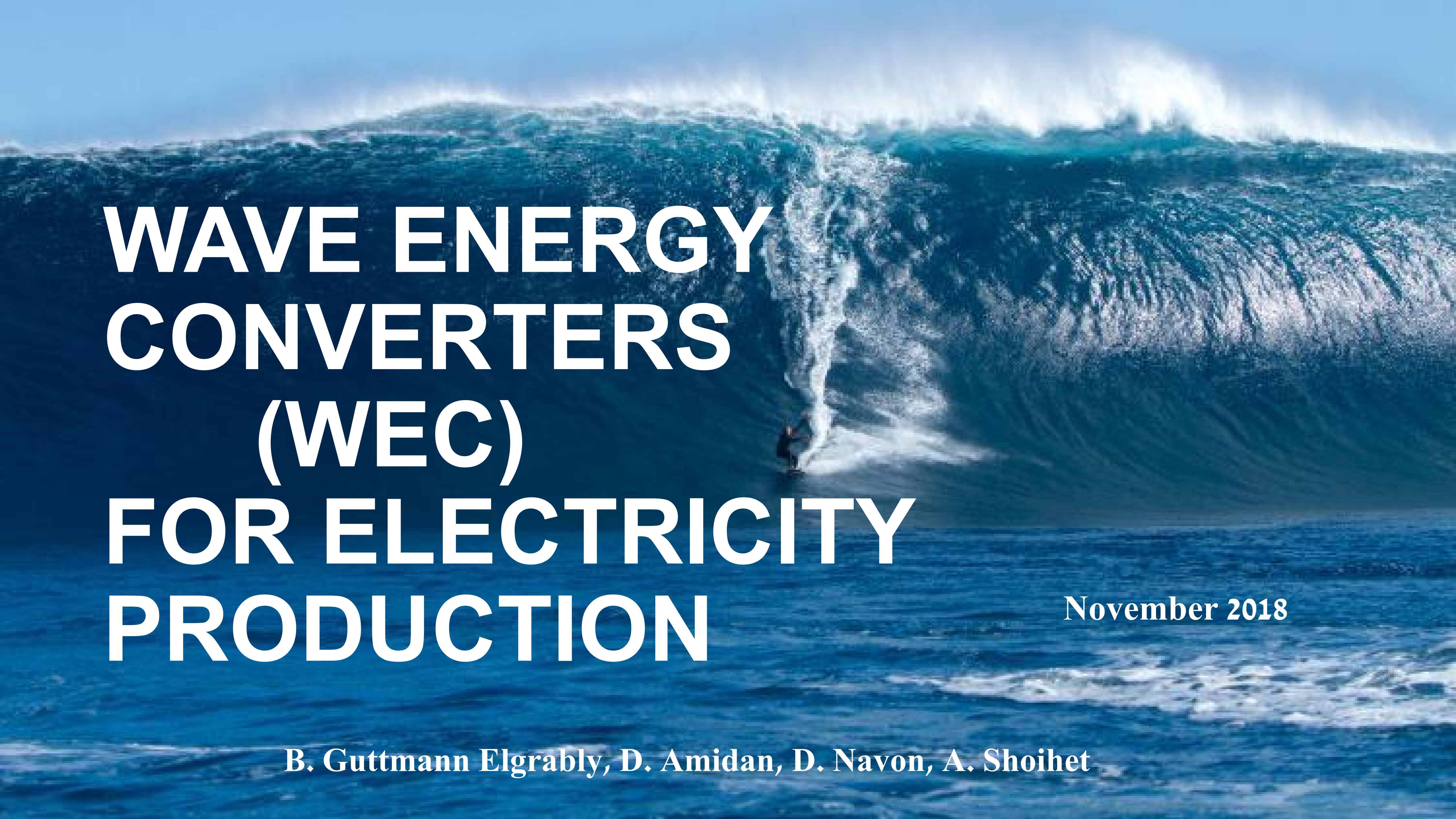


WAVE ENERGY CONVERTERS (WEC) FOR ELECTRICITY PRODUCTION

November 2018

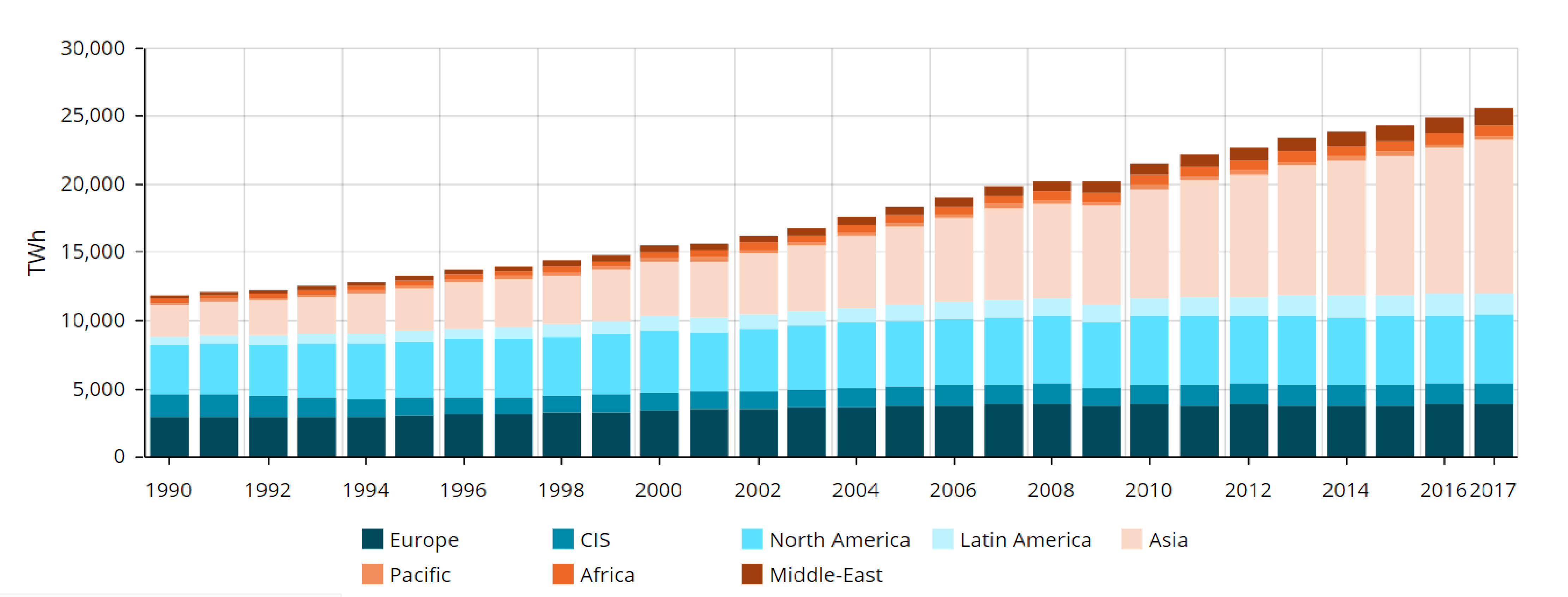
B. Guttmann Elgrably, D. Amidan, D. Navon, A. Shoihet

Content

- World electricity production- current and future.
- Wave source and potential.
- Distribution according to the WEC technology type and location.
- WEC technologies review.
- “Sotenas” project in Sweden.
- WEC advantages and disadvantages.
- Challenges for WEC concepts.
- World WEC installation capacity- present and future.

World electricity production

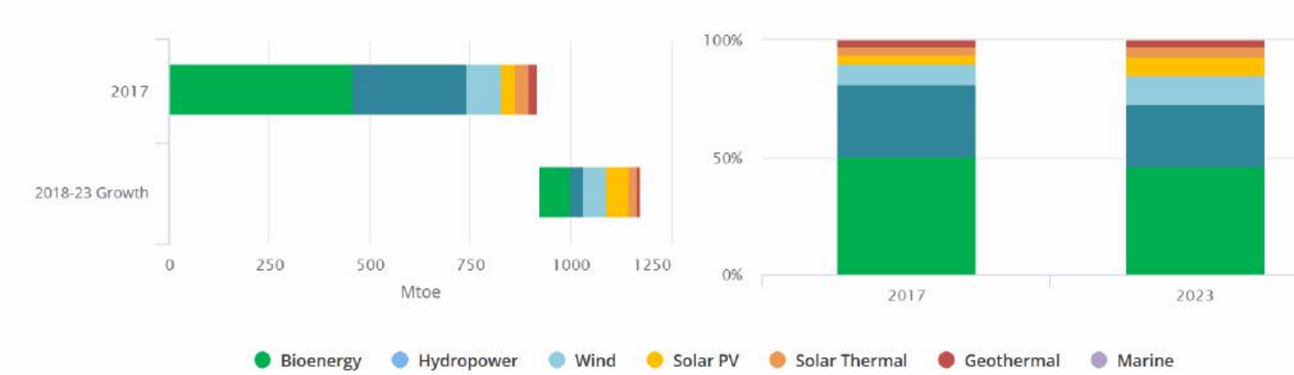
- Total world electrical production in 2017 was ~25,500 TWh (~7 TW generation capacity).

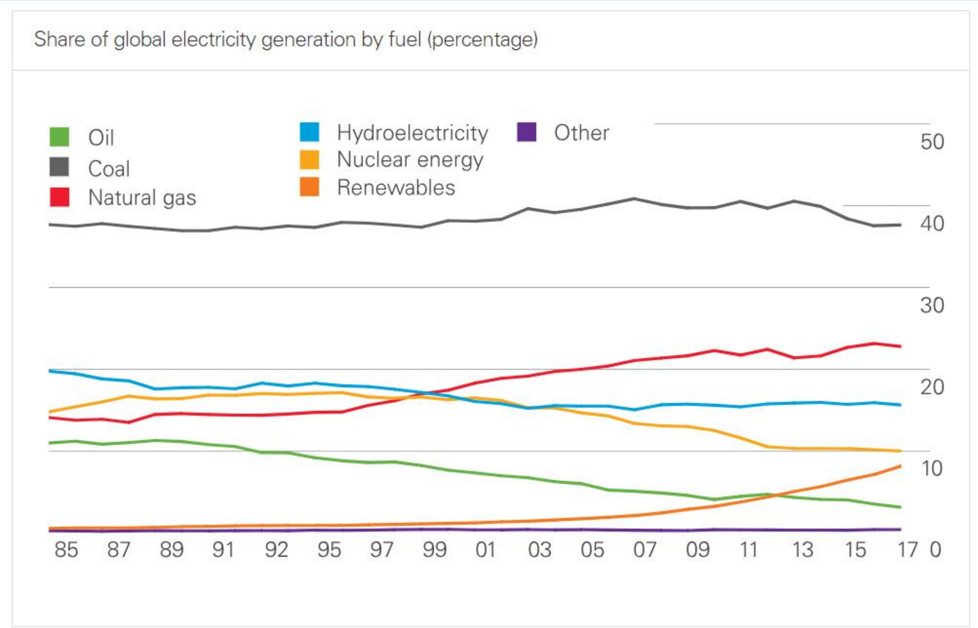


I. Global Energy Statistical Yearbook 2018
II. https://www.power-technology.com/comment/q3-2017-global-power-markets-glance/

World electricity production, by source

- ~22 % of the world electricity production is from renewable sources.
- ~0.02% of the renewable electricity production is from ocean energy.
- ~ 0.5 GW installed **ocean** capacity & ~ 2 MW installed **waves** capacity.

