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Survey of Wave Energy and matured Wave Energy Technology

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Preface

This bachelor concludes my enrollment at the engineering bachelor *Renewable Energy* at the Norwegian University of Science and Technology. Renewable Energy is a part of the Faculty of Engineering and the Department of Energy and Process Engineering.

This bachelor offered the opportunity for me to delve into a subject which I find most interesting - the energy potential of the oceans. My main supervisor, Håvard Karoliussen, made a great effort in making it possible for me to write about this subject. I have always found it interesting how such a big part of our planet is covered by water, yet there are no big commercialised way of exploiting the energy it possesses. This opened my eyes for wave energy, and this bachelor was an opportunity to look for some answers. The purpose of this bachelor were to investigate how mature the current wave energy technologies were, and if they were or could be competitive with integrated energy sources.

I would like to thank my co supervisor from Equinor, Emil Edwind, for the interest and encouragement. Foremost, I would like to thank Johannes Falnes for invaluable help and insight - being a source of knowledge and experience.

Finally, I would like to thank Alejandro Oyarce Barnett for jumping in as a supervisor in the last weeks of my bachelor, when Håvard went on sick leave. He has offered close supervision and excellent guidance and feedback throughout.

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Abstract

The purpose of this bachelor was to convey a survey to understand how mature the wave energy technology has become, and to review if the technology is currently competitive. The main part of the bachelor has been a literary study to find out what has been done up till now. This turned out to be highly dependent on getting in touch with the right people, in order to get at hold of relevant theory.

The bachelor presents five wave energy technologies considered as promising. The results of this bachelor shows a cost comparison of these technologies and other energy sources, and examines the influence of the learning effect on the presented technologies.

The conclusion found in this bachelor is that the wave energy technology are well-tested and functional in relation to producing electricity, and delivering this to the grid. Furthermore, it is concluded to be promising for the technology to move into niche markets, such as remote locations and locations without grid connection. Even if there is not found indications of wave energy technology being competitive on the today's market in this bachelor thesis, it is shown that the technology is technically mature. New scenarios of the market readiness could be achievable through substantial investments in order to reduce CapEx or changes in legislature and incentives based on the climate issue.

Abbreviations:

AC Alternating current

CapEx Capital Expenditure

DC Direct current

EMEC The European Marine Energy Centre

IEA The International Energy Agency

IRENA The International Renewable Energy Agency

LA Line Absorber

LCOE Levelized Cost of Energy

NVE The Norwegian Water Resources and Energy Directorate

OpEx Operational Expenditure

OWC Oscillating Water Column

OWSC Oscillating Wave Surge Converter

PA Point Absorber

PTO Power Take Off

QPA Quasi-Point Absorber

SWH Significant wave height

WEC Wave energy converter

Glossary:

Capture width The length of wavefront which has been totally captured by WEC.

Diffraction When ocean waves spread out on the far side of openings and bend around obstacles.

Heave Motion along the z-axis. Number 3 in figure 2.3.

Pitch Motion around the y-axis. Number 5 in figure 2.3.

Roll Motion around the x-axis. Number 4 in figure 2.3.

Surge Motion along the x-axis. Number 1 in figure 2.3.

Sway Motion along the y-axis. Number 2 in figure 2.3.

Yaw Motion around the z-axis. Number 6 in figure 2.3.

Symbol	Unit of measurement	Description
$A_{parallel}$		Reliability of components in parallel.
A_{series}		Reliability of components in series.
g	m/s^2	The gravitational constant.
H	m	Wave height.
H_s	m	Significant wave height(SWH).
J	kW/m	Wave energy.
k		The number of components which at least has to work in a k- of n-structure.
p		Reliability of individual components in k- of n-structure.
P_s		Reliability of k- of n-structure.
T	s	Wave period.
x		Component in reliability network.
η		Efficiency.
ρ	kg/m^3	Density of sea water.

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1 Introduction

Even if the first known patent of harvesting wave energy is from 1799, wave energy did not get a kick start until the energy crisis of the 70's. At this point the western countries were terrified that they were about to run out of oil. The fear was that the support of Israel, in the Arab-Istraeli war of 1973, would lead to the refusal of supplying the western countries with oil. This lead to the search of new energy sources to avoid the dependency of one source with monopoly in the energy market. At this point the motivation was fear of oil famine, later it became cost, but the motivation to find and invest in new energy sources now(2020) should be to save the world and environment for future generations.

