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Economic feasibility study for wave energy conversion device deployment in Faroese waters

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ABSTRACT

As the world continues to battle with increasing energy demand along with the serious effects of climate change, there is a need for more reliable renewable energy sources. The objective of the present work is to study the economic feasibility for deployment of wave energy conversion devices in the Faroese coastal region. We analyze eight different wave energy conversion concepts under development at nine different nearshore locations in the Faroese coastal region. The nine different locations are classified into three coastal locations — three on the west coast, three on the east coast and three on the north coast. The eight wave energy conversion devices mostly rely on different working principles, though some of these are similar. Results show that there is quite a significant difference in the performance of the devices from coast to coast. There is also a difference between the different conversion devices as they rely on different principles and the suitability of each device varies from location to location. We also show that the Faroe Islands are a suitable location for wave energy converter deployment compared to other places. Furthermore, results show that the performance of wave energy converters in the Faroe Islands can prove to be a direct competitor to offshore floating wind energy.

1. Introduction

The need for developing efficient, optimal and robust technologies for capturing power from renewable resources grows by the minute. The effects from climate change are already disastrous, with recorded extreme heat records all across Europe [1]. As power production transitions from a stable generation from coal, oil, natural gas, nuclear fission, etc., to a more unstable generation from renewables, there is a need for a variety of different renewable sources to feed in to the electricity grid [2]. A clean and efficient source of renewable energy is wave power. This resource has been extensively tested and investigated, but up to this point there are no large-scale commercially available technologies for power generation from waves. However, there are many different companies/technologies on the doorstep to enter the commercial stage. Some examples include: CorPower [3], Mocean [4], EcoWave Power [5], Wave Dragon [6], Wavepiston [7], ExoWave [8], KNSwing [9] and NoviOcean [10].

To make a power generation technology attractive and interesting, there is a need for optimization with regards to the economic perspective. This is one factor which has failed in the past when considering wave power — it has simply been too expensive to produce power from ocean waves, compared to other renewable sources, e.g. offshore wind [11]. The most common metric for the economic assessment is the levelised-cost-of-energy (LCoE), which is defined in Section 2.5.

1.1. Literature review on LCoE

Several studies have focused on investigating the economics of wave power for a specific region based on the available level of data from ocean waves. Ref. [12] identified potential sites and assessed the technical and economic feasibility of harnessing wave energy along the Indian coast. The authors analyzed four different wave energy conversion technologies: Wave Dragon, Pelamis, Oceantec and Aquabuoy. They found that the most economically feasible technology was the Oceantec device which had a LCoE ranging from 354 to 505 EUR/MWh at all sites.

Ref. [13] explored the potential benefits of co-locating a wave energy device with an offshore floating wind farm located off the coast of northern Portugal. The authors conclude that the co-located farm

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would increase the energy production by 19% and the LCoE level with a co-located wave farm is at 105 EUR/MWh.

Ref. [14] examines the feasibility of a hybrid wave-photovoltaic (PV) system in three ports of Iran. They found that the maximum energy production occurred in May and the minimum energy production occurred in November. For the three ports, they found LCoE values of 4420 EUR/MWh, 5010 EUR/MWh and 5120 EUR/MWh, respectively.

Ref. [15] studied the economic feasibility of two wave energy conversion devices along the coast of Brazil: Pelamis and Wave Dragon. They found a LCoE value for the Pelamis device of 149 EUR/MWh and 126 EUR/MWh for the Wave Dragon device.

Ref. [16] investigated the economic feasibility of the Pelamis, the AquaBuoy and the Wave Dragon devices off the coast of northern Spain. They found the best LCoE values for the Wave Dragon at 513.17 EUR/MWh, the Pelamis at 1710.98 EUR/MWh and the AquaBuoy at 2627.60 EUR/MWh.

In [17], the authors investigate the economic feasibility of the same devices as in [16], but for the coast of Portugal. They found here that the Wave Dragon had a LCoE value of 316.90 EUR/MWh, the Pelamis had a LCoE value of 735.94 EUR/MWh, while the AquaBuoy was all the way up at 2967.85 EUR/MWh.

In [18] the authors investigated the economic feasibility of the backward bent duct buoy (BBDB) oscillating water column (OWC) device. The authors investigated the economics with regards to three different discount rates, three different efficiency levels and two different initial capital costs in units of EUR/kW of rated power. The LCoE values ranged from 81 EUR/MWh with the lower capital cost value, the maximum efficiency level and the lowest discount rate, to 1335 EUR/MWh with the higher initial capital cost, the lowest efficiency level and the highest discount rate.

In recent years there has been a special focus on using ocean renewables to supply oil and gas platforms in order to reduce the energy consumption for their oil and gas extraction. Ref. [19] assessed the performance and economic feasibility of seven wave energy devices for a case study site located at an oil and gas platform in the North Sea. They found that the hydrodynamic performance of the wave energy device is not necessarily directly linked with the economic attractiveness. They found that the LCoE ranged from 188 EUR/MWh to 471 EUR/MWh.

In [20], the authors investigate the feasibility of implementing combined wave and solar systems for supplying power to offshore oil and gas platforms. They assessed four wave energy converters and one solar power system for three scenarios: wave power only, solar power only and both combined. Results showed that a combination of electricity sources increased the electricity production, reduced the intra-annual variability of energy production and intermittency issues, increased capacity factors up to 24% and avoided over dimensioning. The LCoE level ranged from 131 EUR/MWh to 263 EUR/MWh and the reduction in emissions was estimated at approximately 281,915 tons/year.

No study concerning the economic feasibility of wave energy converters exists for the Faroe Islands, which according to [21] might prove to be a viable candidate for the first real community running fully on wave power for electricity generation. Small island communities might prove to be ideal candidates for wave power generation, since the demand is not as high as in a cross-country electrical grid network [22].