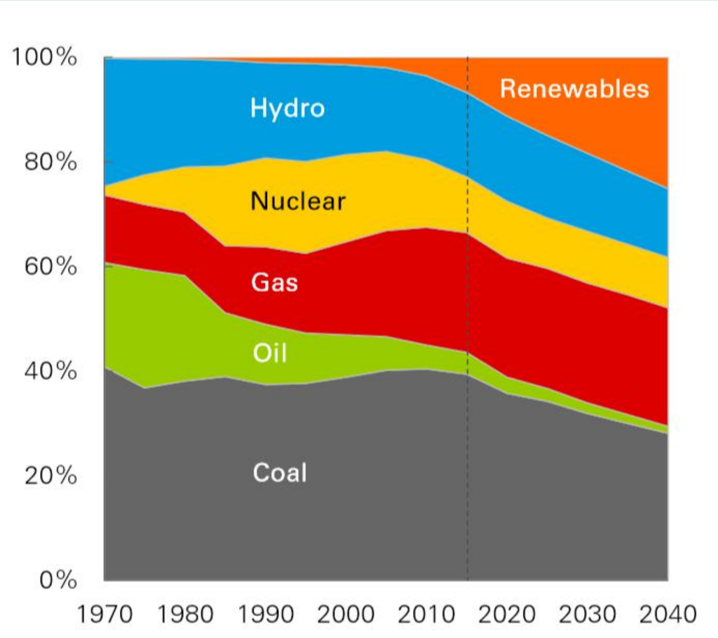




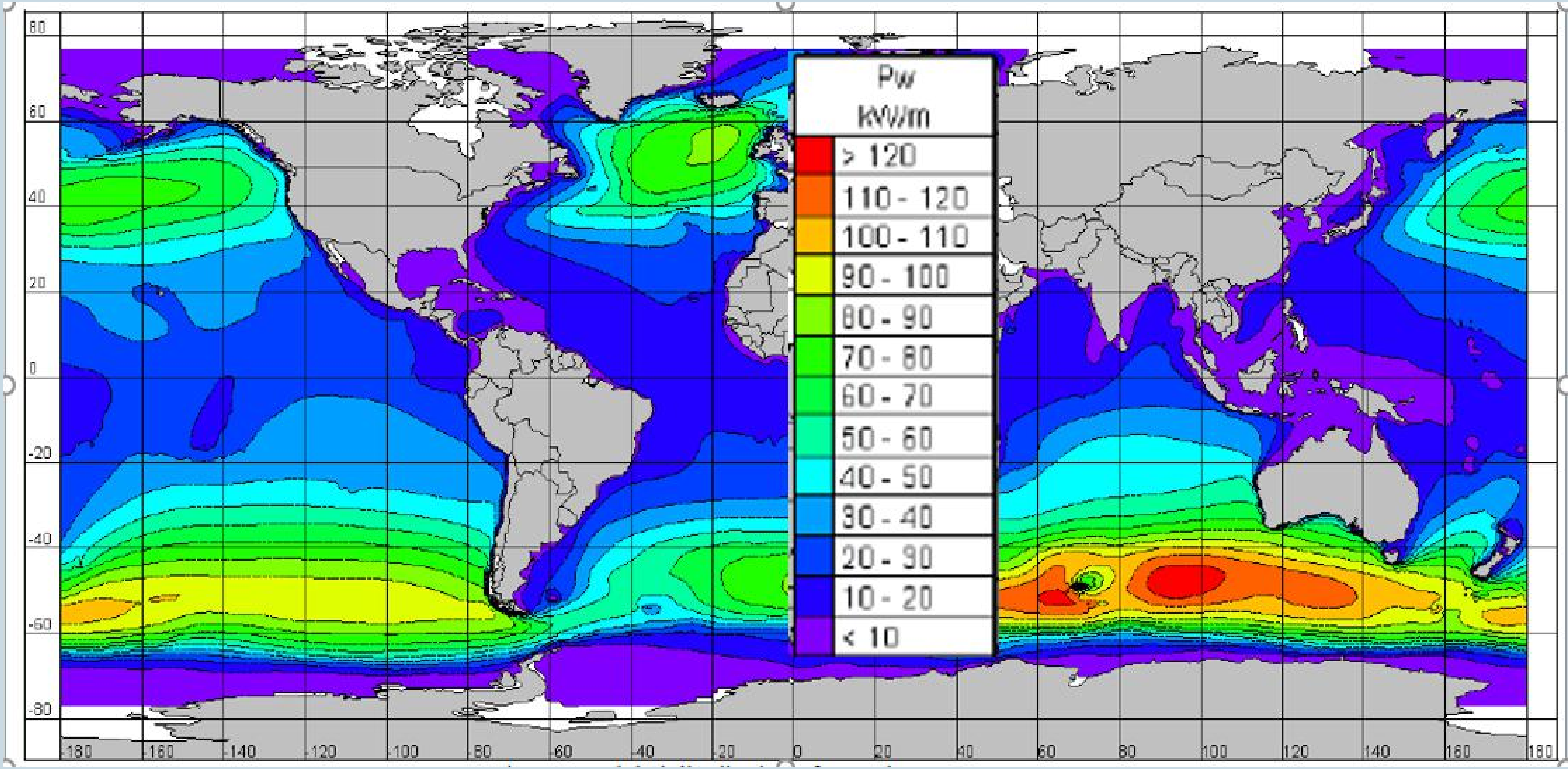
I. https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy/electricity.html
II. https://marineenergy.biz/2018/03/12/global-installed-ocean-energy-power-doubles-in-2017/
III. "World Energy Resources Marine Energy," World Energy Council, 2016
IV. https://www.iea.org/renewables2018/

Future predicted world electricity production in 2040, by source

- **Total world electrical production in 2040 will be ~43,000 TWh.**
- ~27% of the world electricity production will be from renewable sources.
- ~0.5% of the renewable electricity production will be from ocean energy.

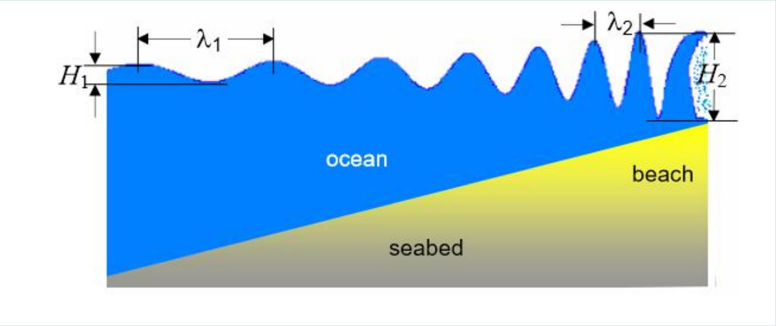


I. "World Energy Resources Marine Energy," World Energy Council, 2016
II. https://www.bp.com/content/dam/bp/en/corporate/pdf/energy-economics/energy-outlook/bp-energy-outlook-2018.pdf



I. A.Cornett, "A GLOBAL WAVE ENERGY RESOURCE ASSESSMENT", Canadian Hydraulics Centre- National Research Council, Ottawa, 2008
II. L. Christensen, E.Friis-Madsen, K.Jens Peter, "The Wave Energy challenge", Aalborg University, Denmark 2005
III. World Energy Council, L. Claeson and Uppsala University
IV. Mean annual wave energy flux in the Mediterranean Sea obtained from the ERA-Interim database, 1979–2013. Data analyzed by HCMR

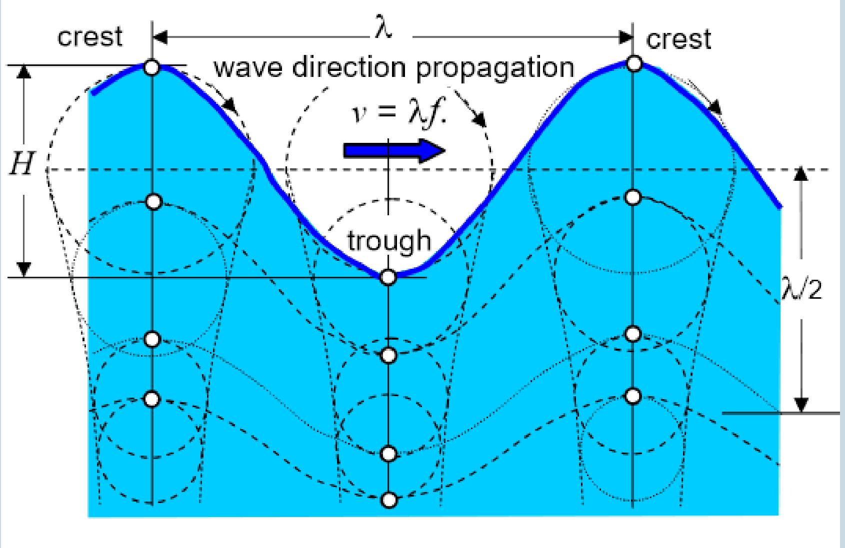
Wave energy potential



- Wave energy calculation

$$P_{Wdeep}\ (\frac{W}{m}) = E(J/m^2) * C_g(m/sec) = \sim \frac{1}{16}\rho g H^2 * \frac{gT}{4\pi} = \frac{\rho g^2 T H^2}{64\pi} = \sim 0.42 H^2 T\ [kW/m]$$