This was the notion of David Ross and several other advocates for wave energy already in 1995. David Ross spent decades trying to illuminate the public of the possibilities of renewable energy, mainly wave energy. Wave power has fought a war against nature, reactions, prejudice and riches. Over the years wave energy has suffered several serious crisis of confident, involving investors becoming cautious. However, wave power has endured, even if somewhat minimized.

In 1995 Ross stated that the waves holds as much energy as the world used at that time. He also underlines that the waves hold that much *energy* that the world consumed, not just electricity. However, the global energy consumption has increased. Aurélien Babarit estimated, in 2017, the global ocean wave energy resource to be 18 500 TWh per year. To put this in perspective, the Norwegian energy consumption of 2018 was 136.7 TWh. Nonetheless, the global energy consumption of 2014 was 110 000 TWh in 2014, which makes the potential contribution from wave power only a fraction of the global need.

Aforementioned, the motivation to invest in renewable energy and therefore wave energy, should be to save the world and inviroment for future generations. As Davis Ross put it in 1995:

"The ultimate prize is an inexhaustible source of non-polluting energy(...)"

The purpose of this bachelor is to take a new look at wave energy, to see how far the technology has gotten. How mature has the research and technology on wave energy become, and is it at this point competitive with current energy production technologies?

The bachelor is written with Equinor as project sponsor, and thus focuses on technology capable of reusing existing structure or connection to off grid platforms. The bachelor is written on the basis of Equinor's visions. They strive to be a driving force of creating a sustainable community and a energy system in balance. Equinor wants to be an example and an inspiration to others on how to get there.

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2 Theory

This section starts with an introduction of the basic theories of wave energy, including the principles of harnesting wave energy and the essential theory for generating electricity. The section also includes the main categories of wave energy converters and several promising wave technologies.

2.1 Introductory to wave energy theory

To understand the possibility of the energy that can be acquired from the ocean, it is important to know the basic equations that correlate with the wave's energy.

The easiest way to understand wave energy is through linear theory. In linear theory, the energy of the wave can be expressed as equation 1. The parameter J is the wave energy, whereas the parameters T and H are the wave period and -height, respectively. The sea water density is represented by the parameter ρ and g is the gravitational constant. The wave energy is expressed as kilowatts per metre of wave front [kW/m][13].

$$J = \frac{\rho g^2 T H^2}{32\pi} = 0.986TH^2 \approx TH^2 \tag{1}$$

For all practical purposes equation 1 may be abbreviated and expressed simply by wave height and -period. This means that if there is a ten second wave approaching, which has a period of ten seconds, with a height of two metres, this wave is carrying approximately the energy of 40 kW/m.

Linear theory also offers equations which depicts interrelation between wave period, -length and -velocity. By assuming linear waves, these parameters will be easier to predict[13]. However, linear theory assumes idealised sinusoidal waves. Nevertheless, this is not the case at all time in actual seas. Figure 2.1 shows measured wave heights every ten minutes, at the location Sleipner A, for the last 24 hours the eighteenth of February 2020[35]. This is an example of how waves often does not follow the sinusoidal form.

