-wave-energy-converters(78b135d9-ea66-43f8-959f-c799dc4df1a9).html

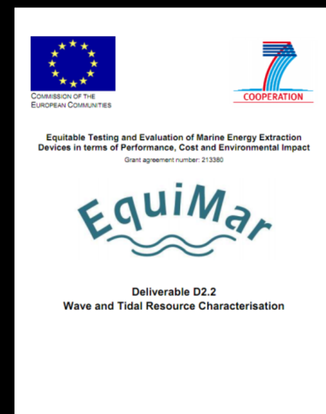
https://www.ocean-energy-systems.org/library/technical-reports/cost-of-energy/document/international-levelised-cost-of-energy-for-ocean-energy-technologies-2015-/

Guidelines and data sources …





www.iea-oceans.org



https://www.wiki.ed.ac.uk/display/EquiMarwiki/EquiMar

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Questions - comments?

Thank you!