"Small is beautiful” - but will small WECs ever become commercial?

Article *in* Transaction of the International Conference on Endodontics. International Conference on Endodontics · June 2018

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Abstract
This paper presents a short overview of the development of wave energy converters (WECs) since the 1970s where the oil crises raised the interest in renewable power generation.
The "small is beautiful" motto is dealt with and dismissed when regarding the commercial viability of utility scale WEC power plants. The potential future developmental pathway towards commercialisation of wave energy is compared to the development of the Danish wind mill sector where the first series production of 22 kW started in 1978 – four years after Prof. Stephen Salter presented his MW sized so called Duck.
The paper discusses the capital expenditure CAPEX and operation and maintenance costs (OPEX) for small and large WECs seen over the WEC lifetime and the resulting levelized cost of energy (LCOE) for power plant size wave energy parks. The following statement is taken from the 2014 JRC Ocean Energy Status Report [8]:
"Maintenance: small-scale devices are associated with reduced maintenance, since they are designed to operate in farms and a defect to one unit may not affect the overall array performance, hence reducing the time necessary for maintenance."
The paper explains why this is a false statement - maintenance costs will inevitably decrease with increasing WEC size.
The paper also justifies that large WECs can obtain relatively low CAPEX and OPEX compared to small WECs, and that large WECs can be expected to match the LCOE for floating wind turbines. Combined offshore wave-wind power plants can be expected to deliver lower LCOE than pure wave or wind parks.

Keywords WEC-types, WEC-sizes, utility size WEC power plants, multi-use platforms.

I. INTRODUCTION

The development of any technology is almost never a smooth or even direct path; some take far longer to realise than others. The design for a human carrying helicopter was theorised in the 1480's by Da Vinci but it was not until 1907 that such a device actually lifted a pilot off the ground. The first windmills were constructed around 1500 years ago, and electrical power was produced by wind turbines 130 years ago. The development of the commercial Danish type horizontal-axis 3-bladed wind turbine was kick started by the oil crisis in the early 1970s with series production of 22 kW windmills. The World's first offshore wind park with 11 units and a total capacity of 5 MW was inaugurated in Denmark less than 20 years later. The plant was in operation for 25 years and was finally decommissioned last year. The upscaling of the Danish wind turbine has continued with the same speed and todays offshore turbines, in Europe, have now a power of more than 6 MW. The reason for this rapid upscaling of offshore wind turbines is primarily the reduction of balance of plant costs on a MW basis, with potential to lower OPEX.

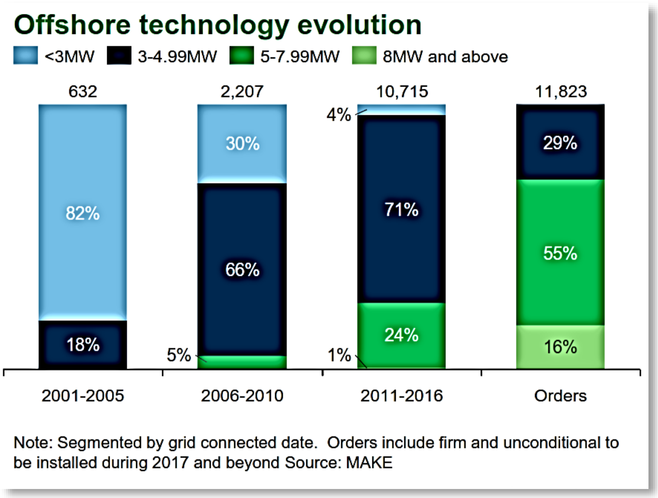


Figure 1 : Development of offshore wind turbine sizes

Between the early 1940s and the 1970s MW size turbines were constructed in many countries without success. The commercial success of the Danish stepwise and bottom up development of wind turbine sizes is therefore generally recognised as the way to do this kind of technical development.