1.2. Contributions and novelty

The present study analyzes the performance in the Faroese coastal waters of eight different wave energy conversion devices currently under commercial development. The performance of the devices is analyzed at nine different locations and is based on:

- An energy production perspective, through the prediction of the annual energy production (AEP) of each device at each location.
- An economic perspective, by estimating the levelised-cost-of-energy (LCoE) for each device at each location.

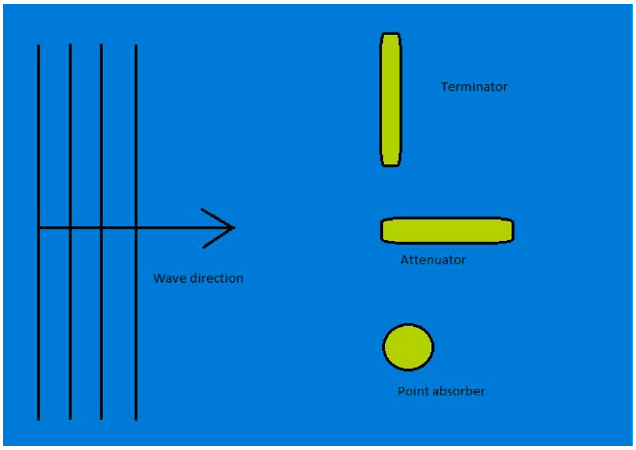


Fig. 1. Attenuator, terminator and point absorber working principle.

Based on the numbers derived from the above calculations, the more promising and cost-competitive devices are compared to offshore floating wind power. This is the real competitor to the wave energy conversion devices analyzed (for Faroese conditions), since due to the steep water depth contours around the Faroe Islands, offshore bottom-fixed wind power is unrealistic.

These contributions will hopefully stimulate the desire for wave energy developers and potential investors to see the Faroe Islands as a realistic candidate for one of the world's first large scale commercial wave farms. This study highlights that the Faroe Islands are one of the best suited locations worldwide when considering energy production and cost of energy. Furthermore, it highlights that for Faroese conditions, wave power is truly a competitor to offshore floating wind power.

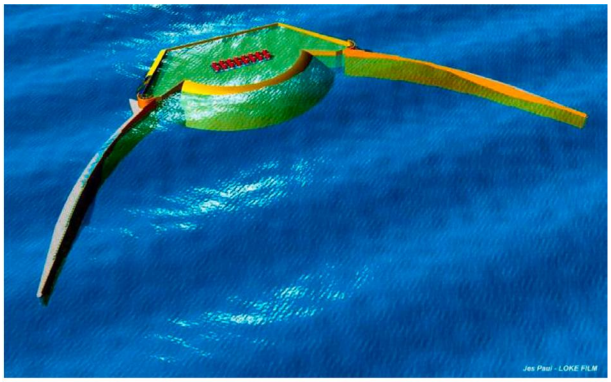
2. Theory and methods

The main working principles of wave energy conversion devices are generally categorized into four types: (1) wave over-topping devices, (2) oscillating water columns, (3) lift-based devices, and (4) wave activated bodies. Other, less commonly used working principles also exist, e.g. submerged pressure differential devices, internal rotating mass and bulge wave devices; but these can generally be absorbed into the main categories [23]. Absorbers based on each of these working principles can further be deployed in one of three main configurations: (a) point absorber, (b) wave attenuator and (c) wave terminator, as illustrated in Fig. 1. This classification is based on the relative size of the device compared to a typical wavelength and its orientation with respect to the direction of wave travel.

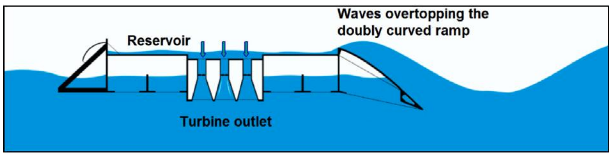
2.1. Wave energy conversion working principles

2.1.1. Wave overtopping devices

Wave over-topping devices capture the water as the waves propagate up a ramp and break into a reservoir. The water then returns to the sea through conventional hydro turbines generating electricity. Two well known devices are the Wave Dragon [24] device and the Sea Slot-cone generator (SSG) [25]. In this study we have focused on the Wave Dragon as this device is still under development. A sketch of the Wave Dragon is shown in Fig. 2 and an artistic impression of the SSG device is shown in Fig. 3. The Wave Dragon device is developed by a Danish company carrying the same name as the device – Wave Dragon Aps – and has been under development for more than 20 years.



(a)



(b)

Fig. 2. A schematic sketch of the working principle of the Wave Dragon device. *Source:* From [26].

2.1.2. Oscillating water column devices

The oscillating water column wave energy device has been subject to vast research and development for more than a century. Oscillating water column devices can be both fixed and floating, as well as nearshore and offshore devices. An oscillating water column is a partially submerged, hollow structure. It is open to the sea below the waterline, enclosing a column of air on top of a column of water. Waves cause the water column to rise and fall, which in turn compresses and decompresses the air column. The trapped air is allowed to flow to and from the atmosphere through a turbine, which usually can rotate in the same direction regardless of the flow direction. The turbine rotation is used to generate electricity. A schematic of the working principle of an oscillating water column is shown in Fig. 4.

In this study we have focused on the KNSwing device, having an oscillating water column as the main driver for electricity generation. This is an offshore floating device, deployed as a wave attenuator device. The KNSwing is a long ship-like barge structure with the main direction of the device parallel to the direction of wave propagation (more details under *Wave attenuators*).

2.1.3. Lift-based devices

The concept of lift-based wave energy converters is relatively new, compared to the other working principles. As stated in [29] few studies exist that deal with these types of wave energy devices. However, in recent years, this type of wave energy conversion concept has received a great deal of attention. The LiftWEC project [30], a large project consortium consisting of 10 partners, deals with the many different aspects of development of a lift-based wave energy converter. Ref. [31] has made a numerical benchmarking of the CycWEC lift based wave energy converter developed at Atargis Energy Corporation [32].

