Ocean power opportunities for Australia

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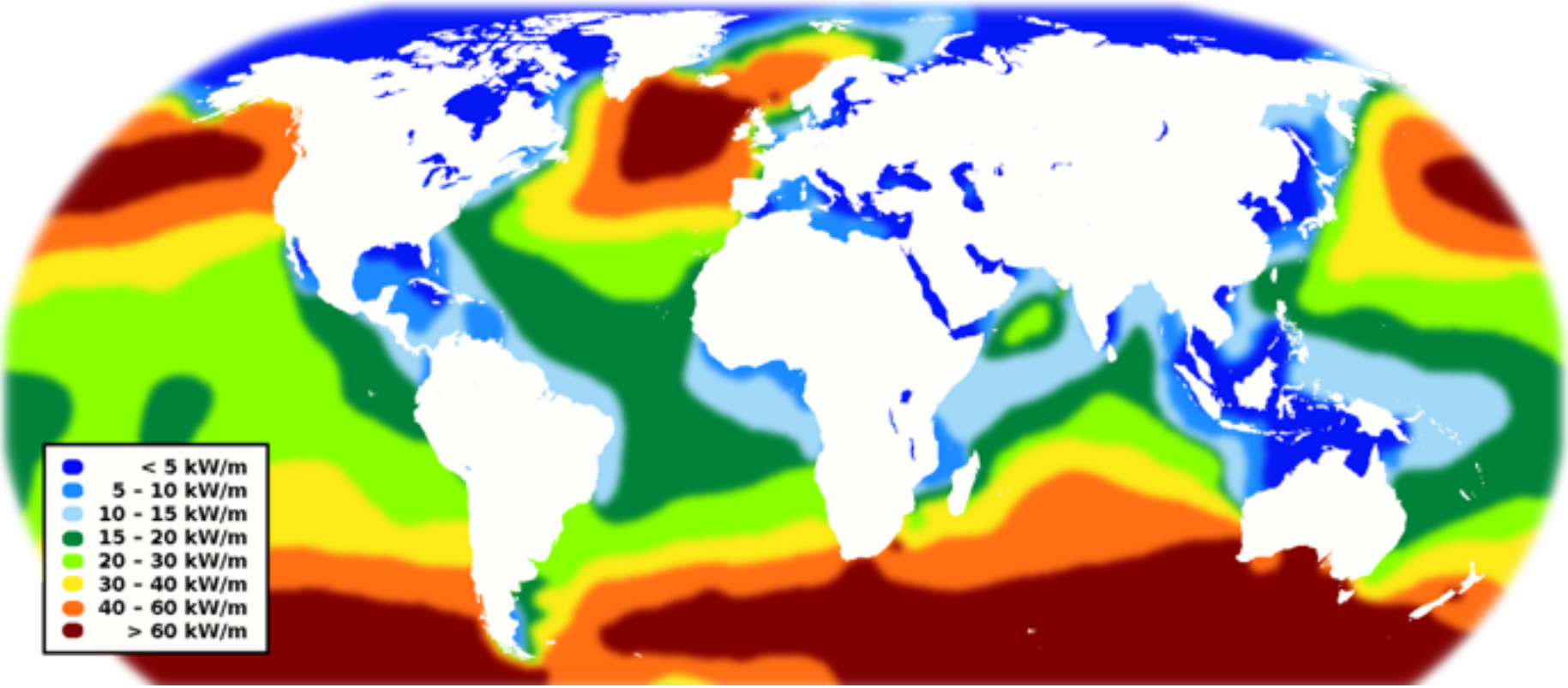
Contents

- Origin of wave energy
- Wave energy technologies and their issues
- Future prospects for Australia

Wave energy is concentrated wind energy

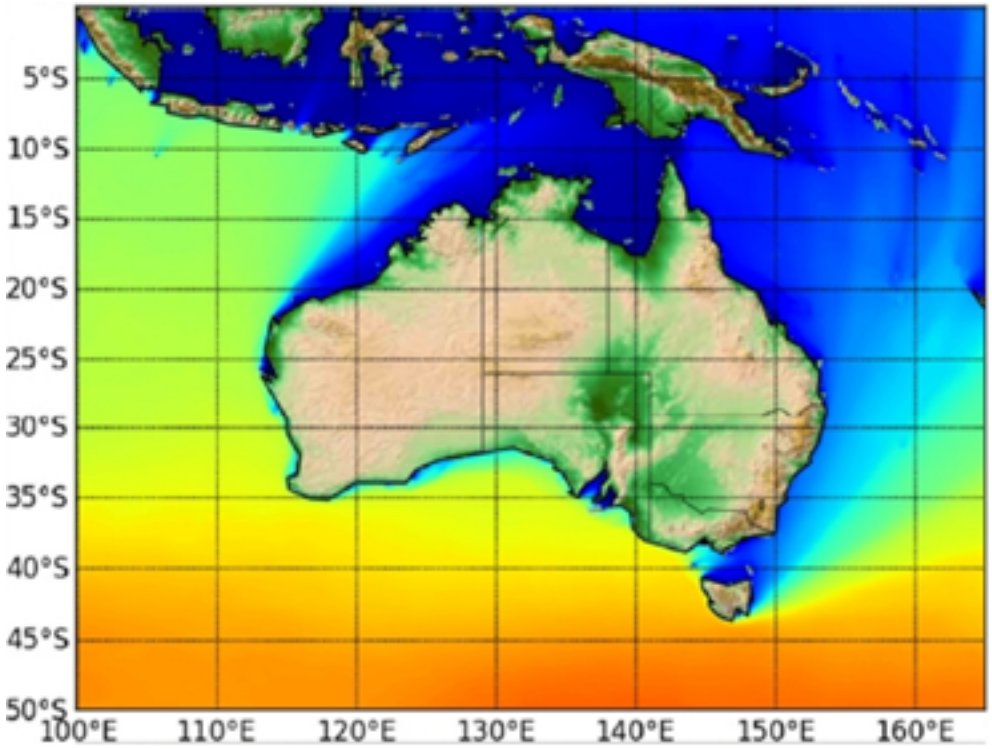


https://upload.wikimedia.org/wikipedia/commons/2/21/World_wave_energy_resource_map.png

- The **swell** is wind power harvested from the **70%** of **Earth's surface** that is ocean
- Like the winds that create it, the swell is most powerful in the Mid-Latitudes

Concentrated and averaged wind energy

Swinburne



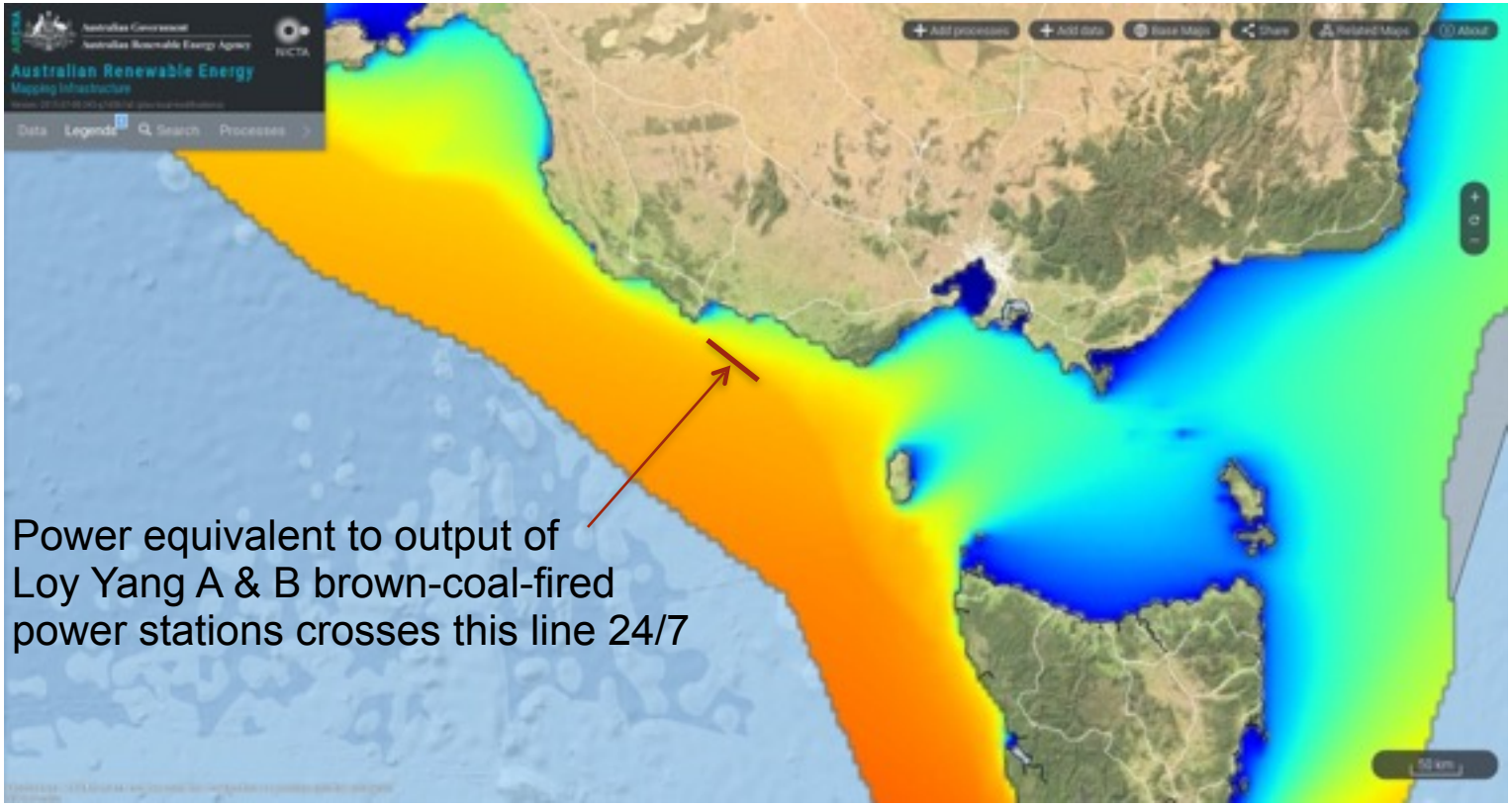
Illesinghe, S. et al., 2017, *Int. J. Marine Energy* (in press)