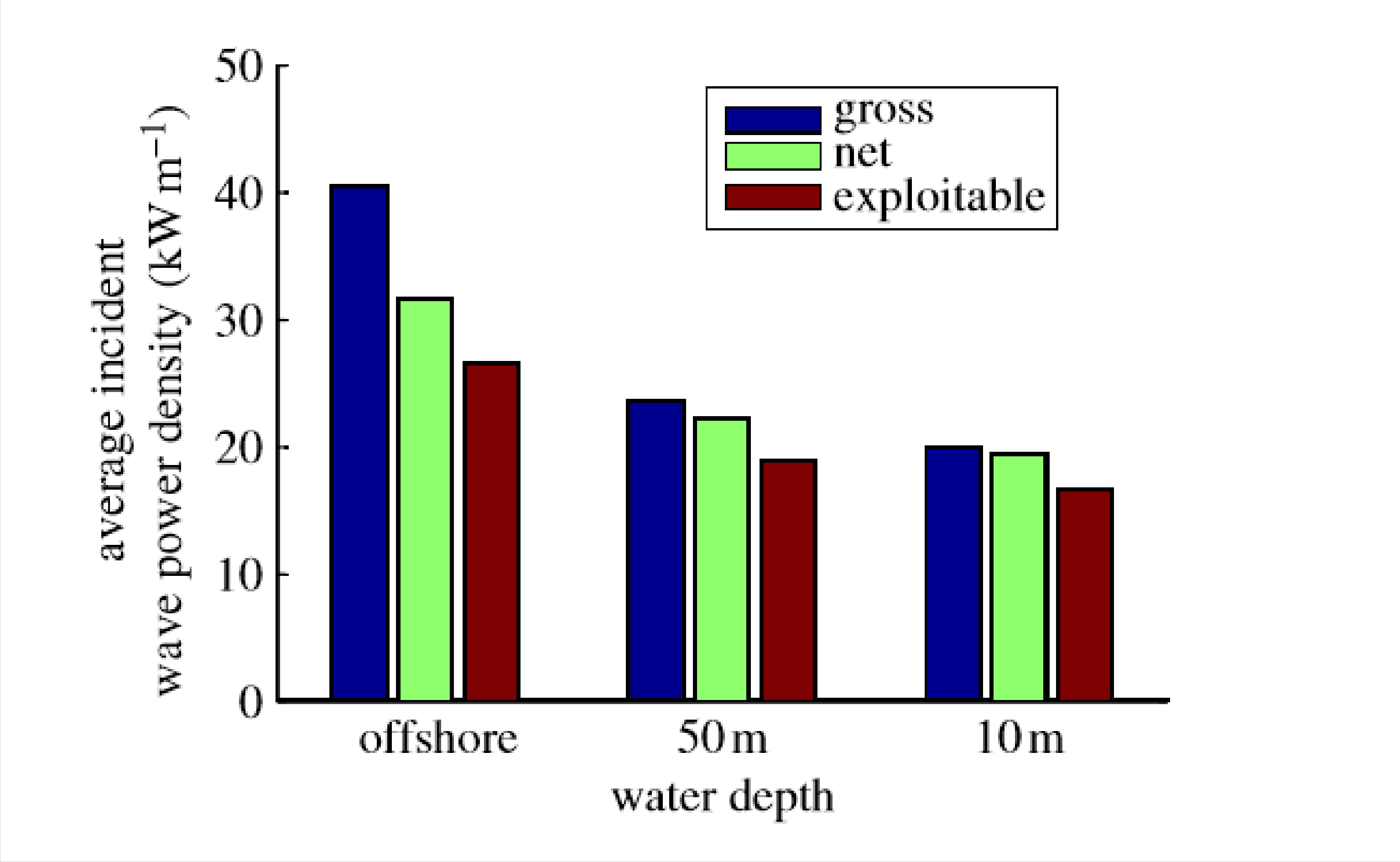
$$P_{Wshallow} = \frac{P}{b} = E(J/m^2) * C_g(m/sec) = \sim \frac{1}{16}\rho g H^2 * gd$$



P_W - wave energy flux in watts per meter of crest length,
b- front wave;
H- wave height, from crest to trough (m);
T- the period of wave (sec);
g- the acceleration of gravity ($9.81 m/s^2$);
ρ- the mass density of sea water ($1025\ kg/m^3$);
d- water depth.

I. L. Christensen, E.Friis-Madsen, K.Jens Peter, “The Wave Energy challenge”, Aalborg University, Denmark 2005
II. L. Rodrigues, “Wave power conversion systems for electrical energy production”, Portugal, 2008
III. E. Rusu, “Evaluation of the Wave Energy Conversion Efficiency in Various Coastal Environments”, Engineers ISSN, Romania, 2014

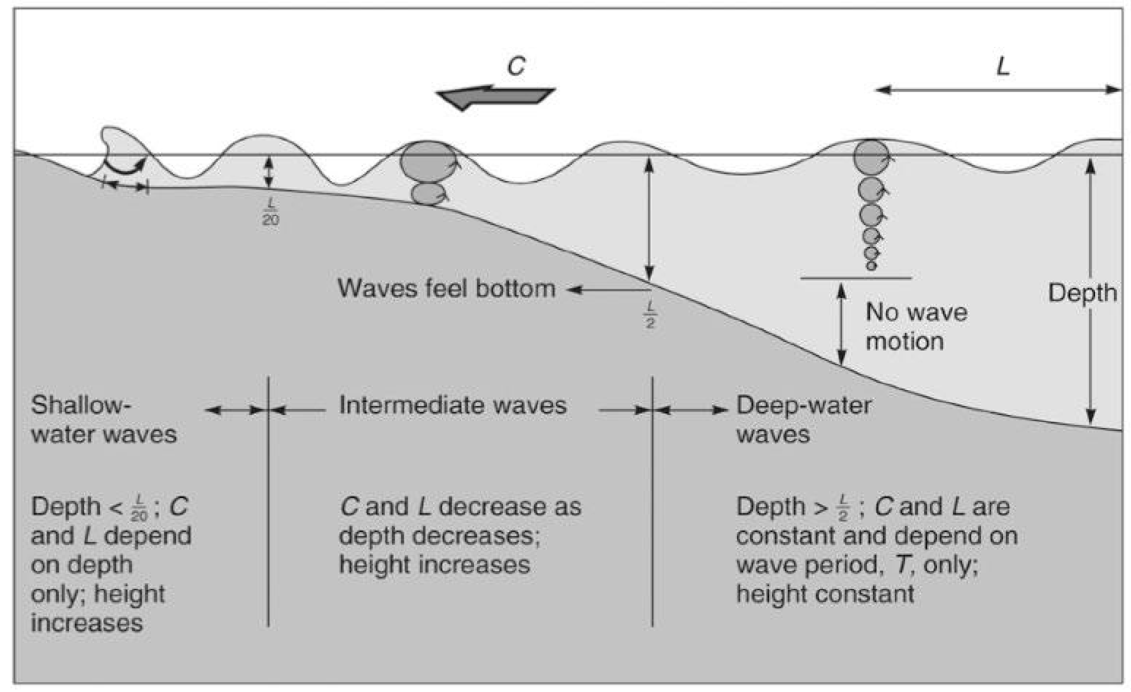
Wave energy potential



I. Waves, Krauss Chapter Nine
II. "World Energy Resources Marine Energy," World Energy Council, 2016
III. Lopez, J. Andreu, S. Ceballos, I. Martinez ,I. Kortabarria, "Review of wave energy technologies and the necessary power-equipment," Elsevier, Derio, 2013
IV. T. WHITTAKER, M.FOLLE, "Nearshore oscillating wave surge converters and the development of Oyster ", Queen's University Belfast, Belfast, UK, 2011

WEC location

- Shoreline devices.
- Near-shore devices, few meters from the shore, 10-20 meter deep.
- Offshore devices, far from the shore, >50 meter deep.