In contrast to the conventional type of wave energy converter types, which utilize buoyancy and radiation/diffraction forces to drive the motion of the structure, the lift-based WECs, as the name indicates, utilize the lift forces on the structure to drive the motion. The main structure comprises one or more hydrofoils which rotate about an axis perpendicular to the incoming wave direction.

Even though we do not have an actual lift-based device in this analysis, we believe it is important to mention this type of wave energy converter, due to its potential as a new way of approaching wave energy capture.

2.1.4. Wave activated bodies

Contrary to OWC and overtopping wave energy conversion principles, wave activated bodies are directly affected by the action of the waves. In wave activated bodies, the wave motion directly drives the power-take-off system for electricity generation from kinetic energy. Wave activated bodies mainly encompass two driving mechanisms — translational motion of the body and/or rotational motion of the body. Fig. 5 shows an example of a wave energy converter using the rotation of the body as the driving mechanism for the power-take-off.

2.2. Wave energy conversion configuration types

Any of the above mentioned working principles (or even combinations of them) can be deployed in one of three main configurations — *a point absorber*, a *wave attenuator* or a *wave terminator*, which will be described in detail in the following.

2.2.1. Point absorbers

A point absorber is a floating device which is small relative to the wavelength of the incident waves. It typically has only one or two power-absorbing degrees of freedom and could be based on any of the above-described working principles.

In this study we have focused on the CorPower C12 device [3], which is planned to be operational in 2028–2030. The EcoWave Power device [5] is a modification of a point absorber, with a floater attached to a piston. Fig. 6 shows an illustration of the most common working principle for a point absorber wave energy device.

2.2.2. Wave attenuators

A wave attenuator is much longer than the target wavelength and oriented with its axis parallel to the direction of wave propagation. The device typically has many degrees of freedom to capture energy as the waves travel along its length. The KNSwing device shown in Fig. 7 is a good example of an attenuator. It is a long barge with 40 OWC chambers, slack-moored to align itself with the dominant direction of wave propagation.

2.2.3. Wave terminators

A wave terminator is also typically much longer than the target wavelength, but with its axis oriented perpendicular to the direction of wave propagation. A classic example of a wave terminator device is the famous spine duck, invented by Dr. Stephen Salter in 1974 [36]. Fig. 8 shows an impression of the spine duck. The WaveDragon concept is a wave overtopping device with only one power-absorbing degree of freedom which is deployed as a wave terminator. Fig. 9 shows pictures of the Wave Dragon converter deployed as a 1:4.5 scale prototype device tested in Nissum Bredning.

2.3. Wave data locations

The wave data used in this study is from an earlier study published in [21], where the spectral wave model, MIKE 21 SW [38] was used to model the wave climate around the Faroe Islands. The numerical calculations were extensively validated against wave buoy measurements and are thus taken to be reliable. We have selected nine locations for analysis in total — three on the west coast, three on the east coast and three on the north coast, as it was deemed that there was little variation between the three locations on each of the coasts. Fig. 10 shows a map of the selected locations.

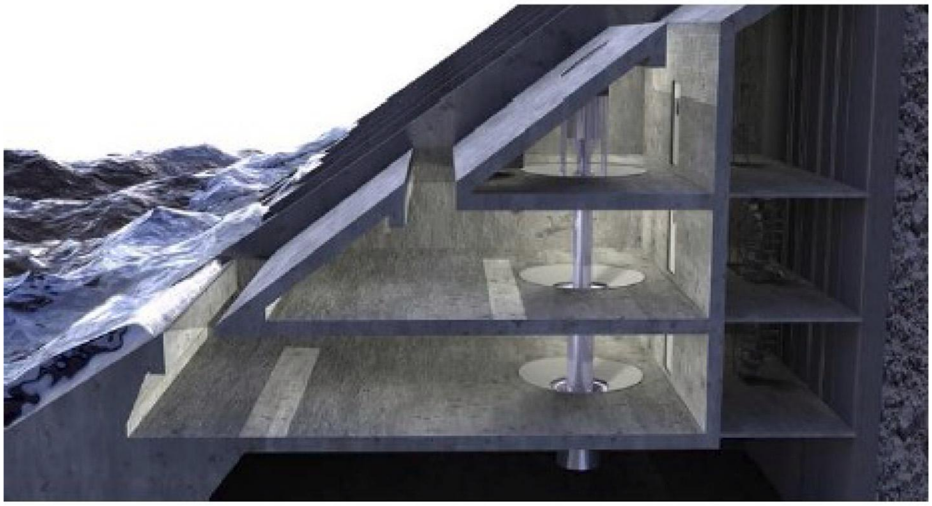


Fig. 3. Artistic impression of the SSG wave energy device.
Source: From [27].

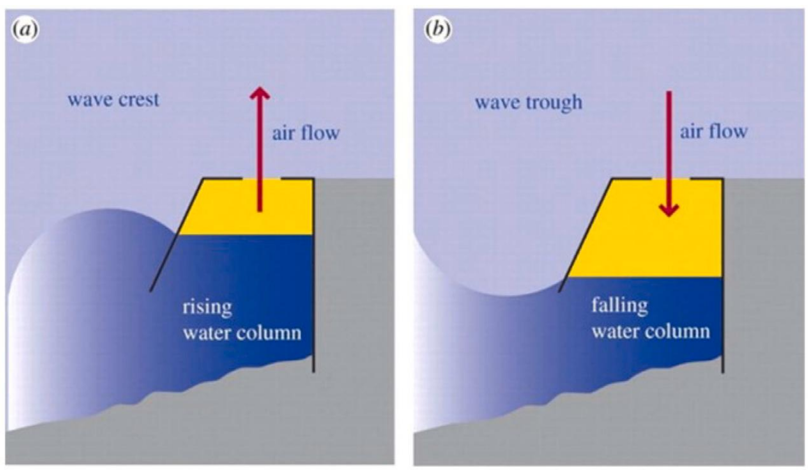


Fig. 4. Oscillating water column working principle.
Source: From [28].