- Owing to the **averaging** over the entire ocean, wave power is only **1/3 as variable** as wind power
- Ocean swell does not disappear when local winds drop
- Wave power thus has potential to meet demand when other sources fail
- Five times Australia's electricity demand arrives on our S coast

Concentrated and averaged wind energy

Swinburne

SW Victoria, located just north of the strongest mid-latitude wind region on Earth, is one of the world's top wave-energy resource locations



http://oa-gis.csiro.au/aremi

Source: Bureau of Meteorology and CSIRO © 2013

Two issues have retarded WEC developments to date

A. There are very **many** concepts

B. Most of them must be **very big**

1. Wave motion is ***reciprocating***: cannot efficiently convert to rotation using one moving part

2. But machines left in the ocean must have as **few moving parts** as possible

Issue 1 **plus** Issue 2 has created an explosion of **diverse inventions**

In most cases each invention is championed by a separate small company – at last count, over 250!

http://www.daff.gov.au/aqis/about/current-activities/ghost_yacht_a_biofouling_nightmare_for_bowen

This unsolved problem: need an **efficient** mechanism but with **few moving parts** has defined the nature of the pre-commercial and commercial market for wave power …

… a 'zoo' of competing machines that all **look totally different** … very confusing for policy-makers and investors … But are they really so different?

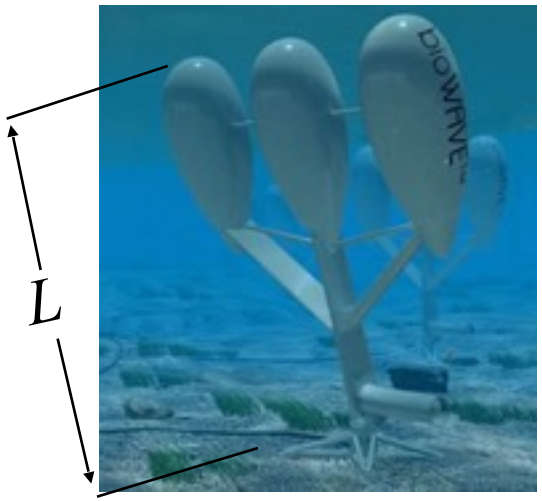
Most Wave Energy Converters (WECs) are designed to have a **natural frequency**, ω_0

Float and spring

Carnegie Wave Energy Ltd

$$\omega_0 = \sqrt{\frac{k}{m}}$$

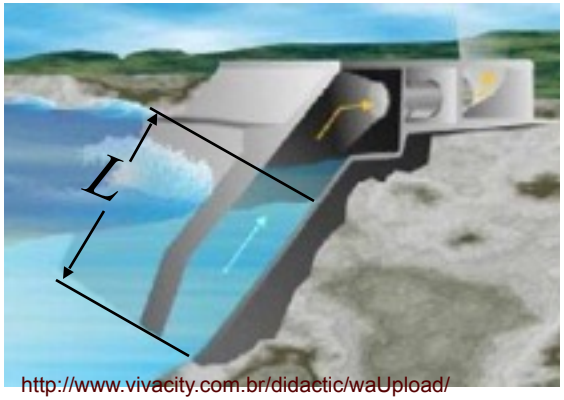
Pendulum



BioPower Systems Pty Ltd

$$\omega_0 = \sqrt{\frac{g}{L}}$$

Liquid pendulum



http://www.vivacity.com.br/didactic/waUpload/eomc400111122012144106.jpg

$$\omega_0 = \sqrt{\frac{g}{L}}$$

$$\omega_0 = 2\pi f = \sqrt{\frac{g}{L}}$$

NSW South Coast, 15 kW/m

f=0.15 Hz $\rightarrow L \approx$ **11 m**

SW Victoria, 60 kW/m

f=0.08 Hz $\rightarrow L \approx$ **36 m**

Very small companies are trying to develop **very big** machines

Oscillating Water Column (OWC)

Oldest-established wave power technology

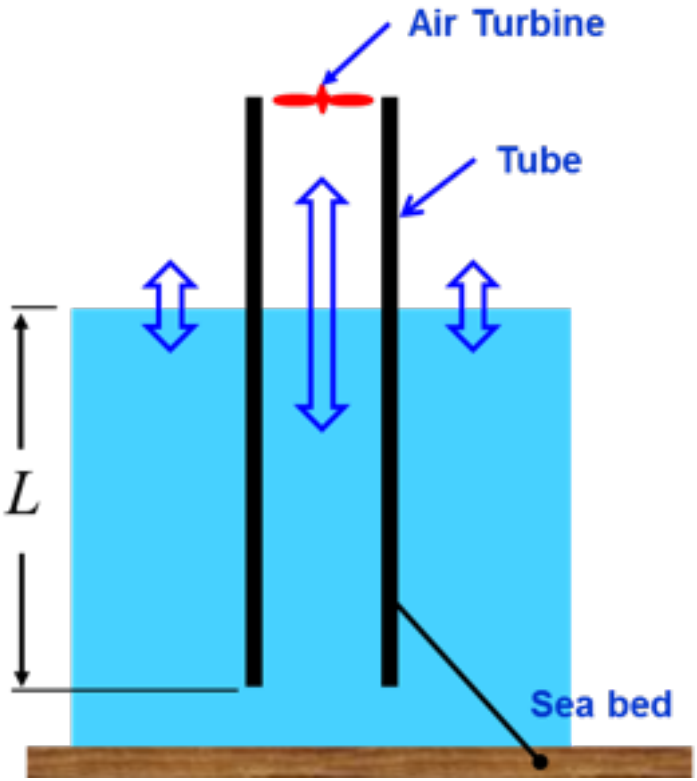
First used 150 years ago to power navigation buoys

Generating electricity since 1970s

No moving parts in the water

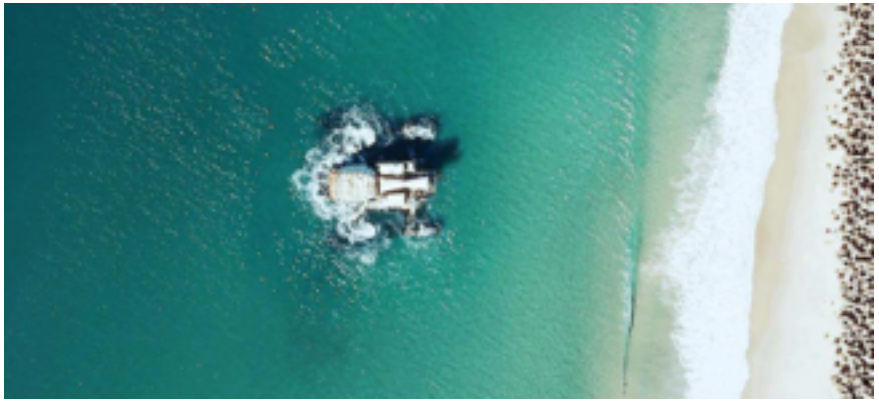
Bidirectional turbine not very efficient

$$\omega_0 = \sqrt{\frac{g}{L}}$$



Ref: Manasseh, R. et al., 2017, *Int. J. Ocean Climate Sys.* **8**, 50-67

Oscillating Water Column (OWC)