I. “World Energy Resources Marine Energy,” World Energy Council, 2016
II. Lopez, J. Andreu, S. Ceballos, I. Martinez ,I. Kortabarria, “Review of wave energy technologies and the necessary power-equipment,” Elsevier, Derio, 2013
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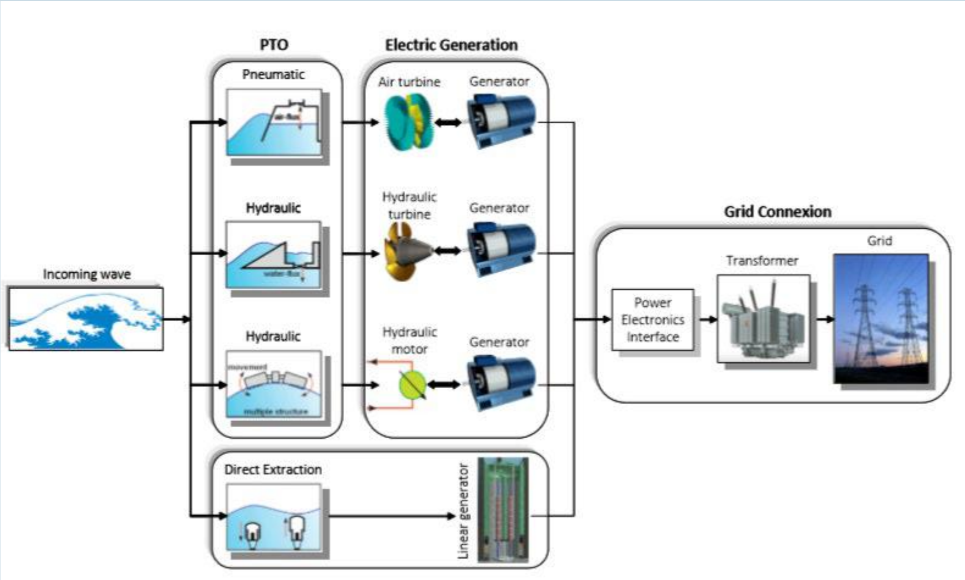
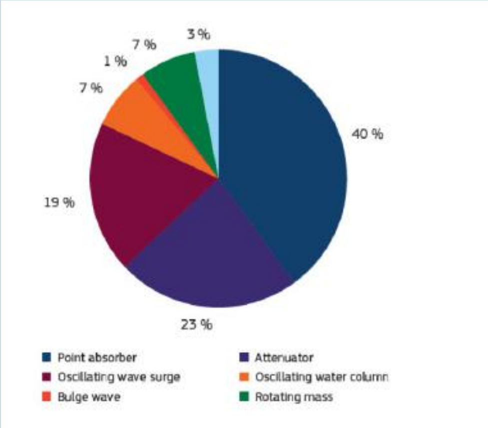
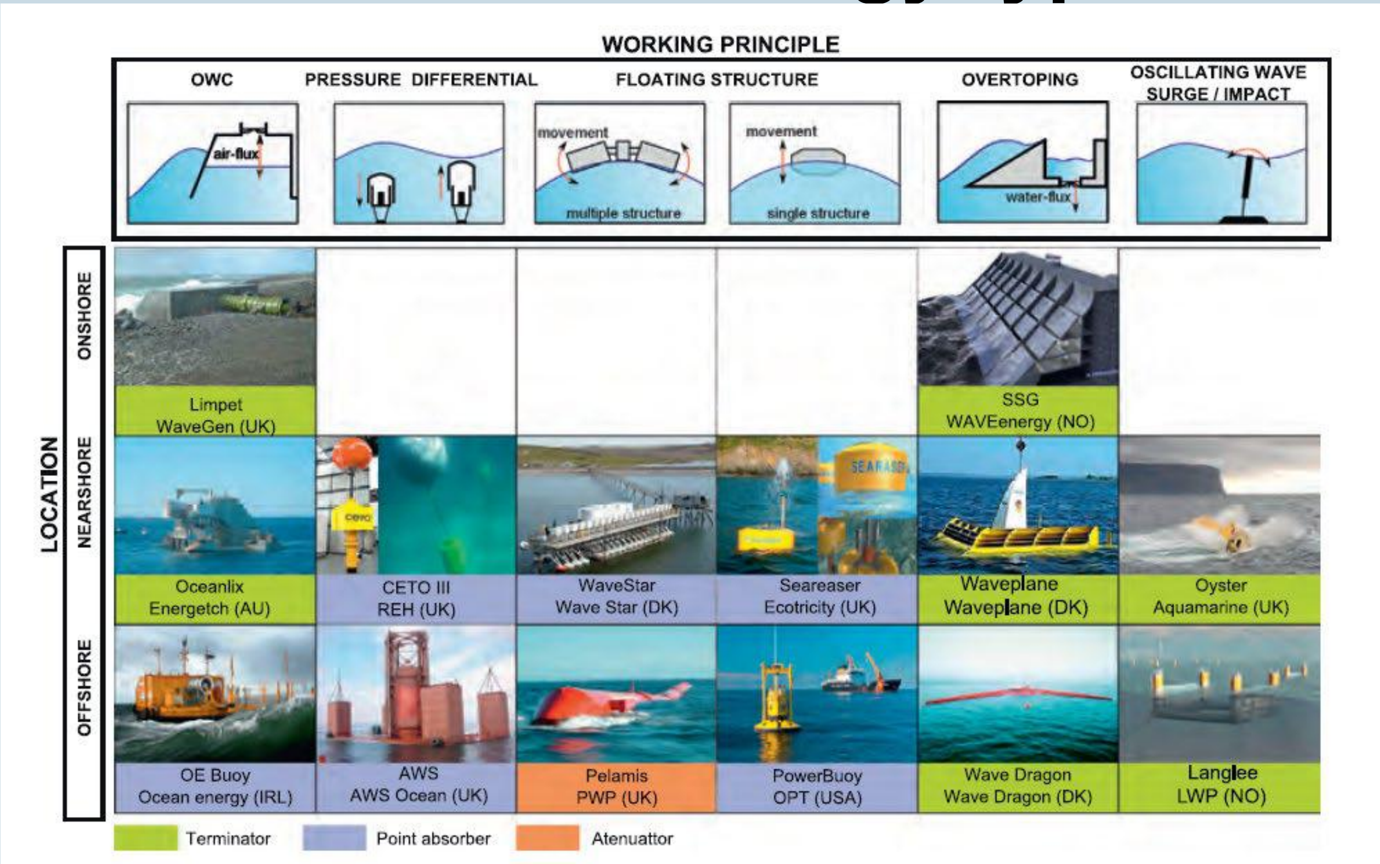
Distribution according to the wave technology type

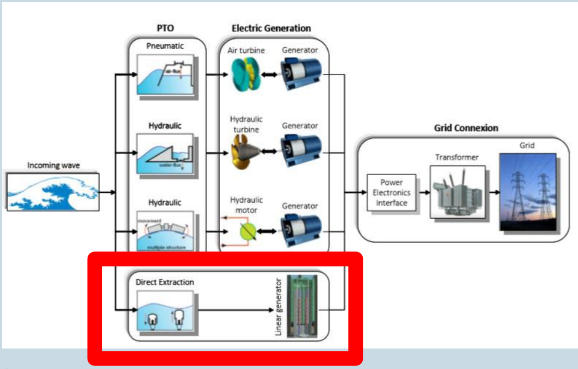


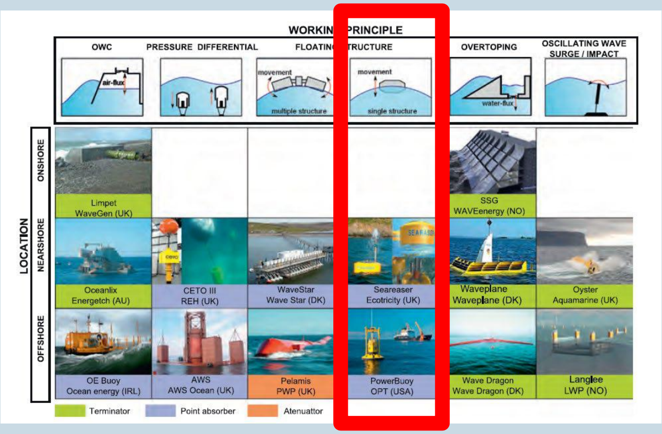




I. World Energy Resources Marine Energy," World Energy Council, 2016
II. Lopez, J. Andreu, S. Ceballos, I. Martinez ,I. Kortabarria, "Review of wave energy technologies and the necessary power-equipment," Elsevier, Derio, 2013

WEC technologies



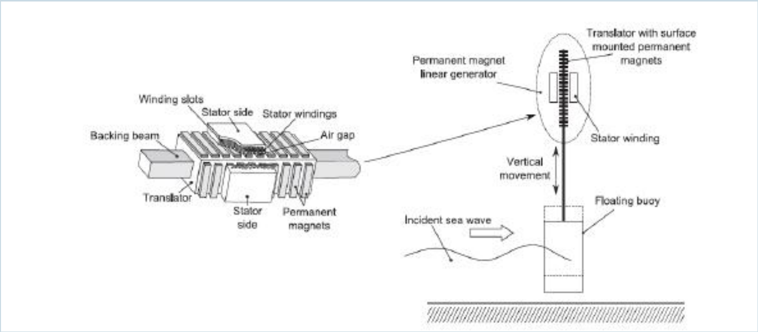


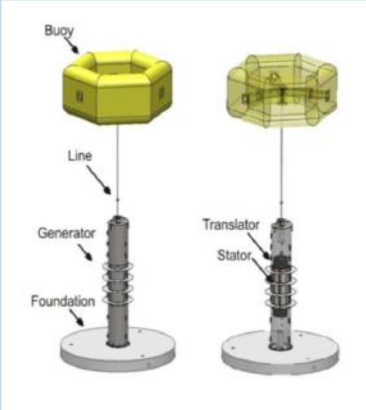
- **Point absorber**
  - Near shore, floating offshore.
  - Can be either moored to the seabed or installed on the seabed through a large foundation mass.
  - Non-directional device, its performance is not affected by wave directionality.
  - Transmit mechanical motion to electricity.
  - Point absorbers are normally smaller in dimension compared to other WECs.
  - One unit can deliver a limited amount.
  - Several units need to be deployed to achieve a required installed capacity.

I. "World Energy Resources Marine Energy," World Energy Council, 2016
II. http://aquaenergygroup.com.au/

Point absorber-AquabuOY - Sotenäs wave power project

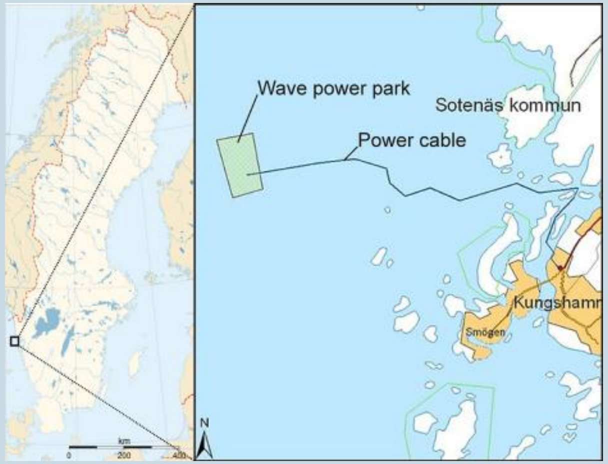
- Linear generators power take off (PTO), deployed on the sea bed.
- Buoy placed on the surface connected to the translator via a steel wire, which captures the energy in the motion of the waves.
- A stator with windings and a translator with permanent magnets constitute the two main parts of the generator.
- The buoy drags the translator inside the generator, and voltage is induced in the stator windings.
- The WECs are connected to marine substations, from where an alternating current can be transmitted directly to the onshore grid.





I. https://www.seabased.com/the-technology
II. http://www.seafaradays.net.in/energy/technology
III. M. Angeliki, I. Dolguntseva, M. Leijon ,"Offshore Deployments ofWave Energy Converters by Seabased Industry AB “, Marine Science and Engineering, MDPI, Sweden, 2017

Point absorber-AquabuOY - Sotenäs wave power project

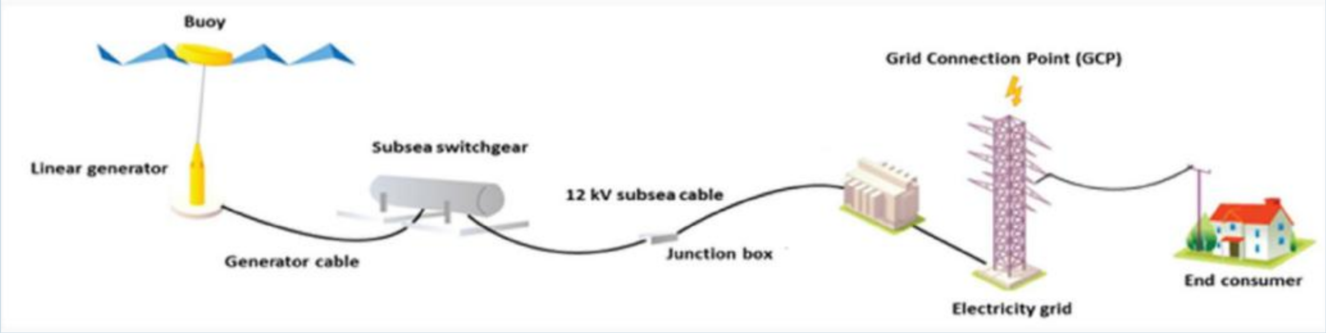


- **Point absorber**
  - **Linear generators, point absorbers (buoys).**
  - The Sotenäs project was a cooperation between Seabased, Fortum, and the Swedish Energy Agency.
  - Location: Skagerrak, North Sea, Swedish waters outside the municipality of Sotenäs, at approximately 50 m depth (offshore device).
  - The installations started in 2012 and was completed in 2015.
  - The world’s largest of its kind.
  - In January 2016 generated electrical power to the Swedish power grid for the first time.