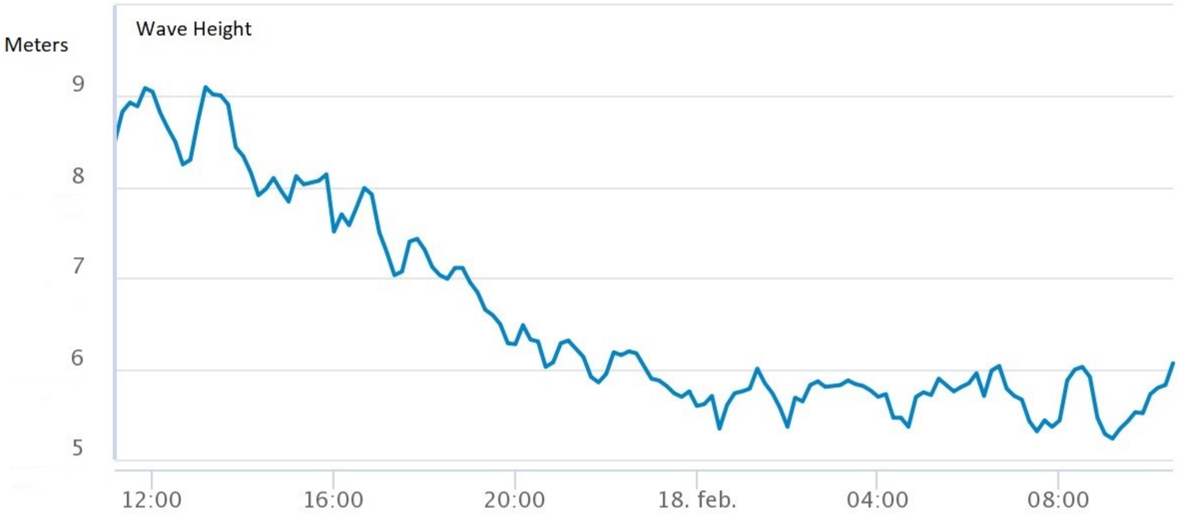

Figure 2.1: *Wave height at Sleipner A 18.02.2020, [35].*

If a Wave Energy Converter(WEC), explained in subsection 2.3, are to achieve energy conversion and survival, the designers must be able to describe and understand the wave patterns shown in figure 2.1[13, section 2.1.2]. These wave patterns, known as random waves, are described in statistical terms - today using probability distribution. Significant Wave Height(SWH) has been, and is today, the most important statistical measure of random waves. This will be further explained below, and is depicted in figure 2.2 as H_s[13]. Wave frequency are also an important parameter for describing complex random seas, which also can be described through statistical terms, but this will not be described further in this text.

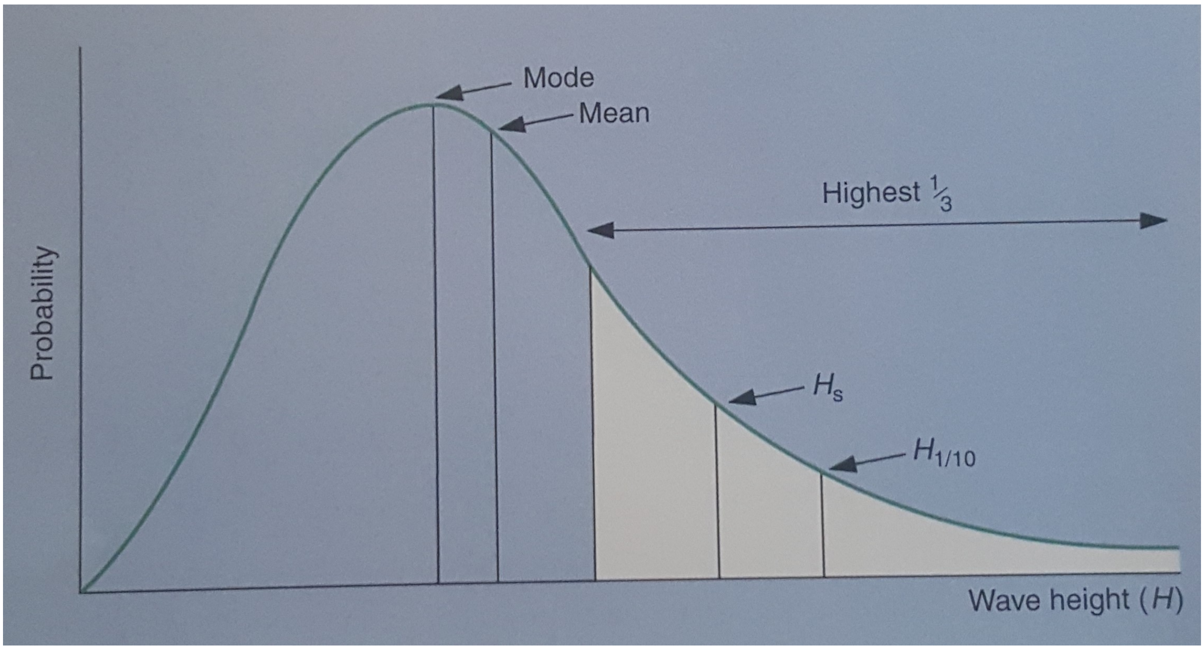

Figure 2.2: *Rayleigh distribution of wave heights[13].*

SWH is defined by looking at the highest third of wave heights and finding the average. In figure 2.2 the highest third is shown by the white colored area, and SWH is represented by H_s. Furthermore, here *mode* is the most probable wave height, *mean* is the average wave height and $H_{1/10}$ is the wave height exceeded by ten percent of the waves[13].