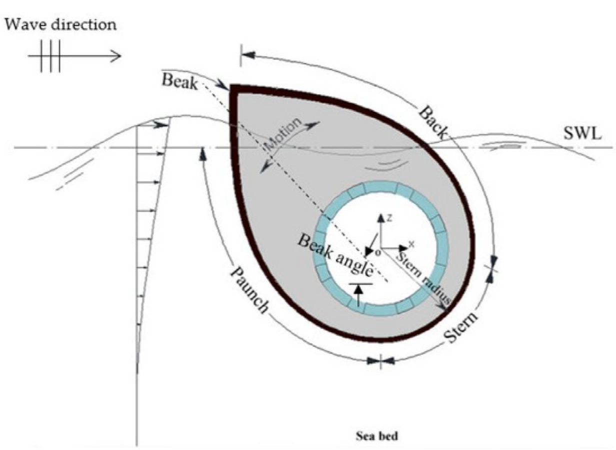


Fig. 5. Example of a wave energy converter using the rotational motion of the main body as the driving mechanism for the power-take-off.
Source: From [33].

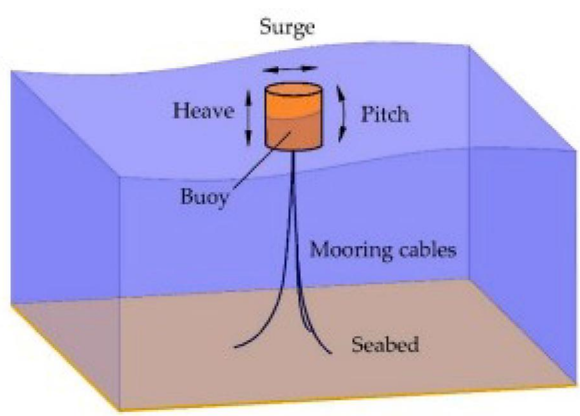


Fig. 6. Point absorber working principle.
Source: From [34].

Fig. 7. Experimental model scale of the KNSwing device.
Source: From [35].

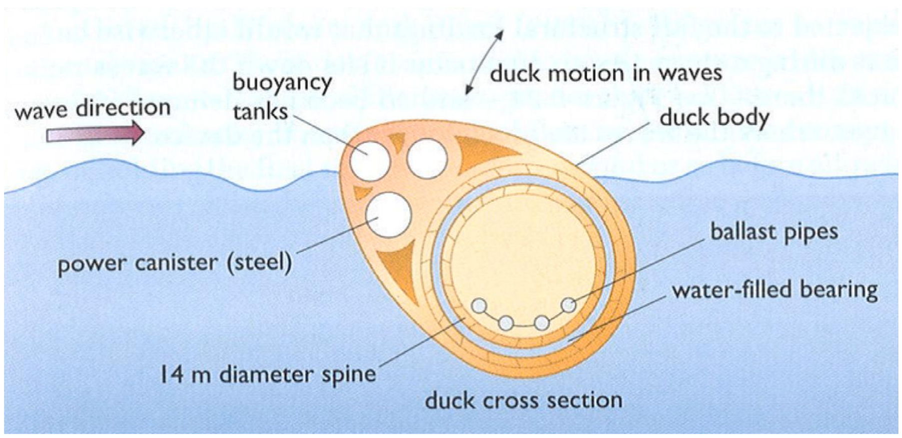


Fig. 8. Sketch of the working principle of the spine duck.
Source: From [37].

Fig. 9. 1:4.5 scale of the Wave Dragon converter.
Source: From [23].

Fig. 10. Map of the selected locations.

2.4. Wave energy device power performance

To evaluate the power performance of the different devices analyzed in this study, we use the same methodology as in [39] to compute the average absorbed power, where the power matrix of each device is multiplied by the scatter diagram of sea states at each location and summed together for all sea states, resulting in

$$P_{abs} = \sum_{i=1}^{N} \sum_{j=1}^{M} P_{ij}\, f_{ij} \tag{1}$$

where N is the number of wave period bins, M is the number of wave height bins, P_{ij} is the power absorption coefficient corresponding to wave condition i, j (the power matrix) and f_{ij} is the occurrence frequency of the sea-state (H_{m0}, T_p) in the ith and jth bin. A visualization of the procedure is shown in Fig. 11 for the E2 location and the power matrix for the KNSwing device.

The annual energy production (AEP) of each device is calculated as the average absorbed power of the device multiplied by the operating hours in a year, assuming the device to be fully operational in a year:

$$AEP = P_{abs}\, 8766. \tag{2}$$

As it is not realistic that the device is fully operational throughout the whole lifetime of the device, the downtime due to storm limitations, maintenance, etc. is usually incorporated when calculating the total energy production of the device as some percentage.

2.5. Levelised-cost-of-energy

The Levelised-Cost-of-Energy (LCoE) is an important metric when discussing the potential deployment of any given energy generation device. The cost of producing (and purchasing) energy is most likely the dominating metric when planning a potential deployment of any type of power plant — wind power, solar power, tidal power, wave power, thermal power, etc. The LCoE is defined as the total cost of commissioning, operating and maintaining the power plant divided by the total energy produced over the lifetime of the plant.

$$LCoE = \frac{CapEx + OpEx\, L_t}{E_P} \tag{3}$$

where $CapEx$ is the capital expenditure for the device, $OpEx$ is the cost related to operation and maintenance of the device, L_t is the lifetime of the device (including downtime due to maintenance and storm) and E_P is the total energy production over the lifetime of the device. This is a more conservative version of the cost of energy definition, because it does not take into account any effects of a possible discount rate on the operational costs or the energy production. By accounting for the discount rate it is possible to get a more realistic estimate of the LCoE over the whole lifetime of the wave energy device.

$$LCoE = \frac{\sum_{t=1}^{n} \frac{CapEx_t + OpEx_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_P}{(1+r)^t}} \tag{4}$$

where n is the number of years the device is operational and r is the discount rate. We have used the latter definition of the LCoE as this gives a more realistic estimate of the cost of energy. Ref. [23] gives a nice overview of the parameters that should be taken into account when calculating the cost of energy.