The history of wave energy converters is much shorter than the wind energy history but goes at least back to the 19th century. Small navigation buoys powered by wave energy were produced in Japan since 1965. Then around the same time when the development of the modern wind turbine took off Professor Stephen Salter presented what was to be known as Salter's duck – a very efficient multi MW offshore device. Since then several large WEC types have been designed, but no floating MW size devices have been tested until now. A good description of the development of WECs in UK until 1999 can be found in "A brief review of Wave Energy" by T W Thorpe [1]

"Small is beautiful"

The "small is beautiful" motto has been heard from time to time ever since the first European Wave Energy Symposium in 1993 (Falnes J. pp. 367-372. 1994). It has however often been forgotten that this is only a valid statement regarding point absorbers, where the economic optimal size can only feed a few hundred kWs to the grid. Since then many point absorbers have been tested both in laboratories and at sea. Most of the proposed point absorbers have no on-board power storage which means that they deliver a highly fluctuating power production: The average production in the most common sea states is usually around 1/10 of the installed generator capacity – i.e. below 100 kW even for large point absorbers with diameters of 15 – 20 meters. This results in a rather low capacity factor in line with photovoltaics – i.e. around 1000 yearly full load hours.

Can the development of wind be copied to wave?

Even though a power plant size wave energy park of 100 MW will need many hundred large point absorbers it has been suggested that this is the best way forward for development of wave energy. World's first offshore wind park wasn't built before reliable turbines of 450 kW had been developed. This 5 MW park had around 2000 yearly full load hours. The primary reason why the Danish development of the modern wind turbine cannot be copied to the wave energy sector is however the fact that even the small 22 kW wind turbines with 5m wings could deliver reasonable revenue to their private owners. The commercialisation of the modern wind turbine had therefore a jump start. 30 years later we saw the same fast evolution happen for solar power. Such a route to commercialisation is obviously not open to wave power as sale of small-scale grid connected devices to private customers is not an option. So, when many ask why the development of wave power has taken so long, the first that comes to mind is that the public support to research and development of the sector has been - and still is - quite inadequate simply because the financial "valley of death" is much deeper and wider as was the case for wind.

II. WAVE ENERGY CONVERTER TYPES

The following figure by Falcão is generally recognised as a good categorisation of WEC types.

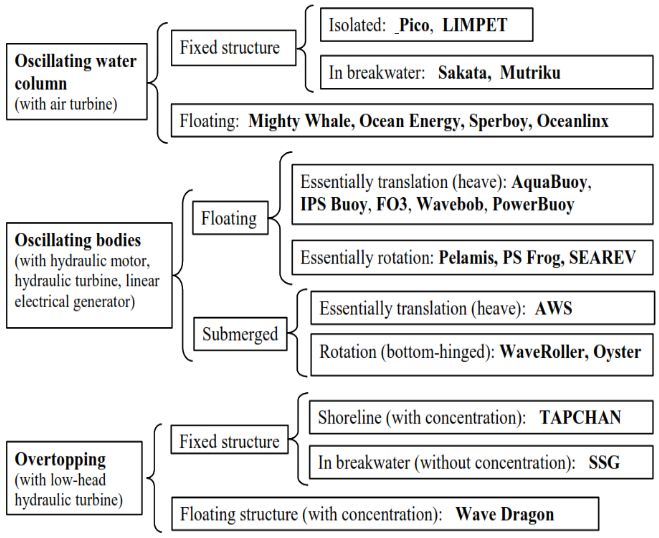


Figure 2: Various wave energy technologies [2]

The table below is an overview of the function of the most important WEC types.

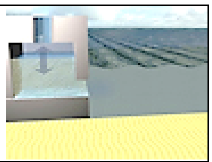
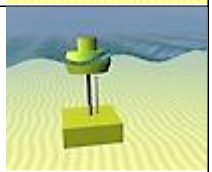
Oscillating water column technologies convert the rise and fall of waves into movements of air flowing past turbines to generate power. Examples: **Pico, Mutriku**	
Surface point absorbers are floating structures that can absorb energy from all directions. They convert the motion of the buoyant top relative to the base into electrical power. Examples: **Aquabuoy, PowerBouy**	
Attenuators are floating devices that are aligned perpendicular to the waves. These devices capture energy from the relative motion of the two arms as the wave passes them. Example: **Pelamis**	
Submerged pressure differential devices capture energy from pressure change as the wave moves over the top of the device causing it to rise and fall. Example: **AWS**	
Oscillating wave surge converters are near-surface collectors, mounted on an arm which pivots near the sea bed. The water particles in the waves cause the arm to oscillate and generate power. Example: **WaveRoller**	
Overtopping devices have a wall over which waves break into a storage reservoir which creates a head of water. The water is released back to the sea through a turbine to generate power. Example: **Wave Dragon**	