Oceanlinx originally founded in 1997 by Tom Denniss as Energetech

Main IP was the design of the bi-directional turbine

First prototype: a single device off the New South Wales south coast

Broke moorings and wrecked

Ref: Manasseh, R. et al., 2017, *Int. J. Ocean Climate Sys.* **8**, 50-67

Oscillating Water Column

Second prototype was an array of floating devices

Size and design of floating platform minimised motion, allowing OWCs to work

Connected to grid at NSW south coast – delivered 2.5 MW

Broke moorings and wrecked during a storm in 2010

Ref: Manasseh, R. et al., 2017, *Int. J. Ocean Climate Sys.* **8**, 50-67

Oscillating Water Column

Third prototype was made of concrete – meant to sit on sea bed

Planned installation in Feb 2014 in the Southern Ocean at Port Macdonnell, South Australia

Ref: Manasseh, R. et al., 2017, *Int. J. Ocean Climate Sys.* **8**, 50-67

Resonators need to be big

$$\omega_0 = \sqrt{\frac{g}{L}}$$

If f=0.1 Hz, $\omega_0 \approx 0.63$ rad/s

$\rightarrow L \approx$ **25 m**

Big machines mean **big risks**, particularly during installation in the ocean

Even though the **underlying concept works**

Oct 2013, Adelaide

Mar 2014, Carrickalinga, SA

Ref: Manasseh, R. et al., 2017, *Int. J. Ocean Climate Sys.* **8**, 50-67

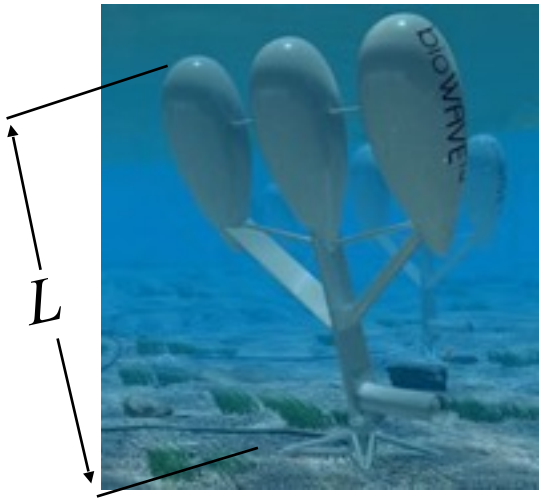
Australian mechanical-pendulum resonators

Biopower Systems founded by Tim Finnigan, a former Oceanlinx employee

Pendulum principle also used in some European devices, e.g. Aquamarine Oyster

Novel triple-blade may benefit by vortex-induced loads

$$\omega_0 = \sqrt{\frac{g}{L}}$$



http://news.cnet.com/i/bto/20080527/biowave_home.jpg

Ref: Manasseh, R. et al., 2017, *Int. J. Ocean Climate Sys.* **8**, 50-67

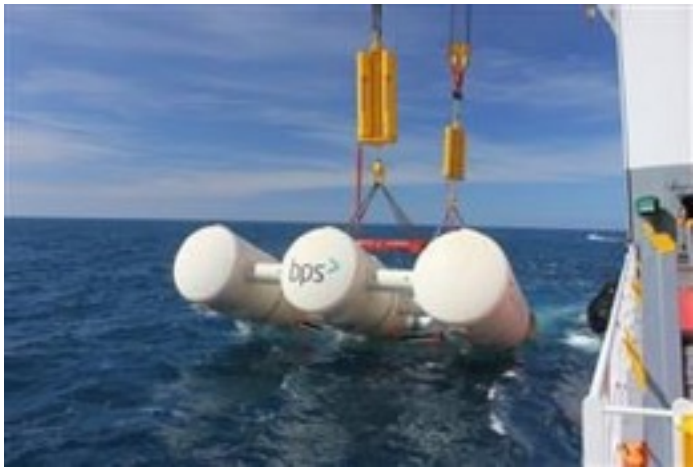
Australian mechanical-pendulum resonators

Swinburne

Biowave prototype successfully installed in Dec 2015 in Port Fairy, Victoria, Australia

Underwater grid-connection in progress, May 2017

Rated at 250 kW



Ref: Manasseh, R. et al., 2017, *Int. J. Ocean Climate Sys.* **8**, 50-67

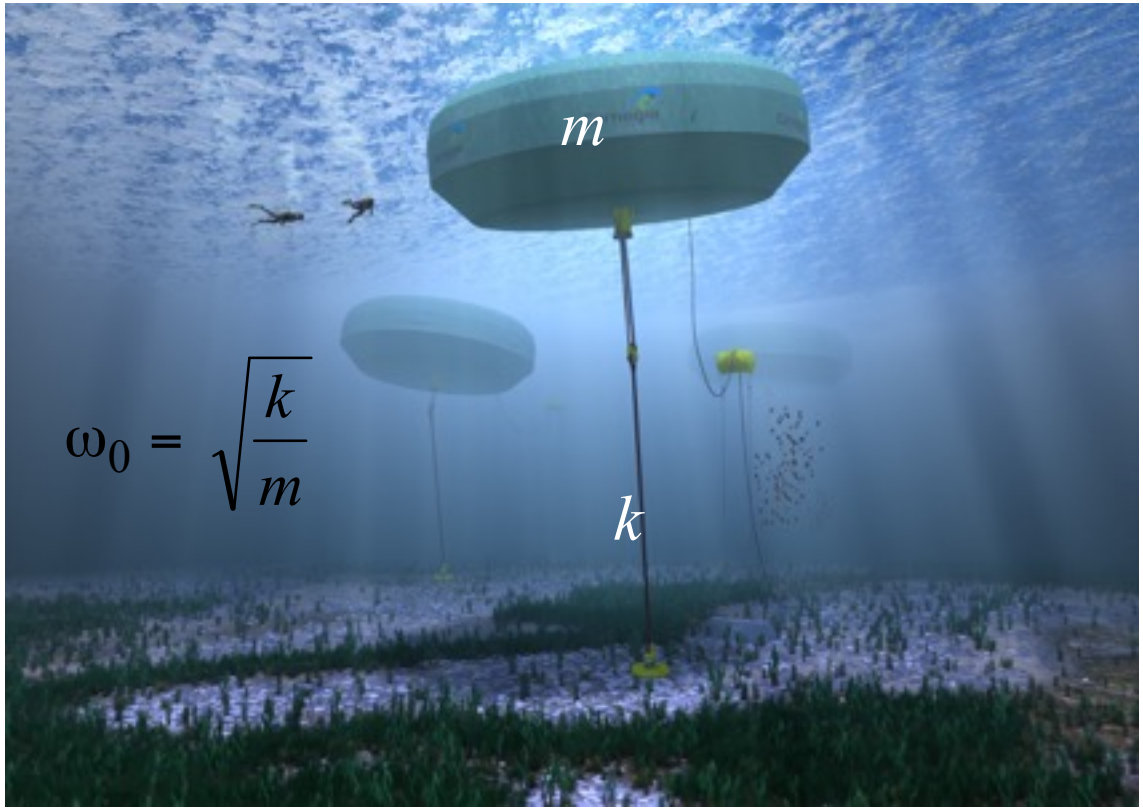
Australian heaving-buoy type resonators

Carnegie Wave Energy is a listed company on the Australian Securities Exchange

Originally a minerals company

Hydraulic fluid pressurised in cylinder drives turbine

Pressurised fluid in cylinder provides ‘spring’



Ref: Manasseh, R. et al., 2017, *Int. J. Ocean Climate Sys.* **8**, 50-67

Australian heaving-buoy type resonators

Swinburne

World's longest-surviving deployment of an array of wave-energy converters occurred over 2015, 50 km south of Perth, Western Australia

Grid-connected, hydraulic turbines on shore

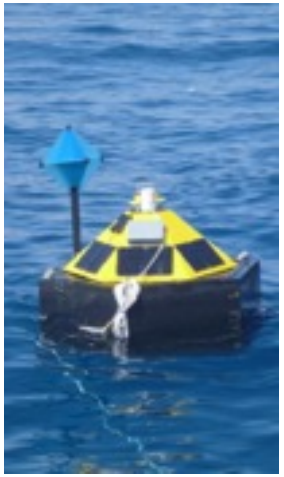
Planned retrieval and re-installation of units went according to plan

Next generation under development twice the size, generators on board

Ref: Manasseh, R. et al., 2017, *Int. J. Ocean Climate Sys.* **8**, 50-67

Other Australian wave energy converters

Wave Mill



Protean

Aquagen

Bombora

Perpetuwave

Waverider

Ref: Manasseh, R. et al., 2017, *Int. J. Ocean Climate Sys.* **8**, 50-67

Wave Energy Conversion issues

A. There are very many **small** start-up companies developing wave energy converters, and they tend to be **under-capitalised**