Since SWH is a well used measure of a sea's roughness, it will be useful to know what a prediction of SWH from a marine weather forecast indicates. Assuming Rayleigh distribution of wave heights, a prediction of SWH will make it possible to calculate and therefore also predict the other parameters in figure 2.2. It is important to consider, while designing a WEC, that a SWH of ten meters will suggest an average wave height of 6.4 meters, but statistically ten percent will exceed 12.7 meters and one percent will exceed 16.7 meters. The WEC must be able to survive even this one percent[13].

The WEC experiences forces from the waves and may, depending on the design, move in different ways and directions. Figure 2.3 illustrates the six modes of motions, when referencing the body of a WEC. The six motions are; surge(1), sway(2), heave(3), roll(4), pitch(5) and yaw(6)[3].

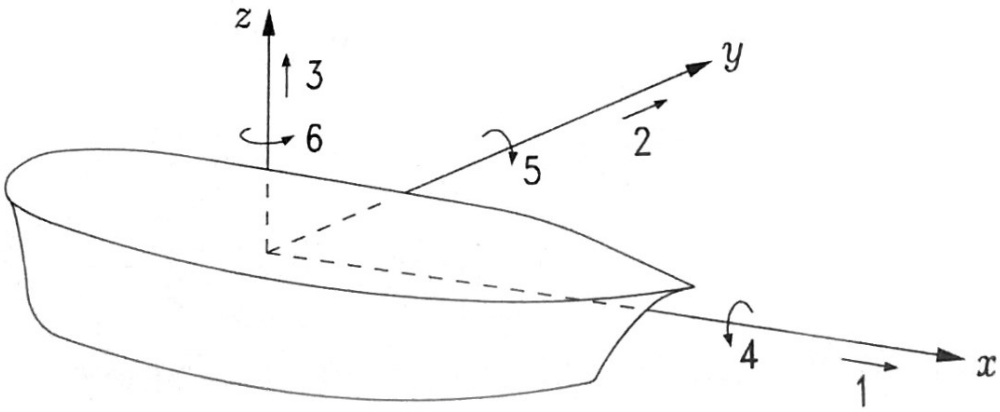

Figure 2.3: *The six modes of motion of a rigid body [3].*

2.2 Principles of wave energy capture

The fundamental principle of wave energy capture is based on the statement that to absorb a wave is to generate a wave[13]. Furthermore, this statement can be expressed as; "to destroy a wave means to create a wave"[3]. In order to absorb wave energy, energy has to be removed from the waves. This is done by a cancellation or reduction of the waves, through destructive interference. Hence, a WEC needs to be good at generating waves in order to be good at absorbing the waves energy[3].

The WECs absorbing wave energy have to generate an outgoing wave, which interferes with incoming waves. The interference has to be done in such a way that there is less energy carried with the resulting transmitted wave than what the incoming waves is carrying with them[1]. Looking back at equation 1, this means that it should be easy to see if a WEC is working by seeing a considerable reduction in the wave's height and/or period.

Theoretically, there is possible to have complete absorption. This is illustrated in figure 2.4. In this figure *a* represents an undisturbed incident wave moving to the right. The waves represented by *b*, describes symmetric wave generation by a floating, oscillating symmetric body. Here, the wave generation is done on otherwise calm waters and in heave mode. The same body is illustrated in curve *c*. Here, the body is working in surge and/or pitch mode, creating asymmetric waves. In curve *d* a theoretical complete absorption is illustrated, and this represent the sum of the previously mentioned curves; a,b and c[3].