I. https://www.seabased.com/the-technology
II. http://www.seafaradays.net.in/energy/technology
III. M. Angeliki, I. Dolguntseva, M. Leijon ,"Offshore Deployments ofWave Energy Converters by Seabased Industry AB “, Marine Science and Engineering, MDPI, Sweden, 2017

Point absorber-AquabuOY - Sotenäs wave power project

- Project scale: commercial.
- Power 3 phase generation capacity of 1 MW with 36 WEC units (30kW per unit).
- Subsea generator switchgear station: weight 120 ton was deployed.
- Core Height :6m.
- Translator mass: ~10 tones.
- Subsea generator Connected to grid via a 10 km subsea cable.
- Permit for operation is 20 years.
- The electricity cost production is ~10 cents per kWh (0.4 shekel per kWh).



I. https://www.seabased.com/the-technology
II. http://www.seafaradays.net.in/energy/technology
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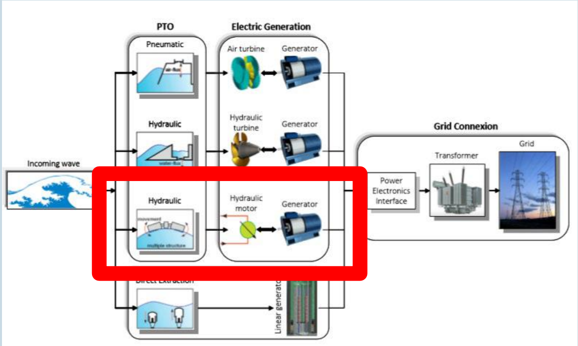
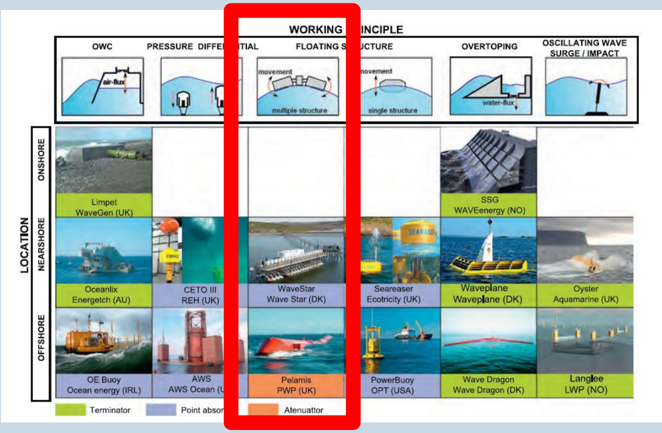
WEC technologies





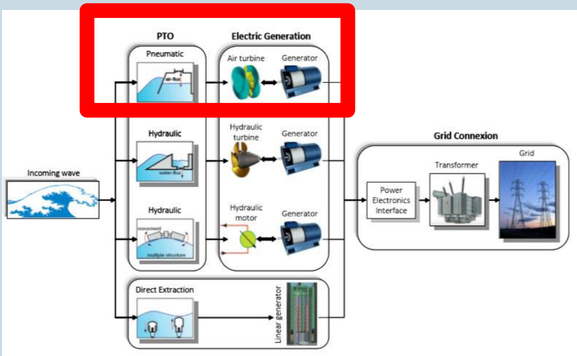
- **Attenuator**
  - Near shore and offshore.
  - Long structures compared with the wave length.
  - Placed in parallel with respect to the wave direction.
  - Attenuators are composed by a series of cylindrical sections linked together by flexible hinged joints that allow these individual sections to rotate relative to each other.
  - The wave-induced motion of the sections is resisted by hydraulic cylinders which pump high pressure oil through hydraulic motors via smoothing hydraulic accumulators. The hydraulic motors drive electrical generator to produce electricity.

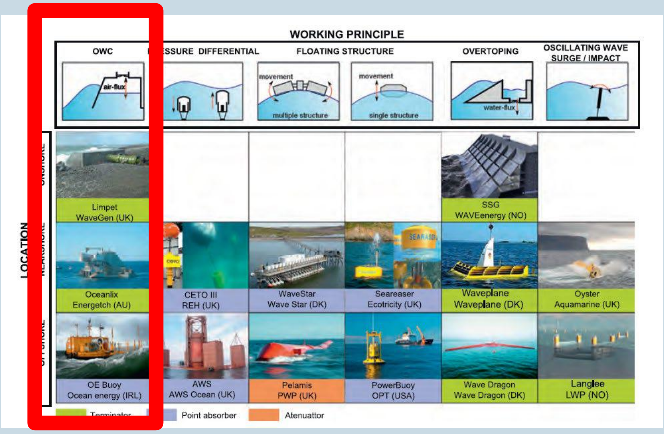
I. The Pelamis Prototype machine at EMEC, Orkney, Scotland, 2007
II. "World Energy Resources Marine Energy", World Energy Council, 2016
III. I. Lopez, J. Andreu, S. Ceballos, I. Martinez ,I. Kortabarria, “Review of wave energy technologies and the necessary power-equipment,” Elsevier, Derio, 2013

WEC technologies

- **Attenuator- ”Pelamis prototype”**
  - First offshore wave machine - generated electricity into the UK grid in 2004.
  - The project cost ~1 million Euro.
  - Water depth: >50, 5-10 kilometer from shore.
  - 4 hydraulic rams (2 heavy and 2 sway).
  - Dimension (Length/Diameter):150m/3.5m.
  - Installed Capacity: 750 kW.

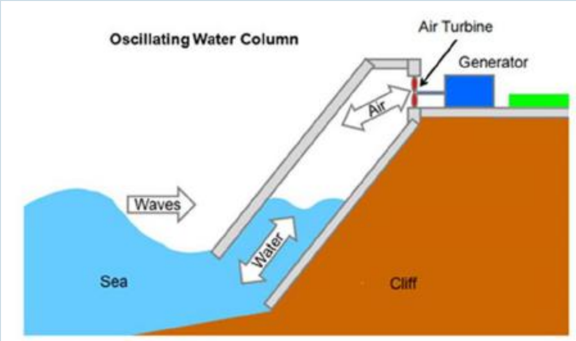
I. The Pelamis Prototype machine at EMEC, Orkney, Scotland, 2007 (http://www.emec.org.uk/about-us/wave-clients/pelamis-wave-power/)
II. "World Energy Resources Marine Energy”, World Energy Council, 2016
III. I. Lopez, J. Andreu, S. Ceballos, I. Martinez ,I. Kortabarria, “Review of wave energy technologies and the necessary power-equipment,” Elsevier, Derio, 2013





WEC technologies

- **Oscillating water columns (OWC)**
  - Onshore ,near shore and offshore.
  - OWCs are one of the first types of WEC developed.
  - OWC use the oscillatory motion of a mass of water induced by a wave in a chamber to compress air to drive an air turbine.
  - The amount of water moves between the two chambers, pushes the same amount of air, the air moves through the air turbine, and the air turbine drives an electric generator that generates electric power.



I. "World Energy Resources Marine Energy," World Energy Council, 2016
II. O.RKim, M.Lee, C.Shin, Y.cho, J.Park, "Anovel Wave Energy Harvesting System for Ocean Sensor Network Application", Suncheonoy, H. National University, Suncheon, 2016

WEC technologies

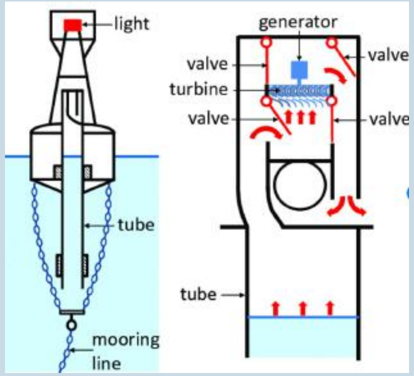
- **Oscillating water columns (OWC) - Limpet**
  - Constructed in the UK Island of Islay, Scotland by Limpet company.
  - Opened in 2011.
  - 2 air turbines, each 250kW.
  - Installed Capacity: 500kW.

I. B. Cuan, J.T.Trevor, M. Folley, H.Ellen, "Overview and Initial Operational Experience of the LIMPET Wave Energy Plant", Queens University Belfast, Northern Ireland, 2002

II. RKim, M.Lee, C.Shin, Y.cho, J.Park, "Anovel Wave Energy Harvesting System for Ocean Sensor Network Application", Suncheonoy, H. National University, Suncheon, 2016

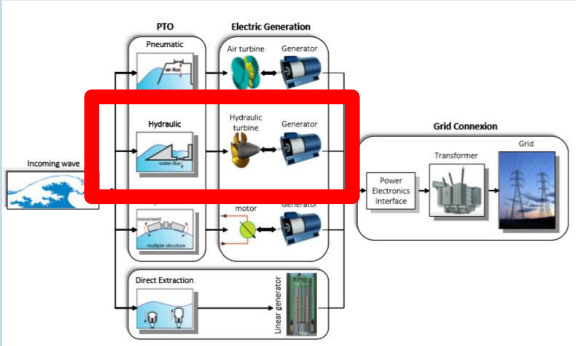
WEC technologies

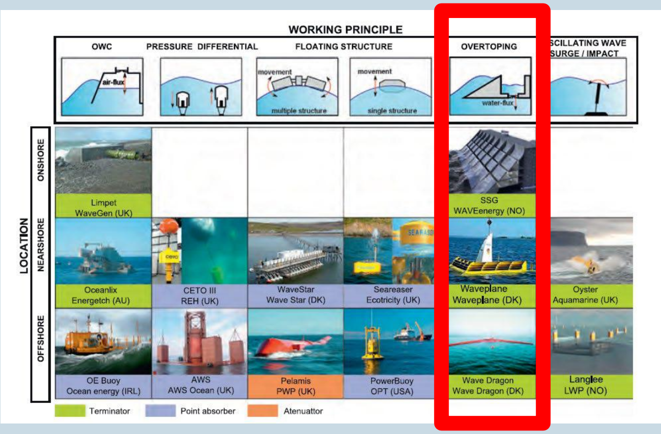
- **Oscillating water columns (OWC) - OE Buoy**
  - Currently under development by Ocean Energy.
  - Was tasted in Scotland by OE Buoy, in 2016.
  - Survived over 3 years in the ocean.
  - 21-24 m water depth, survived 8 m wave.
  - Installed Capacity: 500 MW.