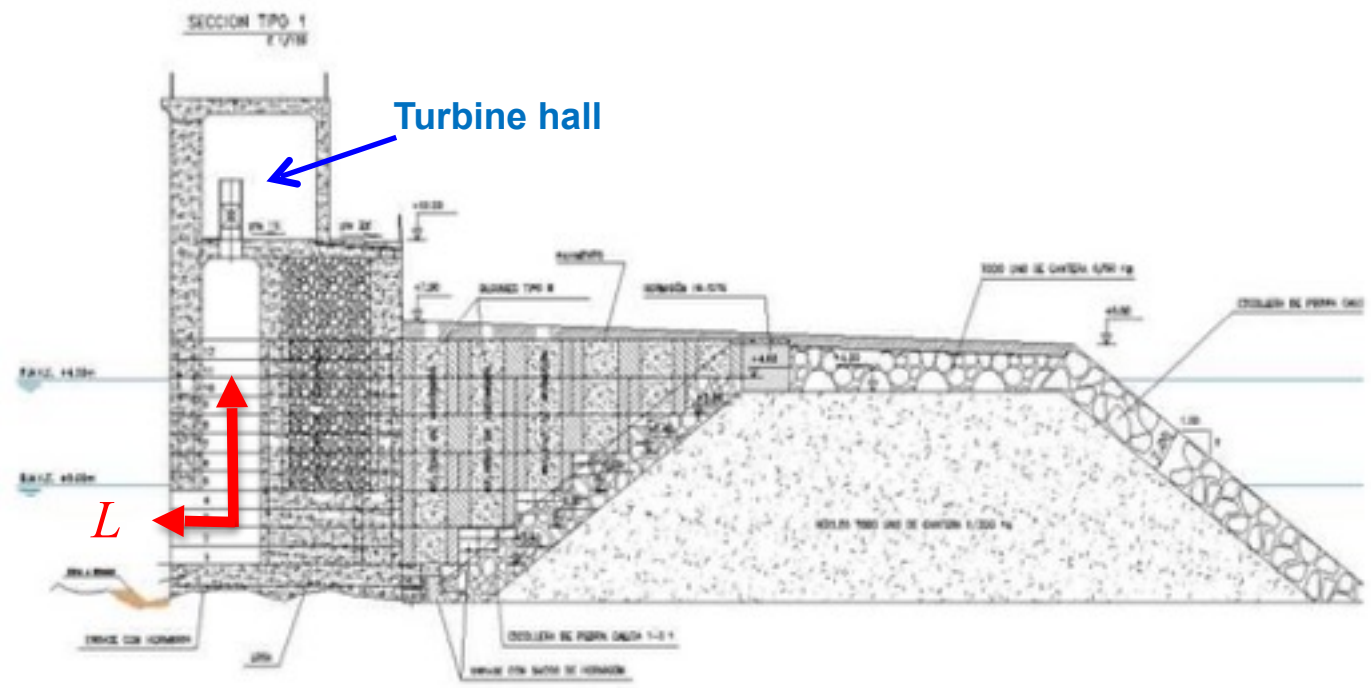
B. These small companies are forced to develop prototypes that **must be large** and thus extremely expensive to deploy

Mutriku grid-connected wave energy array

Operating from November 2011

Mutriku, Basque Country, Spain. Wave-energy converters added to a breakwater proposal just prior to construction of the original proposal

Mutriku grid-connected wave energy array



Operating from November 2011

$$\omega_0 = \sqrt{\frac{g}{L}}$$

An array of 16 **resonators:**

16 OWC chambers deliver 296 kW [1]

$L \approx 10$ m, so f_0=0.15 s … but f=0.10 s

Not that well tuned …

1 Torre-Enciso et al 2010, 3rd International Conference on Ocean Energy, Bilbao, Spain, 6 October 2010.

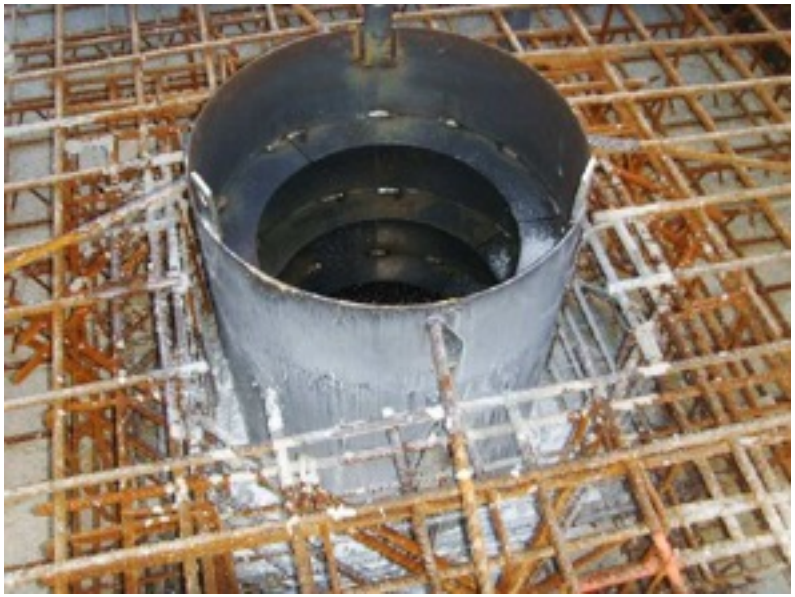
Mutriku grid-connected wave energy array

Mutriku, Basque Country, Spain.

Power plant including research trials 2M euro (about AUD 3M)

After 6 years, 1500 MWh delivered[2]

If the plant cost the same to build in Australia and **if** it sells electricity at **today's** Australian wholesale electricity prices, annual return on investment would be in the **order** of **1%**



The plant output could probably be 3 x greater if designed from the outset

Geographical amplification of tidal energy

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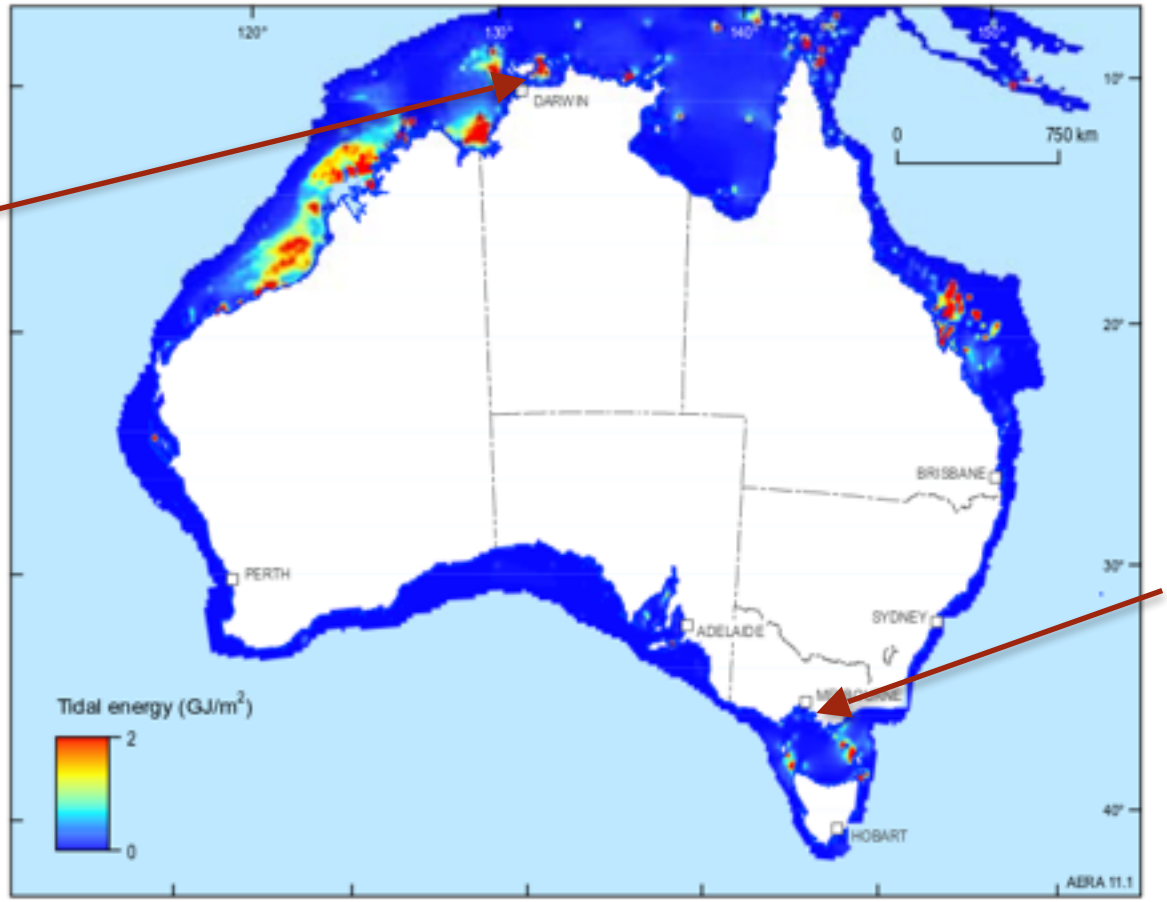
Clarence Strait, Northern Territory



San Remo, Victoria

Figure 11.1 Total annual tide kinetic energy (in gigajoules per square metre, GJ/m²) on the Australian continental shelf (less than 300 m water depth)

Note: The low range of the colour scale is accentuated to show detail. The colour scale saturates at 2 GJ/m² but the maximum value present is 195 GJ/m²

Source: Geoscience Australia

Marine energy export

In 1974, Stephen Salter wrote a seminal paper on wave power[1], saying

"Electrolytic production of hydrogen from sea water looks promising … The installations could be self-propelled … could move out into the Atlantic … storing hydrogen on the way."