Table 1: Generic WEC descriptions and figures [3]

It has in addition been suggested to classify WECs as First, Second or Third generation systems, where onshore and nearshore oscillating water column are considered to be First Generation Systems. Near shore and offshore point absorbers are according to this terminology Second Generation Systems, and large-scale offshore devices are finally classified as Third Generation Systems [4]

The distance from shore of a wave energy parkis of course important as this has a major impact on the grid connection costs. The water depth is however much more important as this decides which WEC types to consider at a given site. Figure 3 is taken from the SI-Ocean project, and near shore is characterised by a water depth below 20m. Water depth between 20 and 50m can be labelled intermediate offshore, and water depth of more than 50m, deep offshore – even if the offshore oil industry defines deep offshore as more than 125m.

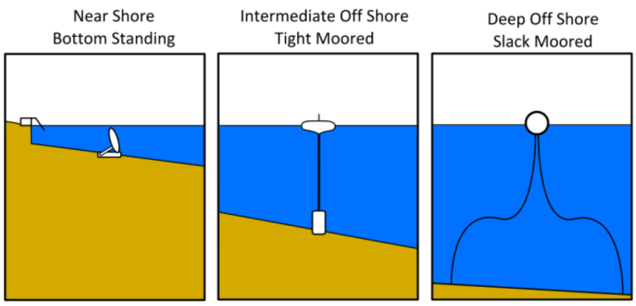


Figure 3: Mooring and Foundation Configurations for WECs [5]

In *"State of the art"* [5], *"State of the art analysis"* [6] and *"Overview of offshore wind and ocean energy technologies"* [7] most of the known and tested WECs are described.

The World's deep offshore areas with suitable wave climates for WEC deployment are much larger than the near shore and intermediate offshore areas. It has however been found that bottom standing devices can obtain quite high efficiencies. It is also an advantage that the relation between the max and average power of the waves is smaller in shallow waters. Thus, it has been claimed that bottom standing devices have the best possibility of becoming a viable technology. This is however not the case:

- The cost of land-based wind has fallen with a factor of five, from the 22kW turbine to today's 3-4 MW turbine. This is partly due to upscaling and partly due to mass production of standardised turbines. Neither upscaling nor mass production of bottom standing WECs are possible.
- The relative high possible efficiency for the flap type WECs is counteracted by the lower wave energy in shallow waters. The efficiency is also hampered by the variable water depth due to tides.
- If the proposed deployment site is close to land it can be very difficult to obtain a consent to install WECs – due to security issues, other use of area and/or environmental concern.
- It is true that the max wave power in storms is reduced in shallow waters, but tidal and storm generated water streams running along the coast can be strong. It is well known that scour around wind turbine piles often is a problem, and what can be even worse for bottom standing devices is moving sand dunes that can cover essential parts of a submerged device.
- Even if the max wave power in storms is reduced due to seabed friction, the forces caused by breaking waves can be much more devastating than the forces experienced at deep offshore sites. This is well known from construction work such as harbour building at exposed coasts.
- Last but not least it should be noticed, that it can be very difficult to do maintenance work on submerged devices as there can be strong water movements right down to the bottom in shallow waters.

Intermediate offshore devices have as an outset much better chances of success than near shore devices. There is however one serious problem facing development of wave energy at these water depths:

If the site is sufficiently far from shore and the wind resource at the site is good there will inevitably be a fierce competition with offshore wind - and wind is no doubt a winner technology. Combined wave- and wind parks may eventually turn out to be a viable solution at these depths.

III. COMMERCIAL SCALE WAVE ENERGY POWER PLANTS

Commercial offshore wave power plants will be of sizes comparable to wind turbine parks – both regarding area and power production. Today's wind parks often have a capacity of several hundred MW. It is therefore recommendable to consider wave energy parks to be of at least 100MW installed power in feasibility studies.