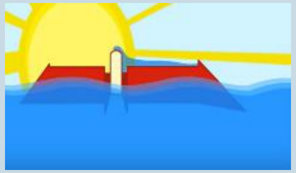
I. B. Cuan, J.T.Trevor, M. Folley, H.Ellen, "Overview and Initial Operational Experience of the LIMPET Wave Energy Plant", Queens University Belfast, Northern Ireland, 2002
II. RKim, M.Lee, C.Shin, Y.cho, J.Park, "Anovel Wave Energy Harvesting System for Ocean Sensor Network Application", Suncheonoy, H. National University, Suncheon, 2016
III. http://www.oceanenergy.ie/gallery#&gid=1&pid=6

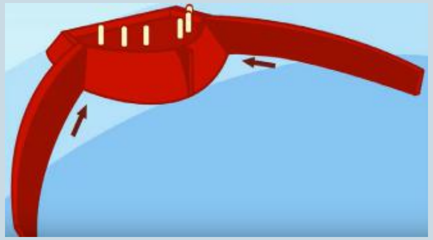
WEC technologies





- **Overtopping devices- Terminator**
  - Onshore, near shore, floating offshore.
  - Overtopping devices or terminator WECs convert wave energy into potential energy.
  - Placed perpendicular to the predominant direction of wave propagation and, in essence, “terminate” the wave action.
  - The heart of the unit is a large floating reservoir. Two reflector wings concentrate the power of oncoming waves, which pass up a curved ramp and into the reservoir.
  - The water returns back to the sea through a battery of number of low-head hydro turbines for converting the pressure head into power.





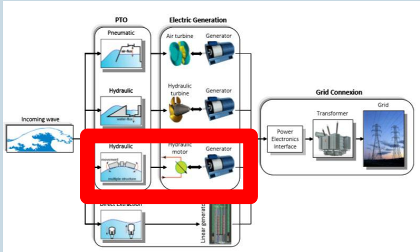
I. "World Energy Resources Marine Energy", World Energy Council, 2016
II. Lopez, J. Andreu, S. Ceballos, I. Martinez ,I. Kortabarria, “Review of wave energy technologies and the necessary power-equipment,” Elsevier, Derio, 2013

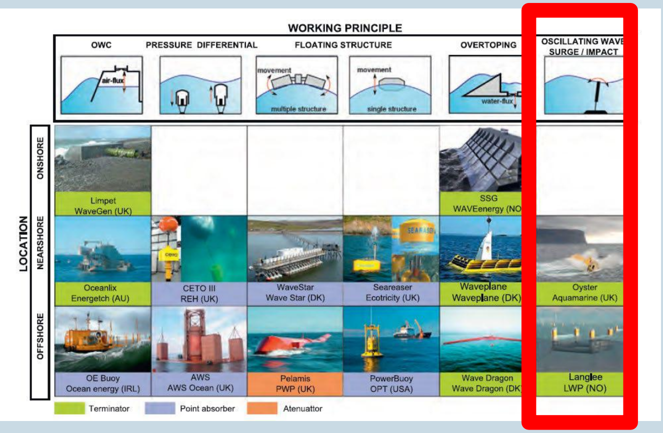
WEC technologies

- **Overtopping devices- Terminator -Dragon**
  - First world offshore WEC.
  - Wave Dragon is the largest known wave energy converter known today.
  - It generated electricity into the Denmark grid in 2003 (during more than 20,000 hours -~2.5 years, a world record).
  - Installed capacity: ~4-7 MW.
  - The project cost 4.3 million Euro.
  - Weight: 237 tons.

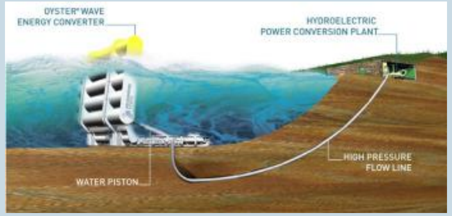
I. The Wave Dragon, Denmark, 2003
II. L. Christensen, E.Friis-Madsen, K.Jens Peter, “The Wave Energy challenge”, Aalborg University, Denmark 2005

WEC technologies





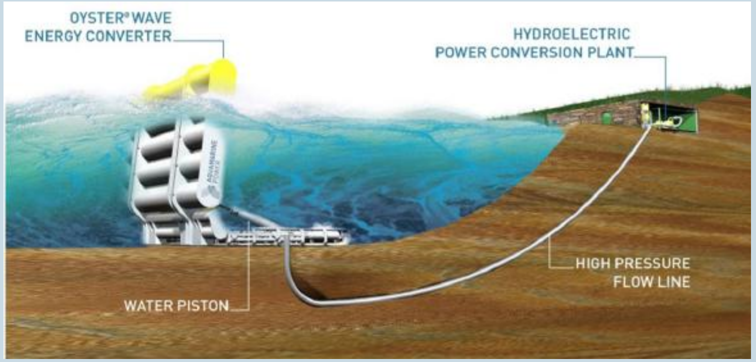
- **Oscillating wave surge converter (OWSC)**
  - Near shore.
  - Oscillating wave surge converters exploit the surging motion of near-shore waves to induce the oscillatory motion of a flap in a horizontal direction.
  - This flap, which is almost entirely underwater, moves backwards and forwards in the near-shore waves.
  - The movement of the flap drives hydraulic pistons which push high pressure water through a pipeline onshore to drive a conventional hydroelectric turbine where it is converted to electrical power.
  - Prototypes of floating OWSC (Bottom-mounted devices-offshore) are already under development.



I. "World Energy Resources Marine Energy," World Energy Council, 2016
II. T. WHITTAKER, M.FOLLE, "Nearshore oscillating wave surge converters and the development of Oyster ", Queen's University Belfast, Belfast, UK, 2011
III. http://www.emec.org.uk/about-us/wave-clients/aquamarine-power/

WEC technologies

- **Oscillating wave surge converter (OWSC) - Oyster1**
  - The first OWSC prototype, Oyster1, was installed by Aquamarine Power, in 2009, at the European Marine Energy Centre (EMEC) in Orkney, Island.
  - In August 2009, this device became the first grid-connected electrical power generation from a near-shore wave energy device in the world.
  - Located 0.5 km from shore in 12 to 20m water depth.
  - Successfully operated for about 6000 hours (during 2 years).
  - Installed Capacity: 350 kW.



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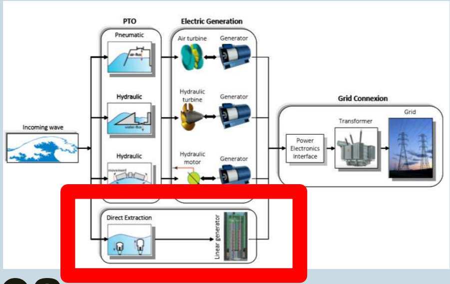
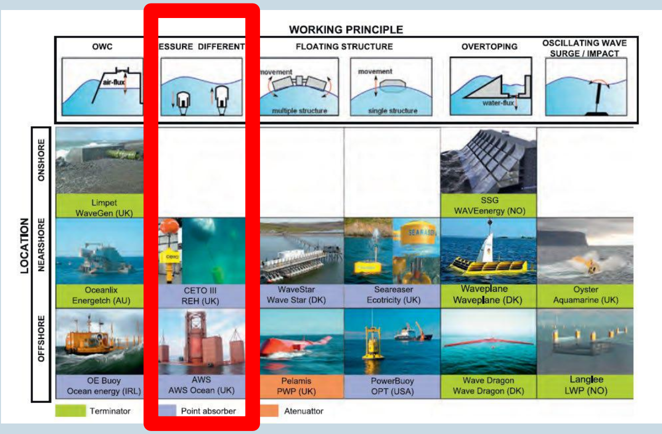
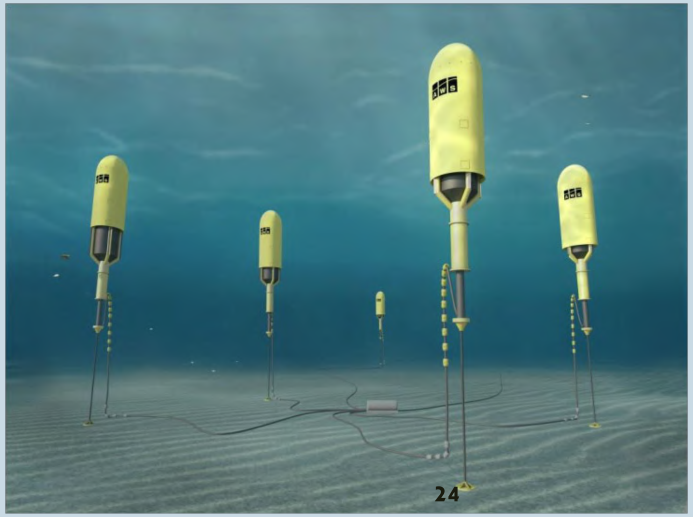




WEC technologies

- **Submerged pressure differential devices**
  - Near shore and offshore.
  - Fully submerged devices, on the seafloor.
  - Archimedes wave swing.
  - The wave swing reacts to changes in sub-sea water pressure caused by passing waves and converts the resulting motion to electricity via a direct-drive generator.
  - Can be configured for ratings between 25kW and 250kW by selecting the appropriate scale.
  - The technology was tested offshore Portugal in 2004.