2.5.1. A sample breakdown of the cost estimates for the KNSwing device

As there are many parameters entering the calculation of the LCoE, it is reasonable to break down the specifics of the different numbers entering the equation. There are for example, many different aspects to consider when dealing with the capital costs and operational costs of a wave energy project.

As most of the devices that we investigate in this paper are developed by commercial companies, we are acting under a non-disclosure agreement, to not divulge sensitive information including the power matrix, and the estimated CapEx and OpEx of the devices. However, we have gotten consent from the developer of the KNSwing device to explain in detail how the different numbers are estimated, especially regarding the CapEx and OpEx.

The KNSwing device is a 150 meter long ship like structure, which is proposed to be built in steel reinforced concrete with a density of 2500 kg/m^3 and a total mass of 12 000 tonnes. The unit cost of concrete, including forming of the structure is estimated to be 250 EUR/ton. The material cost is taken from [40], including a doubling of the cost to take care of execution and man hours. The PTO of the KNSwing device consists of 40 air turbines, each with a unit cost including generators of 500 EUR/kW. The control strategy of the PTO of the KNSwing includes controlling the opening and closing of the air-duct to the air turbine and speed control implemented by direct drive generators, one in each stator. The cost of the control system is included in the cost of the PTO.

The KNSwing device is assumed to be moored by four mooring lines with associated mooring anchors. These are expected to be installed using an Anchor Handling Vessel, installing one anchor and mooring line per day — at a daily rate of 50,000 EUR/day. The total cost of the mooring system is estimated at 300,000 EUR. The installation of the KNSwing and connection to the moorings is done in one day using two smaller tugboats at a rate of 12,500 EUR/day. The connection of the device to the subsea electrical connector is expected to be installed in one day at a cost of 50,000 EUR. The lifetime of the device is expected to be 25 years and the financial discount rate is set at 3.5% [41]. The discount rate varies a lot from country to country and it can be argued that this might be set a bit too low. However, in Danish terms and in a developing energy technology like wave energy, this would seem to be a reasonable discount rate level.

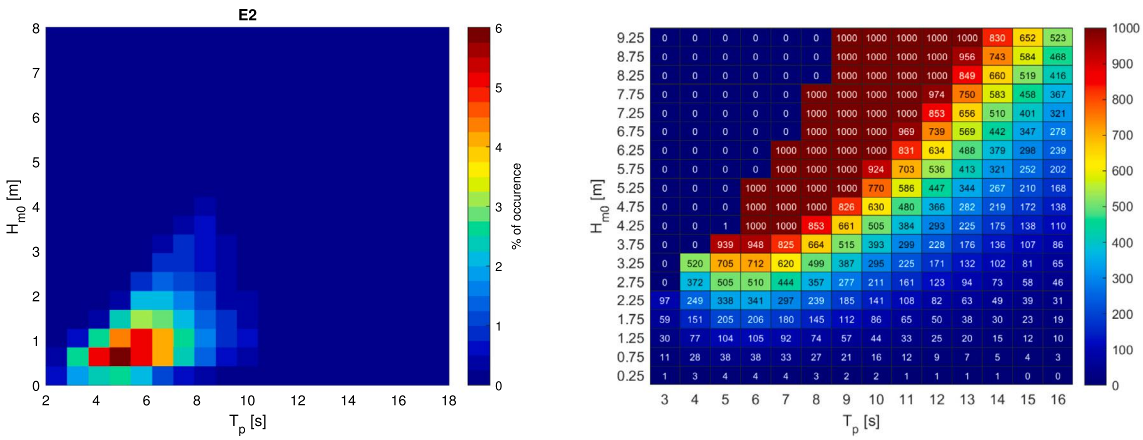


Fig. 11. Scatter data for the E2 location (left) and the electrical power matrix of the KNSwing device (right).

The operational expenditures (OpEx) of the KNSwing device are assumed to be 180 kEUR per year, which includes: minor repair and inspections (e.g. diving inspections), major repairs or maintenance (towing to dock, dry-docking, etc.) and fixed costs for the annual site lease, insurance and management.

This results in a total CapEx value for a single device of 4.5 MEUR and an annual OpEx value of 180 kEUR. Inserting these numbers into Eq. (4) together with the total lifetime energy production, E_P using a particular site's scatter data and the KNSwing power matrix (as illustrated in Fig. 11) gives the LCoE for that site.

These assumptions for the cost estimates of the KNSwing device are expected to be representative for the rest of the devices analyzed in this paper, and the same procedure is followed to compute the LCoE.

2.6. Wave energy devices investigated

As mentioned above, we have investigated a number of different wave energy conversion devices currently under development — most of them on a commercial stage, while the development of the KNSwing device has been conducted mostly by universities and academic institutions.

CorPower Ocean device

The CorPower Ocean wave energy converter is a point absorbing device, with a heaving buoy on the surface absorbing energy from ocean waves. The buoy is connected to the seabed using a tensioned mooring system. The energy stored in the waves is converted into electricity through the rise and fall as well as back-and-forth motion of the waves. The composite buoy, interacting with this wave motion, drives a Power-Take-Off inside the buoy that converts the mechanical energy into electricity. According to CorPower, the device is at a Technology Readiness Level (TRL) at 7 [3]. A description of the TRL can be found in [23].

Eco Wave Power

The Eco Wave Power device is comprised of floaters attached to a harbor or coastal structure. The floaters draw energy from the incoming waves by converting the rising and falling motion of the waves into a clean energy generation process. The movement of the floaters compresses and decompresses hydraulic pistons which pump bio-degradable hydraulic fluid to land-based located accumulators. A pressure is built in the accumulators which rotates a hydraulic motor, which subsequently rotates a generator, converting mechanical energy into electricity to the grid via an inverter [5]. The numbers provided from the developer for the CapEx in the analysis for the Eco Wave Power device do not include installation costs and grid connection. According to [42], the percentage share of installation and commissioning is about 13%. Therefore, this percentage has been added by the authors in the analysis for the Eco Wave Power device.