1: Salter, S. H., 1974, "Wave Power", *Nature* **249**, 720-724

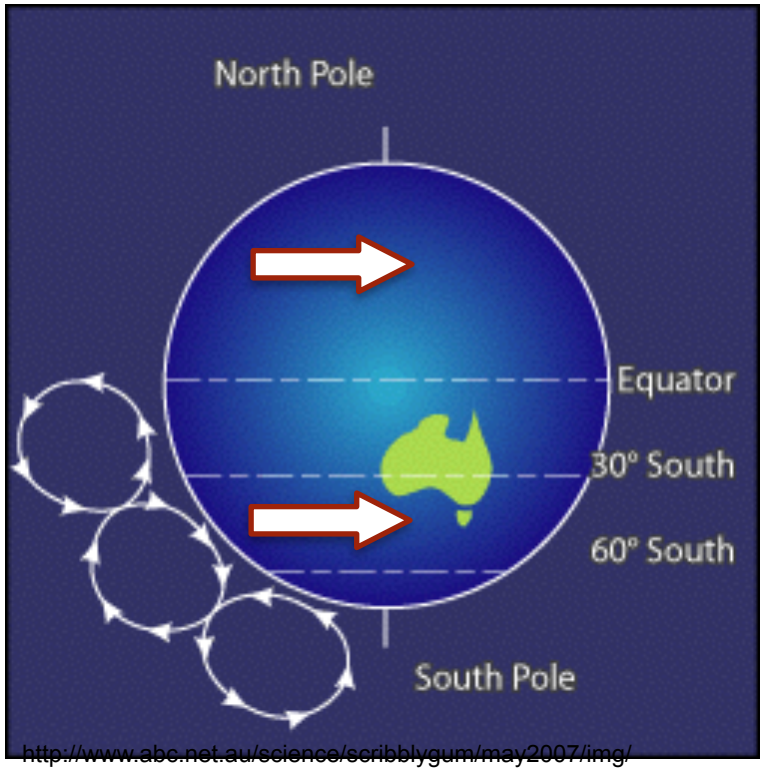
Summary

- SW Victoria, W Tasmania and SW WA are among the world's top wave energy locations
- Many inventions has led to many small companies
- Most operate on the principle of resonance, requiring large size
- The integration of wave-energy converters into coastal-protection infrastructure has been occurring in Europe
- Tidal power is significant in only a few locations worldwide – including Australia's NW shelf
- H_2 generation may offer an energy export opportunity

Extra slides for tricky questions

Origin of wave energy

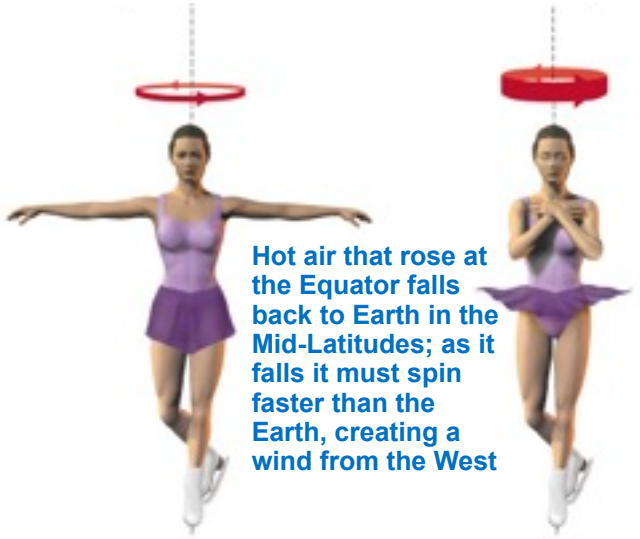
Wave energy is concentrated wind energy



http://www.abc.net.au/science/scribblygum/may2007/img/convectiondiag0.3.gif

The **mid-latitude westerly** winds are the most powerful on Earth

They exist due to the difference in temperature between the Equator and the Poles, plus the principle of conservation of angular momentum



http://www.oswego.edu/~kanbur/a100/images/skater.jpg

1. Wave motion is ***reciprocating***, not unidirectional

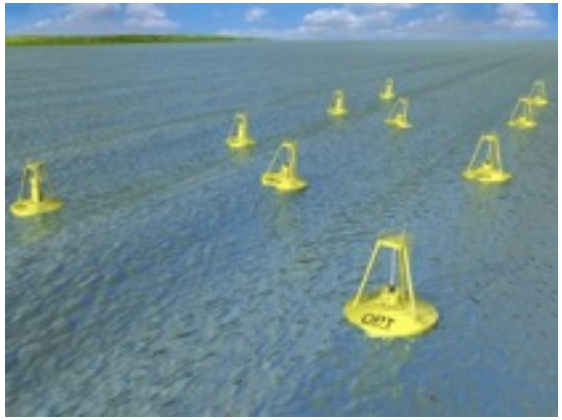
   A rotating shaft is best for electricity generation

   Unidirectional flow easily converted to rotary motion with a **single moving part**

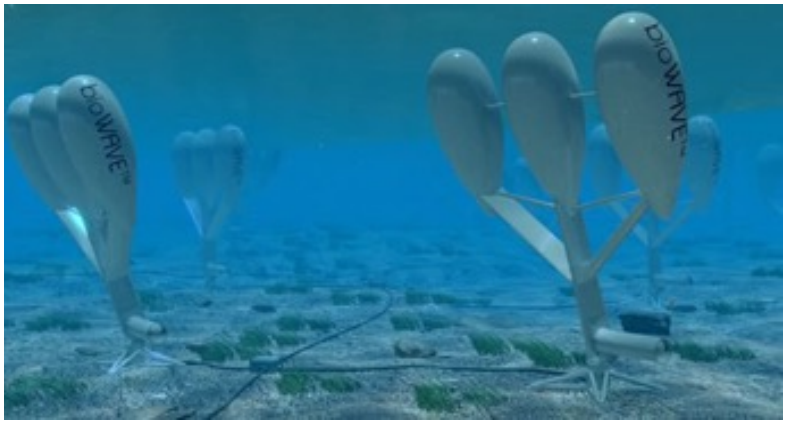
Energy source	Flow direction	Simplest technology
Wind	Unidirectional	Turbine
Water flowing downhill	Unidirectional	turbine
Tidal flows	Unidirectional (for 6 hours)	turbine
Waves	Reciprocating	**??**

Wave Energy Converter arrays

WEC “breakwaters” may be a solid wall … or maybe not



Ocean Power Technologies Ltd.



BioPower Systems Pty. Ltd.

- Owing to **resonance**, WEC arrays can remove wave energy without the machines physically touching each other
- Coastal protection could be “**porous**”, offering some wave reduction without permanently affecting marine ecosystems
- The array could be “**tuned**” by drawing more or less power depending on the coastal-protection versus power-generation needs of each day

Summary

- SW Victoria, W Tasmania and SW WA are among the world's top wave energy locations
- Despite the diversity of wave-energy converter machines, most operate on the same principle of resonance
- The integration of wave-energy converters into coastal-protection infrastructure has been occurring in Europe
- Potential benefits include long-term revenue offsetting infrastructure costs
- Wave-energy converter can also be "porous" or "tunable" barriers, potentially reducing environmental impacts

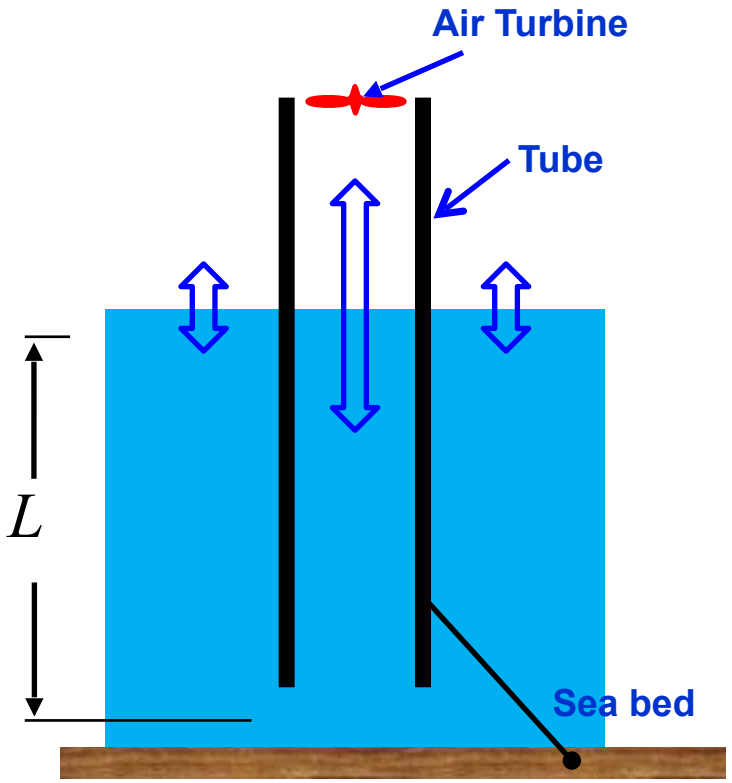
The OWC is effectively a liquid pendulum