I. "World Energy Resources Marine Energy," World Energy Council, 2016
II. http://www.awsocean.com/archimedes-waveswing.html

Advantages

- Worldwide potential (~30,000 TWh/y from waves).
- Renewable and reliable.
- Predictable more then other alternative (renewable) energy sources.
- Stable source: wave power devices can generate power up to 90 percent of the time, compared to ∼20–30 percent for wind and solar power devices.
- Accessible source (about 40% of the world population live within 100 km of the shore).
- Highest surface energy density among renewable energy sources: ~2-3 kW/m^2 compared to wind (~0.4-0.7 W/m^2) or solar(~0.1-0.2 kW/m^2).
- Good scalability (ways and sizes to gather the wave energy).

I. "World Energy Resources Marine Energy," World Energy Council, 2016
II. R.WATERS, "Energy from Ocean Waves", Uppsala University, 2008

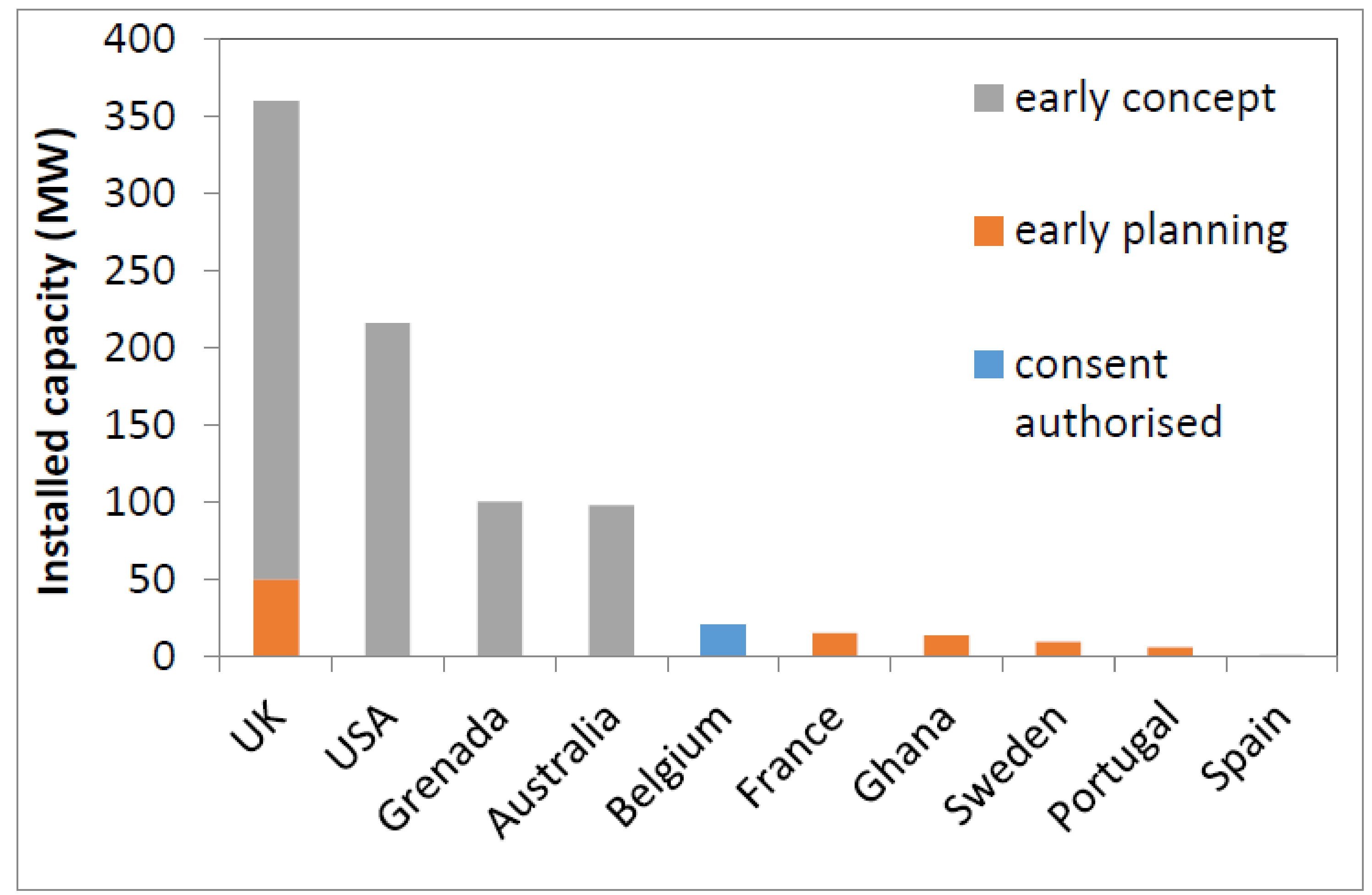
Disadvantages

- Currently high cost of investment.
- Slow technology improvements.
- Weak performance in extreme environmental condition.
- Difficult to transmit wave energy
  - Low wave frequency.
  - Wave height and cycle change.
  - Variable wave direction - off shore.
- Maintenance and weather effects - off shore.
- Noise and visual pollution.
- Negative environmental impact.

Future challenges for WEC

- High survivability and availability.
- Materials development.
- Low operation and manufacturing costs.
- Unit scalability.
- Construction and installation costs.
- Transmission costs and losses.

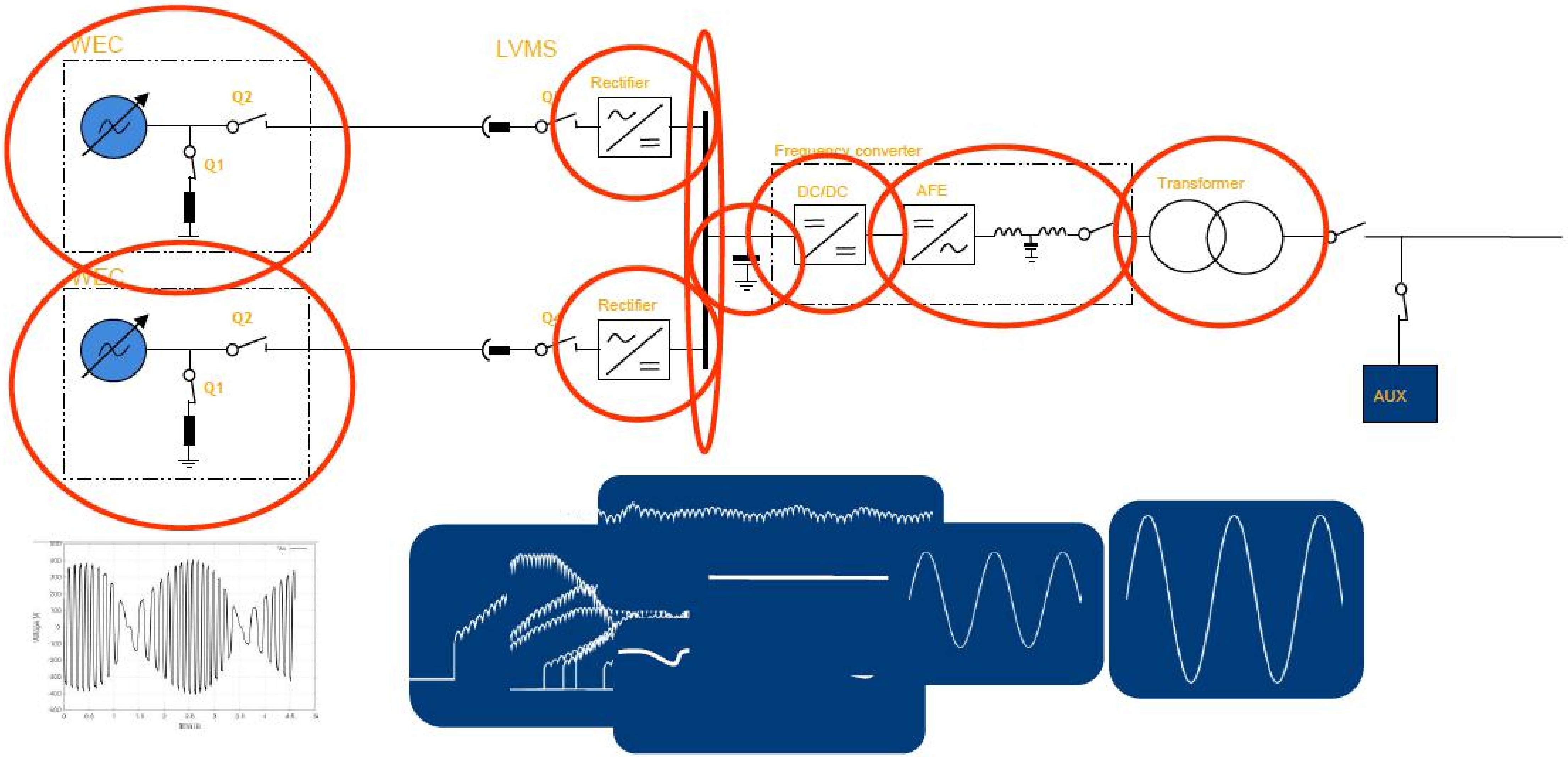
World WEC installation capacity- present and future



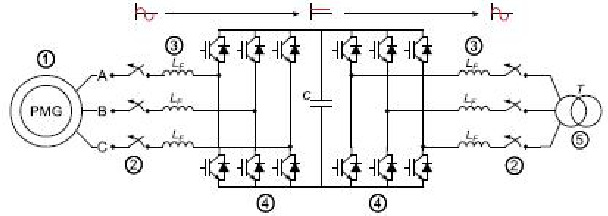
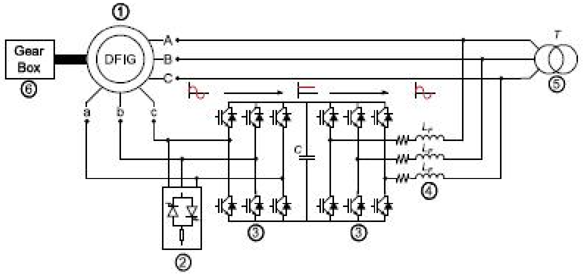
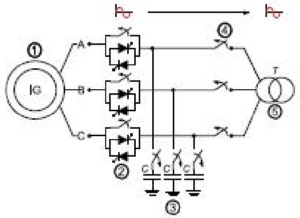
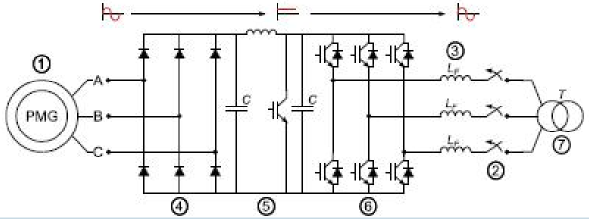
I. "World Energy Resources Marine Energy," World Energy Council, 2016