Exowave

The Exowave wave energy converter, is in principle an oscillating wave surge converter, which extracts the kinetic energy from the ocean waves through bottom-hinged flaps. The flaps are activated by wave-induced orbital motion of the water and pivot about the horizontal shaft. The shaft is connected to a swivel that automatically orients the flap in the direction of the waves. The flap then drives a crank which actuates a cylinder pump [8]. Using Exowave's own name convention the flaps are called cells, while each block consists of three cells and subsequently each cluster consists of 10 blocks.

Wavepiston

The Wavepiston device consists of several energy collectors attached to the same spine-like structure. The energy collectors are vertical plates that move horizontally back and forth due to surging wave action. The energy collectors pump seawater through a pipe, to a water turbine that converts the pressurized water to electricity. The long structure is moored at both ends [7].

Wave Dragon

The basic principle of the Wave Dragon device is to use well-known and well-proven principles from traditional hydro-power plants in an offshore floating platform. The Wave Dragon over-topping device elevates the ocean waves to a reservoir above sea level where water is let out through a number of turbines and in this way it is transformed into electricity [6].

KNSwing

The KNSwing device is a long ship-like structures with oscillating water columns along both sides, where it absorbs the wave energy as it passes down along its hull. Traditionally, oscillating water column devices use bi-directional or self-rectifying turbines to generate electricity. A PTO efficiency of 49% is used (as per the developer). However, increasing the efficiency of the PTO up to 75%–80%, by utilizing one-way energy absorption, as is done in [43], would lead to a significant increase in the annual energy production and a significant decrease in the LCoE.

Mocean Energy Blue Horizon device

The Mocean Energy Blue Horizon device is a hinged raft type of wave energy converter. It is inspired by the Pelamis device [44], but is simpler as it only consists of one hinge, compared to the several hinges of the Pelamis device. It is an attenuator device, i.e. it faces the waves head on and has a power rating of 200 kW.

Table 1
Main specifications for each device.

	L [m]	m [ton]	P_r [kW]
CorPower	11.25	87.5	400
Eco Wave Power	3.6	1.6	1000
Exowave	12	100	350
Wavepiston	320	95	500
Wave Dragon	270	33 000	7000
KNSwing	150	12 000	1000
Mocean			200
NoviOcean	38	150	500

NoviOcean NO500

The NoviOcean wave energy converter is a non-resonant buoyant device that extracts energy from the vertical motion (heave). It is essentially comprised of two main subsystems which are both unique to the wave energy industry — the "rectangular float" and the "inverted hydropower plant PTO". The HPAS (Hydro Power Plant at Sea) is the result of merging these unique subsystems [10].

In Table 1 we have provided the main parameters of each device, e.g. largest dimension L, mass m and rated power P_r:

The values for length and weight of the Eco Wave Power device are for each floater, while the rated power is for the whole device comprising of 100 floaters. The company Mocean Energy wishes to keep the specifications on their device confidential, as this device is currently under development and the design is constantly evolving. Therefore, only the rated power of the device is provided.

3. Results and discussion

3.1. Annual energy production

The annual energy production of the devices varies a lot since they span a large range of sizes and rated powers. The annual energy production of each device at each location is calculated from (4). The results are presented in Fig. 12.

Fig. 12 shows that the energy production roughly follows the rated power of the devices, and increases with the increasing wave climate from eastern to northern to western locations. The Wave Dragon device, with a rated power of seven times the next highest rated device, always produces the most energy. Considering the Eco Wave Power and KNSwing devices, which have the same rated power, the Eco Wave Power device is more productive on the east coast while they are fairly similar on the north coast and the KNSwing device has a larger annual energy production on the west coast. This is presumably due to the different distributions of the two power matrices.

The Exowave and the Mocean device are amongst those with the lowest energy production. However there is a clear variation between the devices for each of the locations. For the east locations the Mocean device outperforms the Exowave, while for the west locations the Exowave has the highest production.

The Wavepiston device and the CorPower device have similar annual energy production at most locations, however at the E3, N1 and N2 the CorPower device outperforms the Wavepiston device.

It is particularly interesting to note that the devices that fall in the same amount of energy production, actually rely on different working principles and power-take-offs. In terms of energy production, the Wave Dragon device is in a category for itself, as well as in terms of working principle being an overtopping device. The KNSwing device and the Eco Wave Power device have somewhat similar energy production, with the KNSwing device being an attenuator device equipped with OWCs and the Eco Wave Power device being a collection of point absorbers. The Exowave converter is a bottom mounted oscillating wave surge converter and the Mocean device is an attenuating hinged-raft.

Table 2
LCoE for the Wave Dragon device at different locations.

Faroe Islands	Portugal	Spain	Brazil
[EUR/MWh]	[EUR/MWh]	[EUR/MWh]	[EUR/MWh]
61.8	316.9	513.17	129.95

3.2. Levelised-cost-of-energy

The LCoE is probably the most important parameter for prospective investors in renewable energy, because it predicts the price of the energy. Fig. 13 shows the LCoE in EUR/MWh for each of the considered devices at each location. The Wavepiston device has the highest price of energy at E1, E2, E3, N1 and N2, while the KNSwing device has the highest energy price at N3 and the Mocean device has the highest energy price at all west locations. At the opposite end, the Eco Wave Power device has the lowest price of energy at the east locations E1 and E2, where the CorPower device has the second lowest and the Wave Dragon has the third lowest at these locations. For the north locations N1 and N2 the CorPower device is lowest just below the NoviOcean device, while the Wave Dragon has the third lowest energy price. At the west locations the CorPower device, the Wave Dragon device and the NoviOcean device have by far the lowest price of energy at approximately 61–62 EUR/MWh and 62–64 EUR/MWh and 68 EUR/MWh, respectively. In the west locations the KNSwing, Exowave, Wavepiston and Eco Wave Power come in somewhat higher at 83, 91 and 92 EUR/MWh for KNSwing, 84, 88 and 89 EUR/MWh for Exowave, 94, 96 and 99 EUR/MWh for Wavepiston and 96, 102 and 103 EUR/MWh for Eco Wave Power.