What types of offshore WECs, i.e. Third Generation Systems, can be expected to match floating wind turbines? The first floating wind farm, Hywind in Scotland, consisting of 5 turbines each of 6MW size was inaugurated in 2017. In the *"2014 JRC Ocean Energy Status Report"* [8], it is predicted that wave power parks made up of hundreds of small-scale devices is a viable solution - one of the reasons being:

"Maintenance: small-scale devices are associated with reduced maintenance, since they are designed to operate in farms and a defect to one unit may not affect the overall array performance, hence reducing the time necessary for maintenance."

This statement is clearly not valid, because the percentage of lost power production only depends on the frequency of defects no matter the size of the devices. Maintenance costs will without doubt decrease with increasing WEC size. It makes economic sense to equip large-scale WECs with more "redundancy" in the PTO system through advanced Supervisory Control And Data Acquisition (SCADA) and PLC or computer control systems with backup. In WECs with more PTO-systems operating in parallel, as is the case for overtoppers like Wave Dragon, a fault on one generator will have no influence on the produced power except in the highest sea states. Equally important regarding OPEX is the fact that the cost of transport to offshore parks and to access the individual WECs counts for a large part of the total OPEX. Large-scale WECs with multiple generators can be designed to allow for easy access even in sea states where it is too dangerous to access WECs like point absorbers where the structure moves in resonance with the waves. It should also be mentioned that it is all but prohibitive costly to maintain small-scale devices where essential parts of the PTO system are under water – or even at the sea bottom as have been seen in many proposed WECs.

Full scale testing

Only few full-scale test of grid connected WECs have been reported, and in addition it is very difficult to find results from testing in accordance with "standards" like *"Protocols for the Equitable Assessment of Marine Energy Converters"* [9], and the ongoing IEC standardization work. Regarding experiences and recommendations for the development of WECs, and equally important how markets and LCOE can be expected to develop, it is important to be familiar with www.ocean-energy-systems.org – and in particular the report *"Cost of Energy for Ocean Energy Technologies"* [10].

Recent Cost of Energy studies for wave

The report "*Cost of energy and Cost Reduction Opportunities"* [11], supplements [10] with relevant findings regarding array cost breakdown. The report states that CAPEX accounts from under half the LCOE for early arrays increasing to around 60% in the commercial stage. It is also important to notice that the estimated OPEX varies between 70 and 380 $/kW per year for the first commercial arrays.

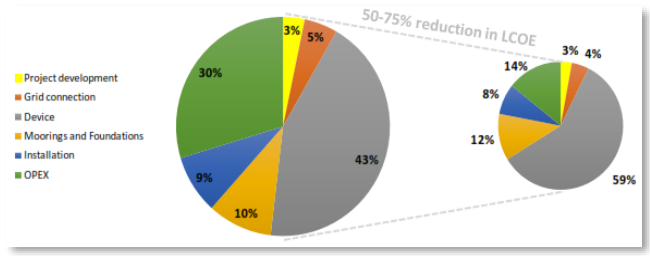


Figure 4: Breakdown of LCOE, early and commercial arrays [10]

The difference in OPEX for small-scale WEC power plants and large-type WEC power plants is significantly higher than the difference in CAPEX.

Yearly power production of small-scale devices

In the summary paper "Numerical estimation of energy delivery from a selection of wave energy converters" [12], the mean average output of a selection of 8 WECs is described. When looking at the annual mean power production for typical point absorbers of the heaving buoy type tight moored to the sea bed – the Seabased WEC is a good example - the paper justifies the good old rule of thumb saying that an average power of around 1 kW per m^3 of float volume is what can be hoped for with a small point absorber in wave climates between 20-30 kW/m. A fully submerged float as used in the CETO device would need to be more than 5 times larger i.e. a power of only 0.2 kW per m^3 of float volume.

Point absorbers are also characterised by the fact that the maximum instantaneous power is 10 to 30 times higher than the average absorbed power measured over an hour. This means that the PTO system in a medium sized power point absorber would need to handle an instantaneous power of several MW. In the paper it is recommended to limit the rated power of such a device to 5 times the average power by means of on-board energy storage components. The back drop of this is of course that there are power losses in such systems and they also increase the OPEX.