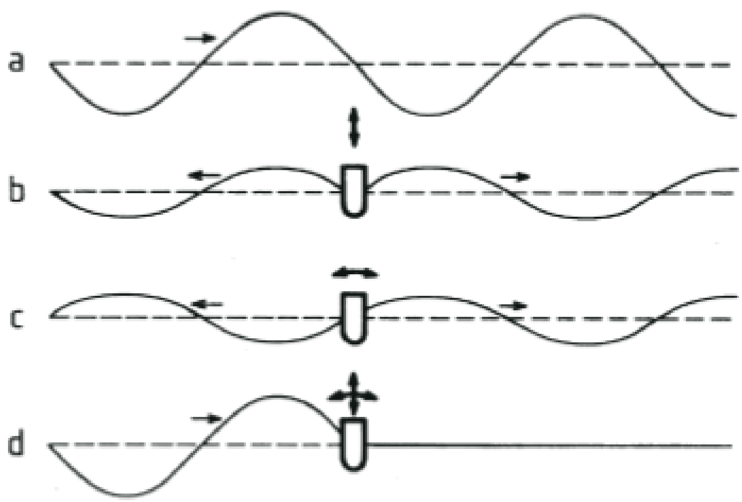

Figure 2.4: *Illustration of theoretical complete absorption [3].*

The principle of wave energy capture is the first step in wave energy conversion, known as primary energy conversion. The schematic principle of extracting wave energy is shown in figure 2.5, where the absorption of the waves' energy is depicted in the first step[17].

2.3 Wave Energy Converters

In order to generate electricity from waves, there is a need for a device which capture and converts the wave energy into another form of energy. This is done with a wave energy converter(WEC)[30]. Figure 2.5 illustrates the schematic principle of extracting wave energy that the WEC needs to be able to do[17]. The first step is explained in section 2.2 and the remaining steps will be further addressed in section 2.4.

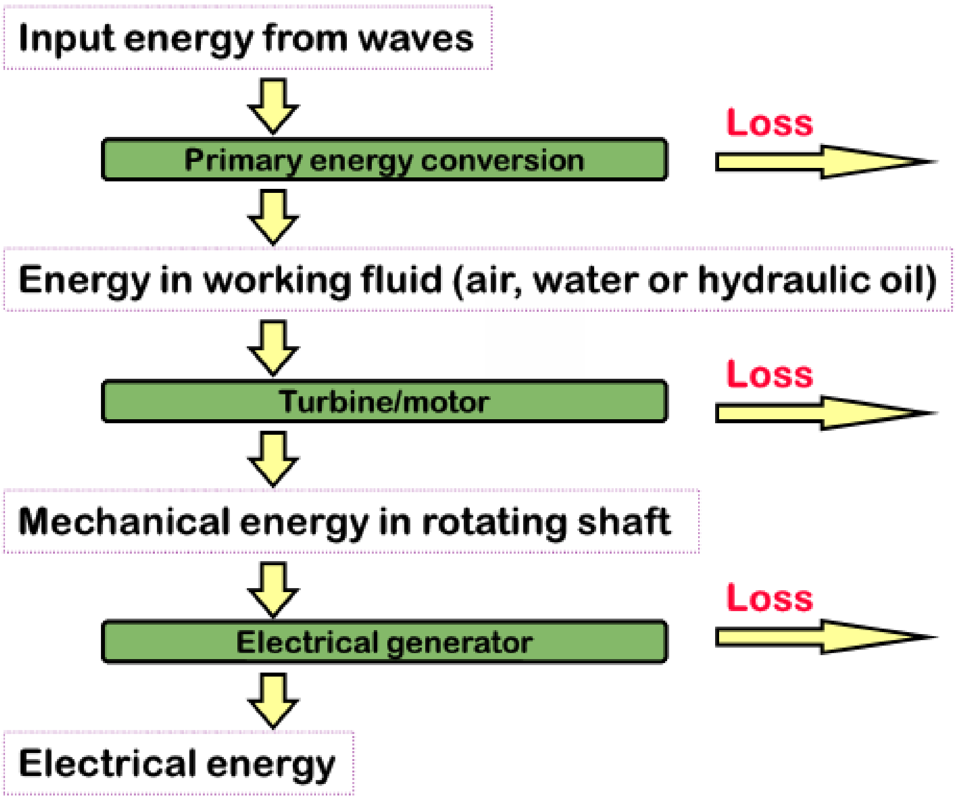

Figure 2.5: *Schematic principle of extracting wave energy [17].*

Figure 2.5 includes illustrations of the losses related to the different energy conversions. The total efficiency of any system with several components is expressed as equation 2. The total efficiency is represented by η_{total}, whereas η denoted with a number up to n represent the efficiency of each individual component[37].