Length of pendulum **tuned** to wave frequency

$$\omega_0 = \sqrt{\frac{g}{L}}$$

So far, the only WEC operated over years … rather than months

http://dnahtigal.files.wordpress.com/2011/05/oceanlinx-wave-energy-barge-port-kembla-nsw1.jpg



Resonators need to be big

$$\omega_0 = \sqrt{\frac{g}{L}}$$

Example: if f=0.1 s, $\omega_0 \approx 0.63$ rad/s

$\rightarrow L \approx$ **25 m**

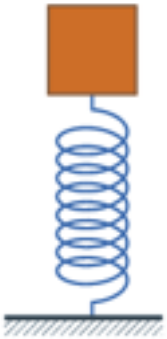
Big machines mean **big risks**, particularly during installation in the ocean

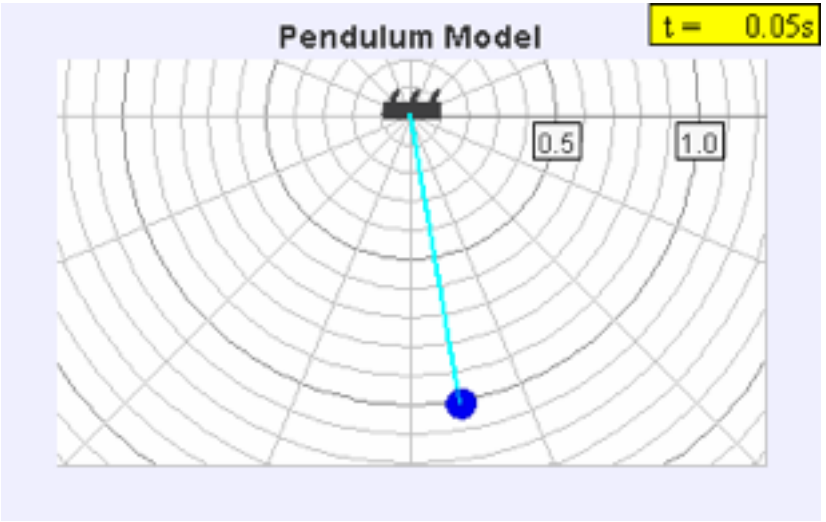
Even though the **underlying concept works**

Oct 2013, Adelaide

Mar 2014, Carrickalinga, SA

Any mechanism that has a **natural frequency**, ω_0, will **resonate** when it is driven with the **same** frequency





$$\omega_0 = \sqrt{\frac{k}{m}}$$

$$\omega_0 = \sqrt{\frac{g}{L}}$$

The **float-on-spring** and the **pendulum** are popular mechanisms with wave-energy converter inventors

Advantage of a resonating WEC

A resonating wave machine can suck in wave power over an area **larger than its physical size**

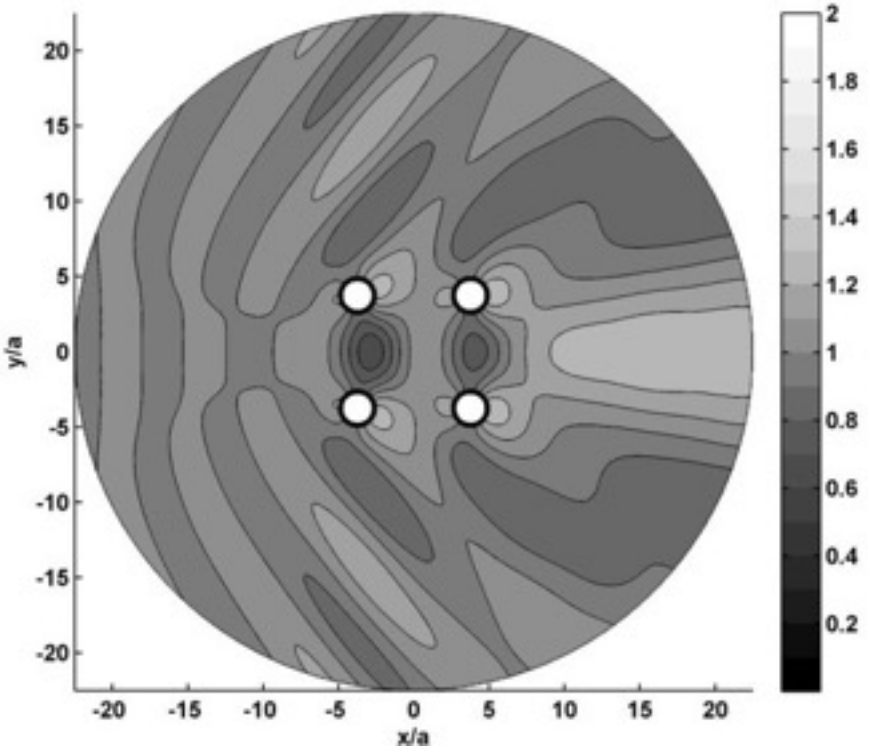
A wind or water turbine only extracts power over its physical diameter

Length of crest over which all power can be captured

$$L = \frac{\lambda}{2\pi}$$

e.g. $\lambda = 180$ m,

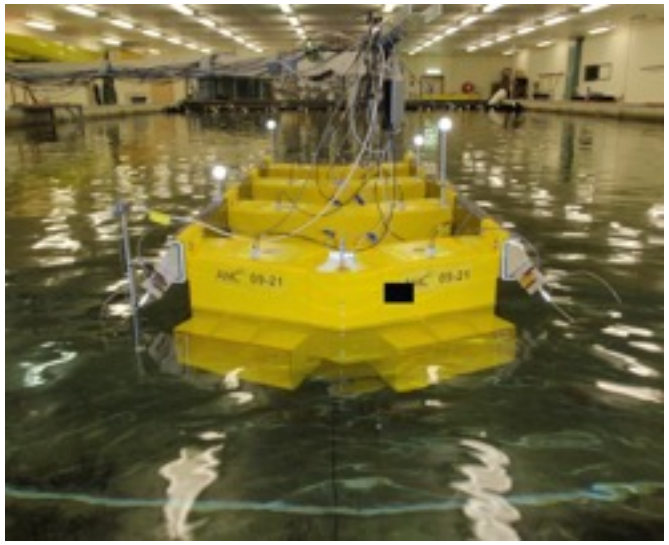
$L \approx 30$ m



Nader J-L et al 2012, *Ocean Eng* **43**, 72-81

Our background

- Investigate wave-power arrays both **theoretically** and via **lab experiments** at AMC
- **Generic** technology types to be studied, so results applicable to many developers
- **Output** publically available web-based tool estimating performance of any proposed array in Australia



Directional Wave Basin, AMC

BioPower Systems
UNIVERSITY of TASMANIA | AMC Australian Maritime College
Carnegie

Oscillating Water Column

These disasters were not due to any problem with the technology

They were due to the way the machine was anchored, or transported

Typical of marine renewable developments worldwide – large capital is needed for large machines in the real ocean environment

Following the disaster in South Australia, Oceanlinx was put under administration

However, the IP was bought by a Hong Kong based concern

In September 2015 Oceanlinx resurfaced as a Taiwan-based company

Its technology is now planned for deployment in Taiwan

Does it give **more** or **less** power than the same number of isolated machines ?

The "q-factor" (**Budal, 1977**) tells us if array operation is beneficial or not

$$q = \frac{\overline{\overline{W}_{PN}}}{N\,\overline{\overline{W}_{P}}}$$

Power from the array

Power from a single, isolated machine

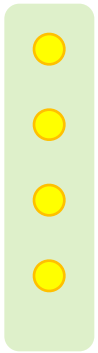
Number of machines

Budal, K., 1977 *J Ship Res* **21**, 248–253.