As mentioned in the introduction today's offshore wind turbines in Europe have a power of at least 6 MW. At most sites in northern Europe such turbines can at least deliver a yearly average power of 3 MW. Small-scale WECs like point absorbers with a diameter of 20 m – much larger than tested until now - can probably reach a capture width of 30%. In a 25 kW/m wave climate such a WEC will then deliver an average yearly power of 0.3 x 20 x 25 = 150 kW. This means that the small-scale WEC park would need to have 20 times as many devices as a wind park with 6 MW turbines to deliver the same yearly power production!

Balance of plant costs

It is generally acknowledged that CAPEX pr. installed MW can be much lower for parks made up from large-scale WECs than for parks of small-scale devices. This is primarily due to the reduced cost of the WECs, but it is also partly due to lower planning, mooring and deployment costs and substantial savings in inter array power cables.

The paper *"Impacts on the Electrical System Economics from Critical Design Factors of Wave Energy Converters and Arrays"* [13], delivers a good overview of how cabling cost varies in dependence of WEC size.

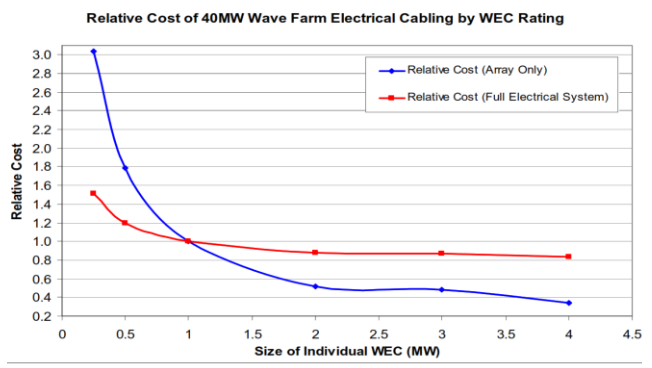


Figure 5: Relative cost of electrical cabling in wave farms, [13]

The relative cost of mooring will likewise fall significantly with increased WEC size. Taken together savings in cabling and moorings can reduce the total CAPEX for a wave farm considerably if MW size converters are installed instead of small-scale devices.

The study *"Performance and economic feasibility analysis of 5 wave energy devices off the west coast of Ireland"* [14], shows as expected that the cost of energy reduces significantly with increased farm size. It also shows that the reduction varies for the different device types – see figure 6.

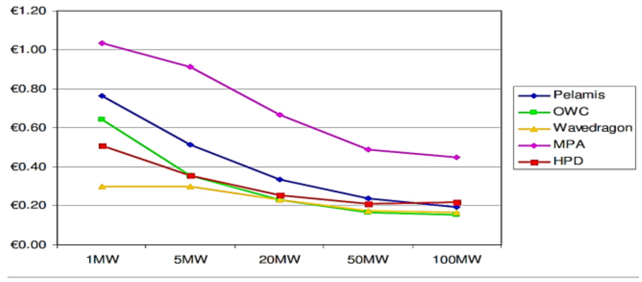


Figure 6: Cost of electricity in €/kWh [14]

Comprehensive studies on wave energy

The book *"Ocean Wave Energy Conversion"* [15], gives a good overview of the ocean wave energy resource and the potential markets. Many WEC types are described – also more exotic types than the ones mentioned in this article. Also lists of WECs tested in large scale since 2001 and photos of many of the devices, can be found in the book.

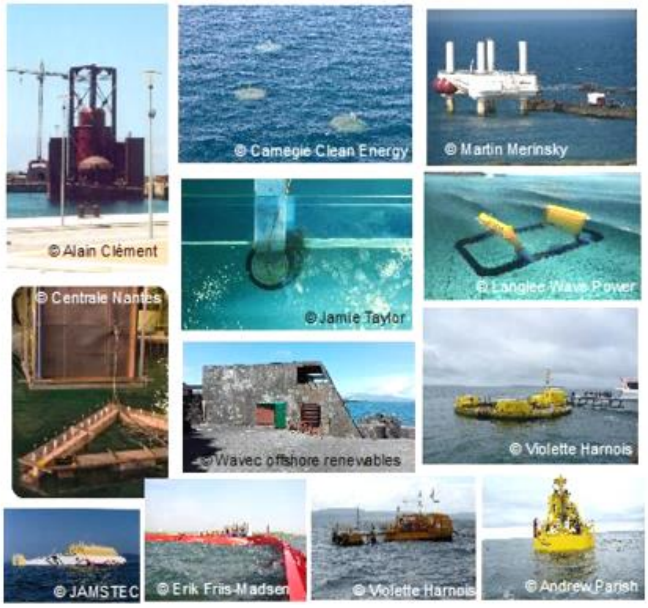


Figure 7: Examples of tested WECs whose capture width have been reported [15]