It is important to highlight, that the assumptions behind the cost estimates for each of the devices vary from developer to developer, as some devices are better suited for some locations compared to others. Furthermore, the numbers provided on CapEx and OpEx from the developers are based on estimates, and not on in-depth analyses of the actual costs for installation and maintenance. Also the cost estimates are based on installation capacities of several 10's of MW and in some cases 100's of MW, and not on single device deployment as these would not make any sense with regards to commercialization. Given the inherent uncertainties in such cost projections, the numbers shown in Fig. 13 should be taken as indicative of the likely range for LCoE at each of these locations rather than precise values for these specific concepts.

3.3. Comparing the Faroe Islands case with other locations

As mentioned in the Introduction, several studies have been conducted to assess the economics of wave energy in different parts of the world. Therefore, it is natural to compare the results from these studies with the Faroe Islands assessment to determine the suitability of deploying wave energy converters in the Faroe Islands compared to other locations worldwide.

As only a few of the wave energy devices investigated in this study have been analyzed in other regions of the world, we will here focus on the ones that have been analyzed elsewhere.

The Wave Dragon device has been analyzed for the Portuguese coast in [17], for the Atlantic coast of Spain in [16] and for the coast of Brazil in [15]. Table 2 compares the LCoE of the Wave Dragon for the different locations. As Table 2 shows, the numbers vary a lot. This is partly associated with the difference in wave energy flux at the different locations, along with different assumptions behind the CapEx behind the calculations.

The NoviOcean NO500 device has been analyzed for a number of places around the globe. On the company's website, they have presented numbers for LCoE in terms EUR/MWh. Furthermore, they provide a rather detailed cost model for the CapEx and OpEx, based on the array power rating, the water depth and the distance to the

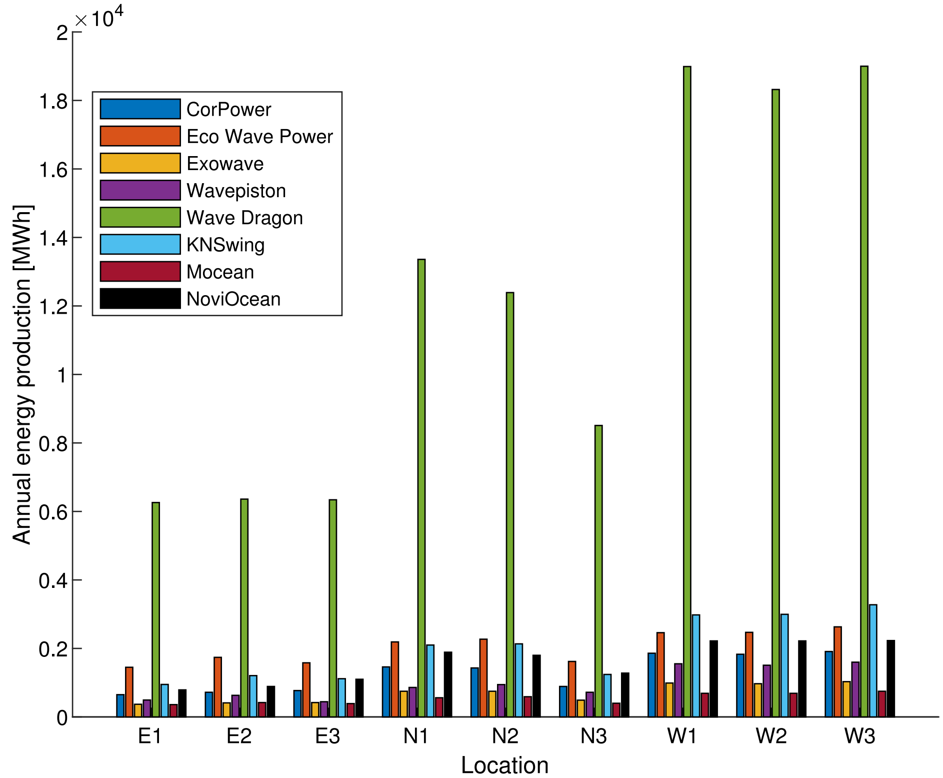


Fig. 12. Annual energy production of each device at each location.