- $q > 1$: the array increases power output
- $q < 1$: the array decreases power output

The importance of q

Waves

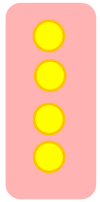


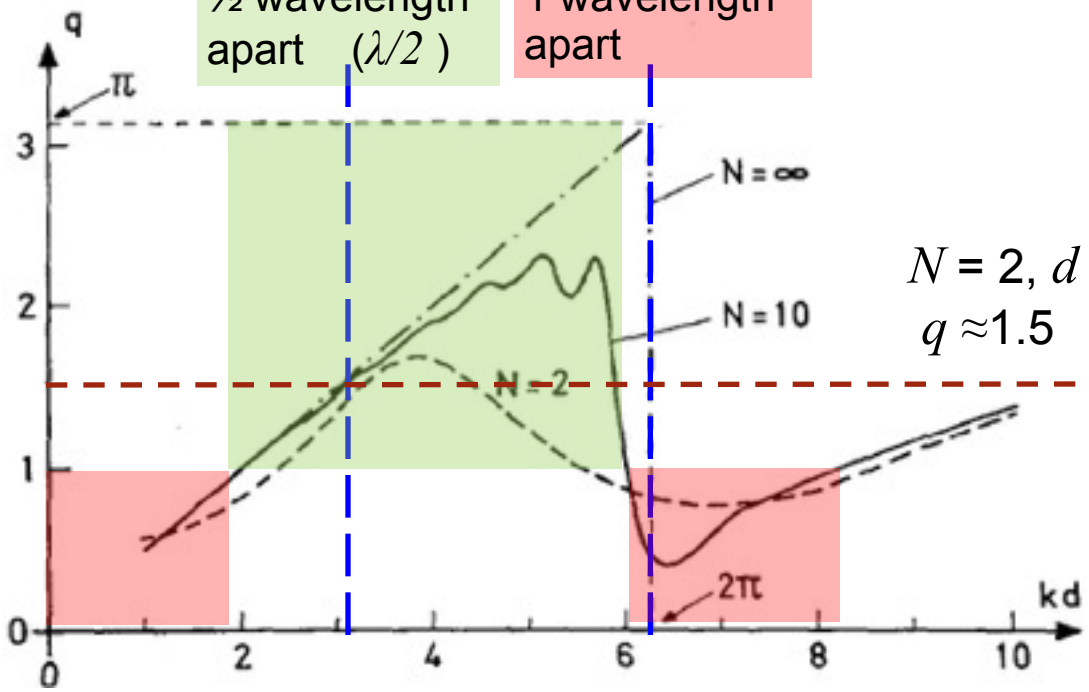
- $q > 1$: the array increases power output
- $q < 1$: the array decreases power output

Machines ½ wavelength apart ($\lambda/2$)

Machines 1 wavelength apart

Waves





$N = 2, d = \lambda/2$:
$q \approx 1.5$

Budal, K., 1977 *J Ship Res* **21**, 248–253;

Coastal protection case study 2

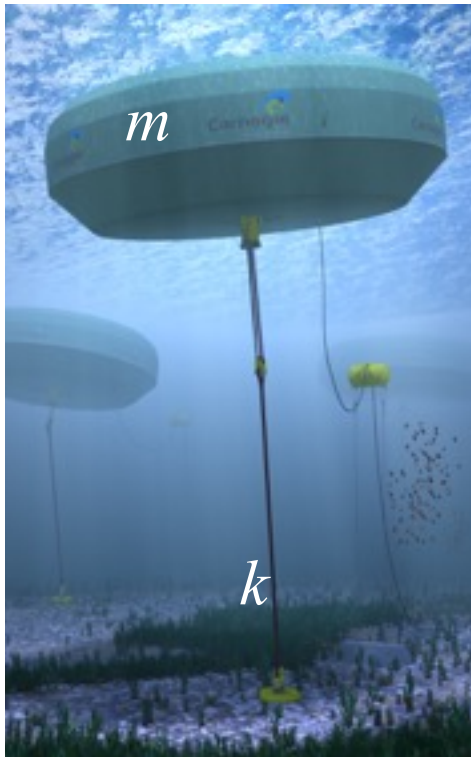
Courtesy Prof F. Arena, Università Mediterranea di Reggio Calabria, Italy