The study delivers many useful findings regarding the viability of wave power. Unfortunately, it is also stated that: *"...developers of wave energy converters should concentrate their effort on the development of technologies adapted to these water depth of 10–20m."*. All entrepreneurs who have worked in this depth zone at exposed coasts know however that it is extremely difficult and costly to construct and maintain any kind of installations in this zone – see also p.3 in this article.

In *"Handbook of Ocean Wave Energy",* [16], many useful rules of thumb can be found. This is most relevant and important with respect to the main objective of this article:

"Scalability: At full scale, a WEC needs to be a multi-MW device in order to be economically viable. In order to be able to continue significantly improving its LCOE, it needs to be scalable, meaning that it should be capable of further enlarging its dimensions (like offshore wind turbines do). Many WECs unfortunately reach their optimal dimensions at too low dimensions, making it not possible for them to become multi-MW WECs (>5 MW). This does not include the multiplication of WECs as this will not have a significant influence on the average infrastructural and technology costs and thereby will not significantly improve the LCOE of the WEC or project."

This rule of thumb is found by calculating the cost of energy for generic WEC farms based on offshore wind energy experience with 3.6 MW turbines for which detailed cost breakdown exists. The calculations for the example 90 MW WEC array are made for two different sizes of WECs, namely 0.75 MW and 3.6 MW. To keep it simple the cost of the small and large WECs have been set equal - even if there is clear evidence for lower cost per MW power for large-scale WECs. The findings are the following:

The base LCOE (cost without OPEX) derived for all CAPEX except the cost of the WECs are 0.031 and 0.074 €/kWh for large and small WECs respectively. This means that the general development, infrastructure and commissioning costs weigh about 2.5 times higher on small than on large WECs. When adding the OPEX cost to the base cost, the LCOE over the lifetime of the WEC arrey, excluding the CAPEX for the technology itself, increases to 0.063 for large WECs and ***0.191 €/kWh*** *for small WECs – or about 3 times the LCOE for the large WECs.*

It is quite easy to extrapolate these findings to compare with today's offshore wind turbines of 6 MW or more and WECs of same size, and at the same time use realistic size point absorbers of 0.15 MW capacity. The results of the calculations quoted from [16] are however sufficient clear when compared to the verified cost of the wind turbine park, which has a LCOE including CAPEX for the wind turbines of only **0.117 €/kWh**. This is way below the **0.191 €/kWh** LCOE for the 0.75 MW WEC park, where the CAPEX for the wave devices is not included!

However, many developers still consider it possible for Third generation large scale offshore WEC parks to compete with offshore wind even at water depths below 50 m – i.e. with bottom standing wind turbines. The Danish Partnership for Wave Power has as an example set a goal where offshore combined wave and wind parks in the Danish part of the North Sea have a 15€/MWh lower LCOE than traditional wind parks.

Floating offshore wind

The report *"Floating Offshore Wind: Market and Technology Review"* [17], shows clearly that floating wind turbine parks can be expected to have much higher LCOE than today's offshore wind. The report states however also that the possible market for floating wind alone in Europe is huge. It is in competition with floating wind there is an obvious chance for offshore wave energy parks to be successful – eventually in coexistence with wind turbine parks.

The title itself of the report *"Economic Benefit of Combining Wave and Wind Power Productions in Day-Ahead Electricity Markets"* [18], tells that there clearly is synergy effects of combined wave and wind parks with regard to the electricity markets, which eventually can lead to higher feed-in prices. In line with the findings in [18], Graham Sinden found that in a country like UK the lowest variability in the power supply is obtained by installing more wave than wind power and just 5% tidal stream power.