II. Lopez, J. Andreu, S. Ceballos, I. Martinez ,I. Kortabarria, "Review of wave energy technologies and the necessary power-equipment," Elsevier, Derio, 2013

Thank you for your attention

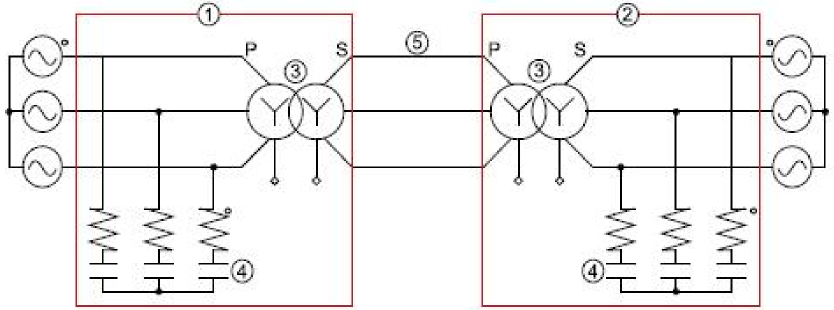
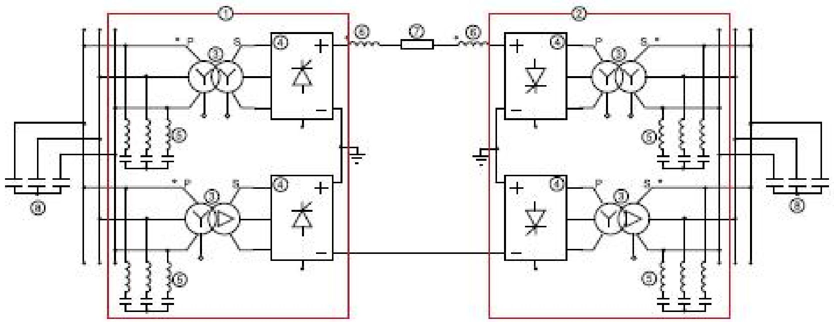
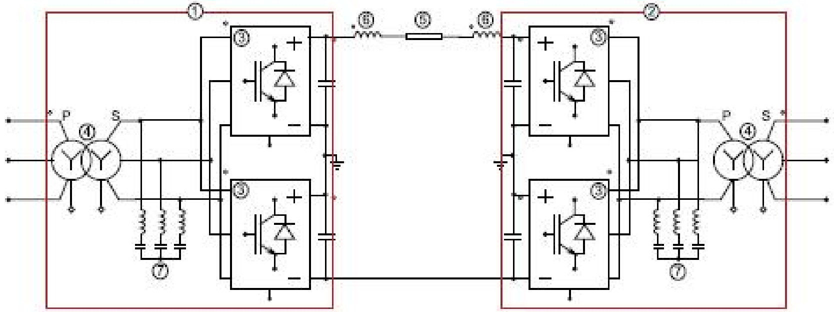

WEC
Q2
Q1
WEC
Q2
Q1
LVMS
Rectifier
Rectifier
Frequency converter
DC/DC
AFE
Transformer
AUX

Conversion topology

	Topology	Description
(a)		① Permanent magnet generator: rotatory or linear ② Main switches ③ Input and output filters ④ Input controller rectifier and output controller inverter in back-to-back configuration ⑤ Step-up transformer
(b)		① Double fed induction generator ② Crowbar ③ Input rectifier and output inverter in back-to-back configuration ④ Output filter ⑤ Step-up transformer ⑥ Gear box
(c)*		① Induction rotatory generator ② Soft start system ③ Reactive compensator ④ Main switches ⑤ Step-up transformer
(d)		① Permanent magnet generator: rotatory or linear ② Main switches ③ Output filters ④ Input uncontrolled rectifier; diode bridge rectifier ⑤ Shunt ⑥ Controller inverter ⑦ Step-up transformer

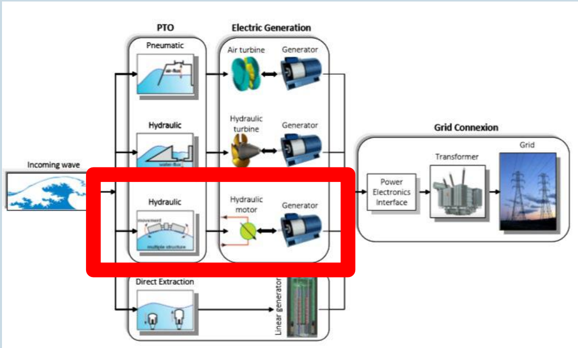
I. Lopez, J. Andreu, S. Ceballos, I. Martinez ,I. Kortabarria, “Review of wave energy technologies and the necessary power-equipment,” Elsevier, Derio, 2013

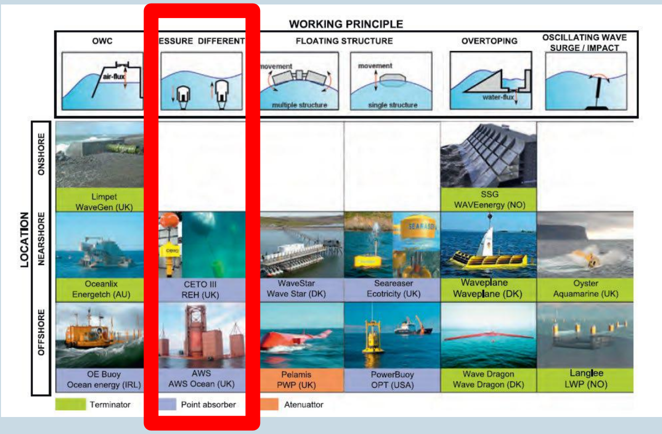
Transmission topology

Transmission topologies	Description
	① Offshore substation ② Onshore substation ③ AC transformers ④ Reactive compensation bank ⑤ AC submarine cables
	① Offshore substation ② Onshore substation ③ AC transformers ④ Converters ⑤ AC filters ⑥ DC filters ⑦ Filtering reactance ⑧ Reactive compensation bank
	① Offshore substation ② Onshore substation ③ HVDC VSC converters ④ Transformers ⑤ Filtering reactance ⑥ DC filters ⑦ AC filters

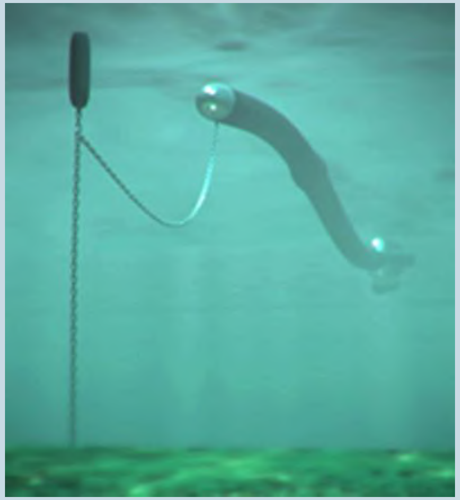
I. Lopez, J. Andreu, S. Ceballos, I. Martinez ,I. Kortabarria, “Review of wave energy technologies and the necessary power-equipment,” Elsevier, Derio, 2013

WEC technologies



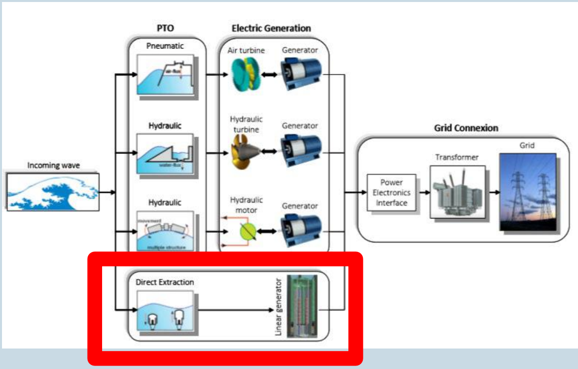


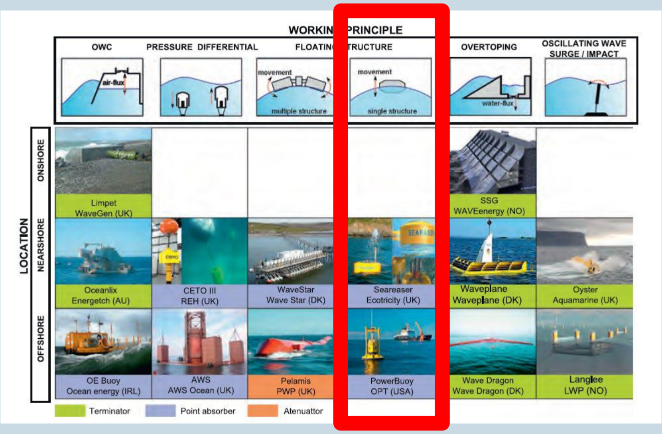
- **Bulge wave devices**
  - Offshore- deep water.
  - The “Anaconda” tube is designed to be anchored just below the sea’s surface, with one of its ends facing the oncoming waves.
  - Large distensible tube, made of rubber, closed at both ends and filled with water.
  - As the bulge wave travels within the device it increases in size and speed.
  - The kinetic energy of the bulge is used to drive a turbine at the end of the tube.
  - “Anaconda” wave powered device was invented in UK.



I. http://www.energy.soton.ac.uk/anaconda-wave-energy-converter-concept

WEC technologies





- **Rotating mass converters**
  - Offshore, deep water.
  - Rotating mass wave energy converters use the motion of the waves to spin a rotating mass, creating mechanical energy.
  - The rotating mass creates power through a electrical generator.
  - An example of this device is the Penguin by Wello, Orkney, Scotland.
  - Installed Capacity: 500 kW.

I. https://tethys.pnnl.gov/annex-iv-sites/wello-penguin-emec
II. Lopez, J. Andreu, S. Ceballos, I. Martinez ,I. Kortabarria, “Review of wave energy technologies and the necessary power-equipment,” Elsevier, Derio, 2013
III. http://www.emec.org.uk/about-us/wave-clients/wello-oy/