… it is an array of **resonators**

Float-on-spring

Stiffness k in “spring” provides restoring force resisting float buoyancy, m

$$\omega_0 = \sqrt{\frac{k}{m}}$$



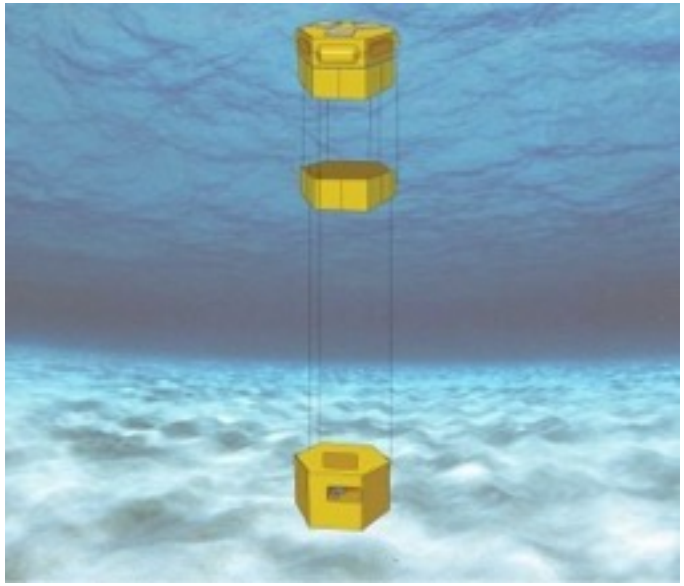
Carnegie Wave Energy Ltd

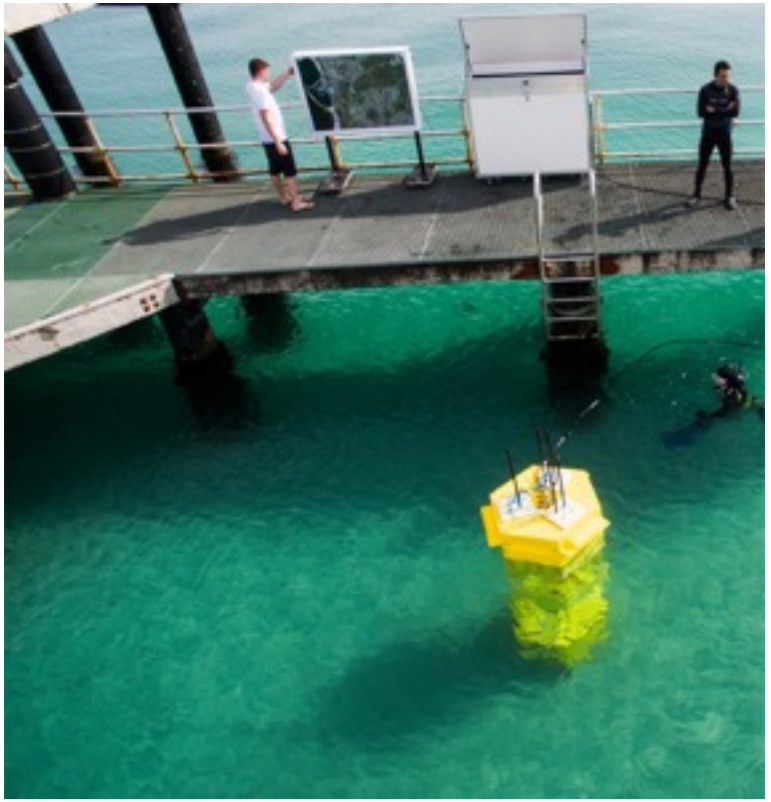
Australian heaving-buoy type resonators

Protean proposed an array of heaving buoys, floating

Each with an individual generator

A single prototype was trialled



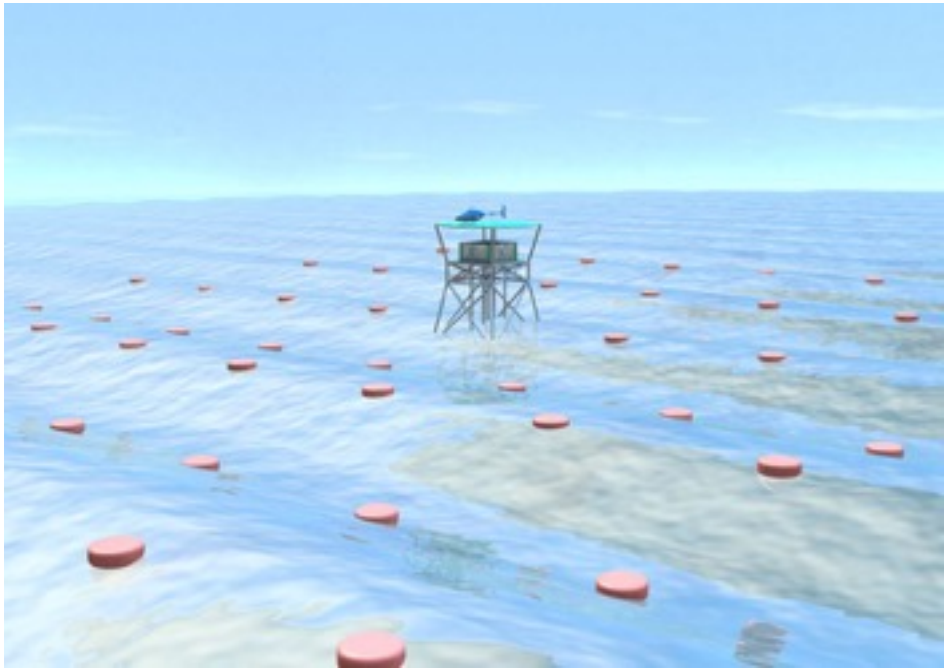


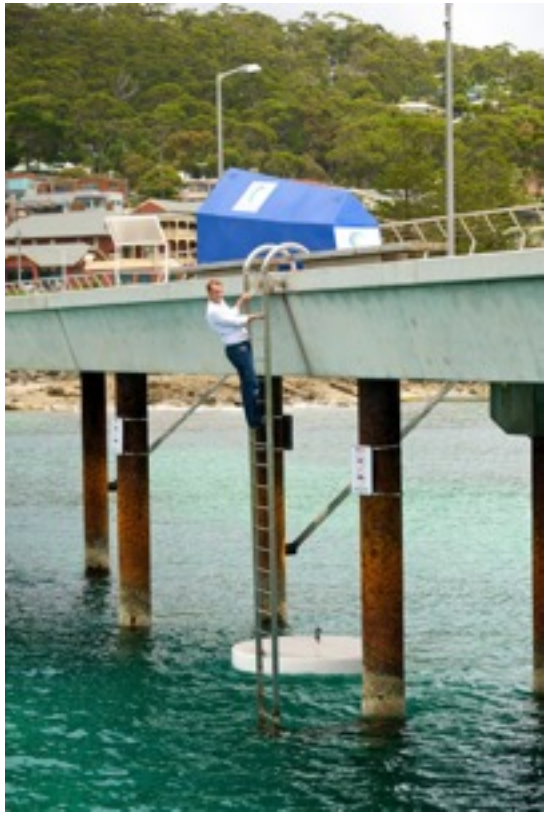
Australian heaving-buoy type resonators

Aquagen proposed an array of heaving buoys, floating

Connected by mechanical cables to central generator

A single prototype was trialled





Australian non-resonating device

Bombora Wave Power is a 2012 start-up company

One of the world's few non-resonating wave energy converters

Array of flexible bladders drives air through one-way valves

Probably suitable for shallow, near-shore deployment

Currently undergoing lab and ocean-prototype testing

Mutriku grid-connected wave energy array

Mutriku control room protective outer doors

Mutriku turbine hall with public viewing booth

Civitaveccia harbour walls, Italy

Courtesy Prof F. Arena, Università Mediterranea di Reggio Calabria, Italy

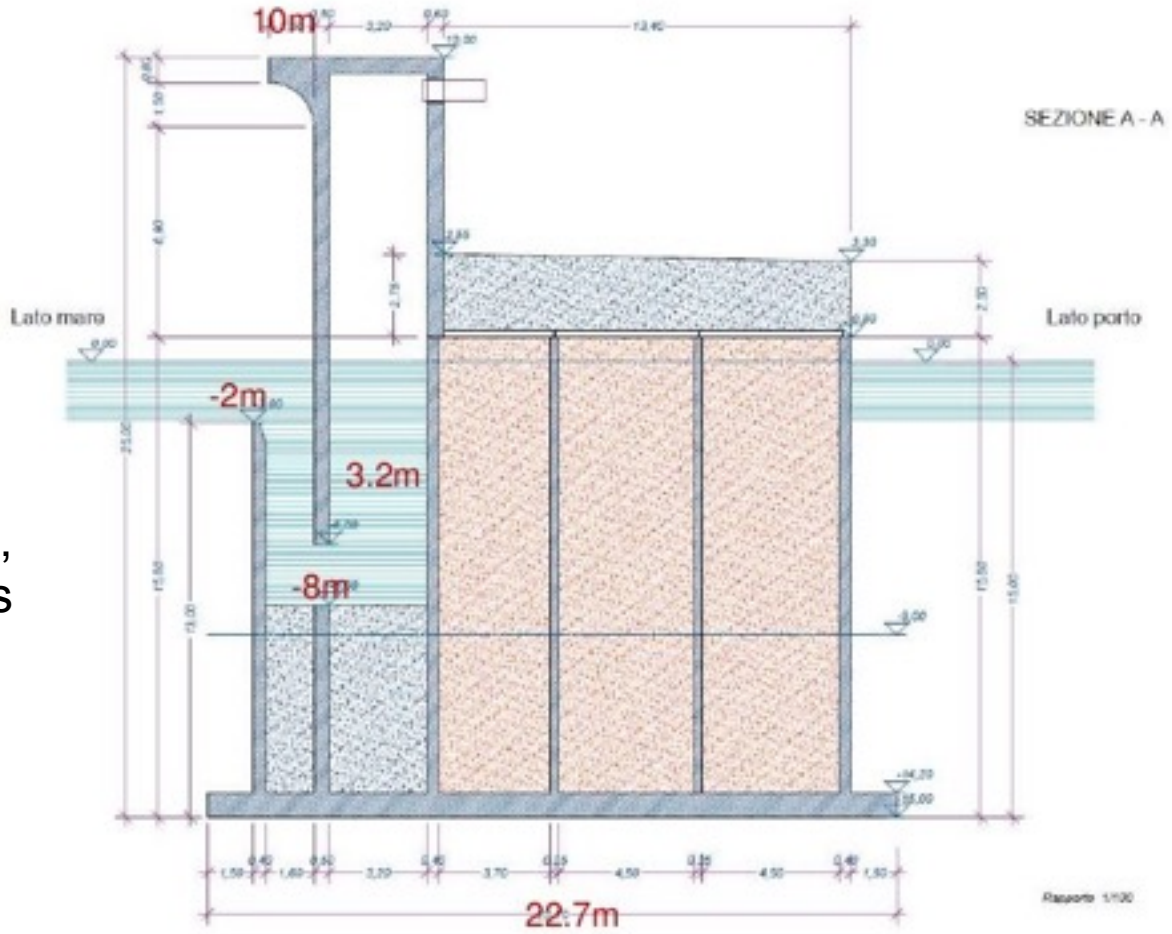
Civitaveccia, Italy: as at Mutriku, Spain, the **need** was for a new port breakwater

However, structure was **designed from the outset** to incorporate wave energy

17 caissons, 124 OWCs, 2.5 MW output

Civitaveccia harbor walls, Italy

$L \approx 10$ m,
so f_0=0.15 s



Courtesy Prof F. Arena, Università Mediterranea di Reggio Calabria, Italy

Civitaveccia harbor walls, Italy

Courtesy Prof F. Arena, Università Mediterranea di Reggio Calabria, Italy

Civitaveccia harbor walls, Italy

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Environmental opportunities

- Wave-generated currents bring nutrients and organisms that help to sustain near-shore marine life
- They also build up and remove sediment and sand
- Altering these currents could have unexpected environmental and engineering consequences

http://www.cleaneryarrabay.vic.gov.au/assets/~/media/OSS/Images/Factsheets/weedy_seadragon_516x387.jpg

Australian tidal power developments

Atlantis Resources tested these two low-velocity tidal devices in a narrow passage at San Remo, Victoria, Australia in 2002

100 kW

Completed trials in 2006

150 kW

Completed trials in 2008

Shifted operations to Singapore in 2006

Shifted entirely to London in 2008

Australian tidal power developments

Elemental Energy Technologies tested this low-velocity tidal device at Newcastle, NSW, Australia in 2011

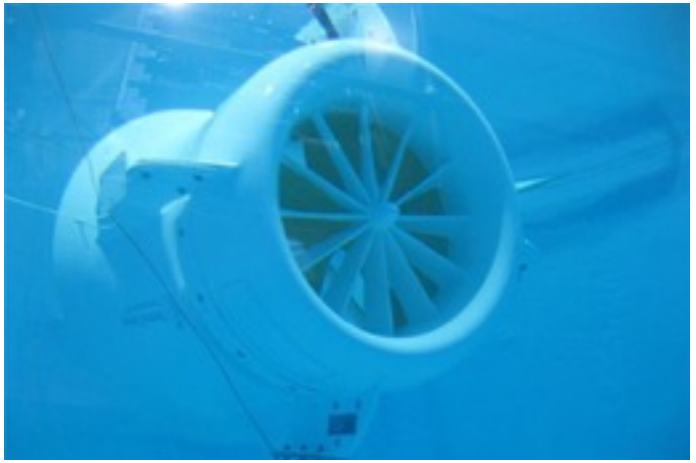
2 kW

Further tests in India, at the Defence Research & Development Organisation

Now manufactured under licence from EET by Indian company Kirloskar Integrated Technologies Limited in Pune

Tenax Energy was established in 2007

Proposes to use the EET-Kirloskar device in the Clarence Strait, Northern Territory, to power city of Darwin



Alan Major, Tenax