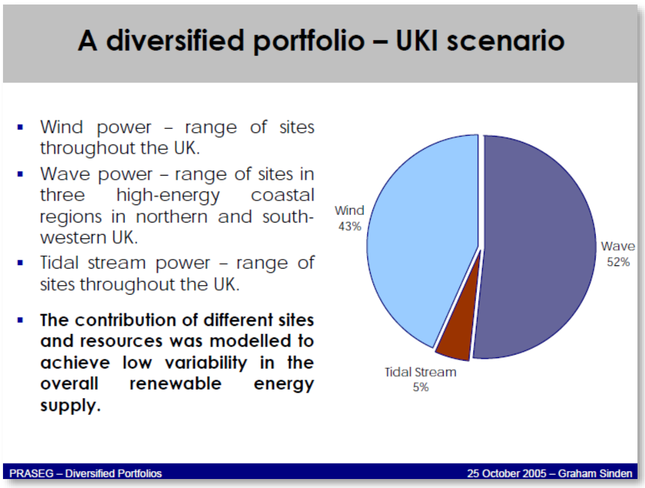


Figure 7. An example of optimal shares of wind, wave an tidal

An example of combined wave and wind

Wave Dragon is a very large floating overtopper device, which by nature has a highly stable power smoothing reservoir platform. It has therefore from the very beginning been designed to host two standard type wind turbines.

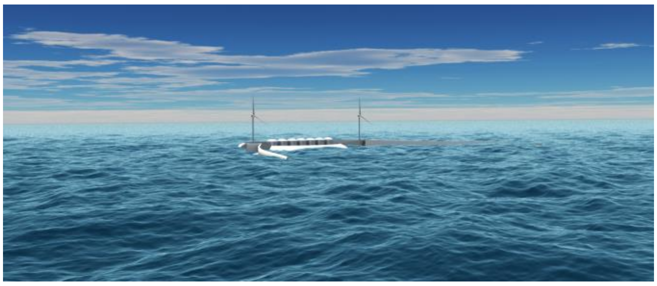


Figure 8. Wave Dragon with two wind turbines.

Combined wave-wind platforms of this kind can deliver a much lower LCOE than pure wave converters or deep offshore wind turbines. This has been shown in the papers *"Feasibility and LCA for a Wave Dragon platform with wind turbines"* [19] and *"Wave Dragon - 'Coldward and Stormward* [20].

In table 2 the LCOE is calculated for a 7 MW Wave Dragon, for two 2.3 MW wind turbines and for the combined wave and wind energy device (WWEC) with 11.6 MW installed power.

	LCOE	Annual production
Wave Dragon 7MW	61.5 €/MWh	20.0 GWh
Siemens WT 2 x 2.3MW	40.0 €/MWh	18.4 GWh
WWEC 11.6MW	51.2 €/MWh	38.4 GWh

Table 2. Expected LCOE of Wave Dragon with wind turbines

As can be seen the combined Wave Dragon-wind turbine option (WWEC) results in a LCOE 17% lower than the Wave Dragon only option. It should be mentioned that as both Wave Dragon and floating wind turbines are not in commercial stage yet, the results are attached with some uncertainty, but a conclusion can nevertheless be drawn. The variation of LCOE for proposed floating wind turbines is very high. The average LCOE for the various concepts is found to be in the range 119.0 – 155.3 €/MWh, which in any case is much higher than the WWEC solution.

IV. RESULTS & FINDINGS

It has been justified why the motto "small is beautiful" belongs firmly in the past with regard to the development of commercial viable wave energy converters.

Nearshore wave energy will inevitably have high LCOE in comparison with offshore wave energy parks and has also relatively quite limited deployment possibilities.

In a long-time perspective offshore wave energy will have to compete with floating offshore wind regarding LCOE even if wave power has the advantage of being more predictable than wind power. Studies have fortunately shown that combinations of wave and wind will be able to deliver competitive LCOE and feed power to the grid with very low variability - eventually securing a capacity credit value.

Offshore power plant size wave parks can develop into a viable solution by using large-scale WECs – eventually in combination with wind.

So, the answer to "will small WEC's ever become commercial" is: probably not.

Will wave energy then ever become commercial?
Yes - most certainly it will!

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