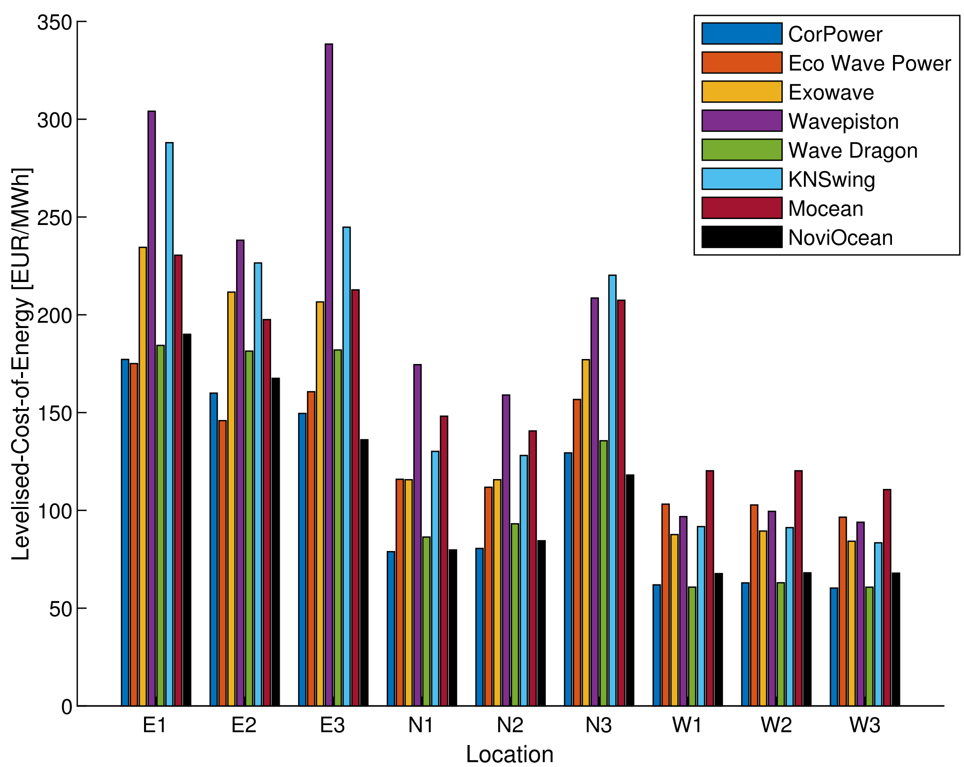


Fig. 13. Levelised-cost-of-energy of each device at each location.

Table 3
LCoE for the NO500 device at different locations.

Faroe Islands	Haltenbanken	Belmullet	Lisbon
[EUR/MWh]	[EUR/MWh]	[EUR/MWh]	[EUR/MWh]
68	84	68	79

nearest port. From this it is possible to derive values for the LCoE, CF, AEP, etc. We have compared the NoviOcean NO500 device at a number of sites presented on the company's website and for the most favorable site in this study in terms of LCoE. Table 3 shows the LCoE in EUR/MWh for the selected sites compared with the Faroese site. Table 3 shows that the numbers for the LCoE are in the same order of magnitude — indicating that the assumptions for the calculation of the LCoE are identical. Therefore it can be stated that this is a more realistic comparison compared to the one in Table 2.

Many of the companies owning the devices analyzed in this study have a long term projection of the LCoE in order commercialize their devices. These long term projections are derived from expected and estimated trends in the global economy, which we see now has taken a turn towards higher inflation in the aftermath of the COVID-19 pandemic. CorPower Ocean states in the presentation of the EUScores project [45] that the LCoE for their device will drop to 70 EUR/MWh when they have an installation capacity of 600 MW — which is well in line with the results for the more favorable locations in this study. Wavepiston presents on their website that at pre-commercial scale in 2025 they have reached a LCoE of 200 EUR/MWh, while their utility scale energy price will be as low as 40 EUR/MWh in 2032. This is also well in line with the results obtained in this study — which are taken to be estimates for 2028–2030 landing on a LCoE of 94 EUR/MWh for the most favorable location.

It is worth noting that the internal differences between the devices, mostly in terms of LCoE, vary to quite a significant extent from location to location. This is due to the suitability of each device for each of the analyzed locations. The scale and size of the analyzed devices are given beforehand and not optimized to each of the locations, leading to a significant "waste" in materials, due to the inability of the device to produce energy to their full potential. Therefore, each analyzed device should be optimized with regards to the intended deployment location, such that the resonance period of the respective device is as close as possible to the most frequently occurring wave period at the location. This was done in [21] where the authors analyzed four types of wave energy devices in Faroese coastal waters in terms of the capture width ratio (CWR) of each device, allowing for the possibility of varying the size of each device in order to match optimal energy production conditions. As the aim of the current study was to analyze wave energy conversion devices currently under commercial development, we did not want to alter any of the dimensions of the devices in order to suit the specific deployment location.

3.4. Comparison with offshore floating wind power

As the offshore wind power industry has already reached a commercial level and is in rapid growth [46], this is the main competitor for the wave power industry to reach commercialization. Tidal power is also making a large impact and significant progress [47], but this technology is approximately at the same maturity level as the wave power industry. Some studies have been conducted in order to map out the levelised-cost-of-energy of wind power in the Northeast Atlantic Ocean, e.g. [48,49]. In [48] the authors conclude that the LCoE of offshore floating wind power in locations close to the Faroe Islands are approximately 95 EUR/MWh. These number are valid for locations some kilometers off the shore in the Faroe Islands. Comparing this to the LCoE for some of the lowest values from the wave energy converters analyzed in this study (62 EUR/MWh for CorPower, 62 EUR/MWh for Wave Dragon and 68 EUR/MWh for NoviOcean NO500), deployment of wave energy conversion devices is truly a competitor to the offshore floating wind power industry.

However, the authors in [48] highlight from their background review that experts anticipate 20%–30% cost reduction by 2030 in offshore floating wind, leading to a LCoE level for offshore floating wind in the same range as for the above mentioned wave energy conversion devices.

4. Conclusions

In this work we have analyzed eight different wave energy converters at nine different locations in the Faroe Islands to assess their performance. The assessment is based on the annual energy production, capacity factor and the levelised-cost-of-energy. The numbers for the aforementioned parameters vary a lot between the devices, but also from location to location. The western lying locations all yield the most favorable LCoE values for all the devices.

The three most favorable devices in terms of LCoE are the CorPower device, Wave Dragon and the NoviOcean NO500 devices. These have LCoE values of 62 EUR/MWh, 62 EUR/MWh and 68 EUR/MWh, respectively, at the most energetic locations. Comparison of these values with other locations in the world, where economic feasibility studies have been conducted, the Faroe Islands are truly a suitable location for wave energy converter deployment.

Comparing the assessment of the wave energy converters with offshore floating wind power, this work concludes that wave energy is truly a competitor to offshore floating wind power in terms of levelised-cost-of-energy.

CRediT authorship contribution statement

Bárður Joensen: Data curation, Formal analysis, Funding acquisition, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Harry B. Bingham:** Project administration, Supervision, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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