$$\eta_{total} = \eta_1 \cdot \eta_2 \cdot \eta_3 \cdot ...\eta_n \tag{2}$$

The η may also represent subsystems, consisting of several components, within the total system which the total efficiency is to be found. This would apply in the example of figure 2.5 where each principle may be though of as a subsystem of the WEC. To follow up the example aforementioned of a wave carrying 40 kW/m, the potential energy that the WEC may absorb with a *capture width* of 4 meters are 160 kW. The capture width is the length of wavefront which has been totally captured and absorbed by the WEC. All WECs has a theoretical maximum capture width. It is the ratio between the theoretical maximum capture width and the actual capture width which makes up the efficiency of the first principle - the primary energy conversion[16].

Assuming 4 meters of capture width is the theoretical maximum of this example, this represent 100% efficiency. If the efficiencies of the two following principles were 60 and 70 %, equation 2 gives a total efficiency of 42 %. The power output in this case would then be 67.2 kW.

There is a wide variety in the design of WECs, and there is no set way of categorising them. This text will address two ways of categorisation. In the book *Ocean waves and oscillating systems*, Johannes Falnes propose a way of classification by size of the wave energy converter device in the updated version of 2020[21].

The classification of Falnes uses the categories Point Absorber(PA), Quasi-Point Absorber(QPA) and Line Absorber(LA). PA and LA will in this case be the extremities of the classification, while QPA is a classification to bridge the gap between them[3]. The PA was defined in 1975 by Falnes and Budal as a WEC where the horizontal extent of the device is considerable smaller than one wavelength[1]. Brian Count specified this definition, and Falnes adopts this in *Ocean waves and oscillating systems*. This adds that the WEC's horizontal extent has to be less than 1/20th of the incident wavelength. This specification is added in order to justify the assumption of negligible wave diffraction on the PA[3].

Line absorbers are WECs where one of the horizontal extents are at least one wavelength and the other is considerable smaller than one wavelength. Traditionally, a LA where the long side is parallel with the wave direction is called an attenuator, and where it is perpendicular is called terminator[3]. However, attenuator and terminator will not be used in this context later, since this can be confusing with the categories used by The European Marine Energy Centre(EMEC) explained below.

The category QPA is, as mentioned above, meant to bridge the gap between PA and LA. This means that a QPA has a horizontal extent between 1/20th and one wavelength. In the case of QPAs the wave diffraction is not negligible[3]. Since Falnes uses a relation between horizontal extent and wavelength to categorize different WECs, one device may shift category depending on the wavelength on the incident waves. Furthermore, if a WEC is designed as a PA, the designed extent of the device will indicate what wave climate this PA apply.

The European Marine Energy Centre categorise WECs within the eight groups listed below [30]. This is a classification based on how the different WEC technologies work. Thus, this text will try to offer a classification from both Falnes and EMEC to make it easier to understand how the technology work and what kind of wave environment it suits.

1. Attenuator
2. Point absorber
3. Oscillating wave surge converter
4. Oscillating water column
5. Overtopping/Terminator device
6. Submerged pressure differential
7. Bulge wave
8. Rotating mass

Those devices that do not fit in to any of the categories listed above is placed in the group *Other*. This may be unique, very different and/or somewhat controversial designs[13, 30]. However, in the fast moving wave energy scene, there is a need to adjust occasionally. Since 2013 the number of categories has increased by two - Bulge wave and Rotating mass [13, 30].

In the following sections, 2.3.1 to 2.3.8, each category will be explained.

2.3.1 Attenuator

The attenuator is a floating device that operates parallel to the direction of the waves. It has two or more sections that moves with the waves, capturing energy through exploiting the relative motion between the sections[13, 30].

The Pelamis is a classic example of an attenuator, both in the categorization of Falnes and EMEC. To further illustrate how an attenuator work the Pelamis will be used as an example. Still attenuators may differ from this.

Pelamis is an attenuator as described above, composed by multiple sections linked by hinged joints. The Pelamis is depicted in figure 2.6. The relative motion between the sections is restrained by hydraulic rams. These pump fluid into high-pressure accumulators. In order to drive the induction generators, standard variable displacement hydraulic motors is used. This system is housed within the Pelamis. The motors draws a controlled flow from the accumulators to drive the generators. The displacement of the motors is varied in response to the slow change in pressure in the system. This is done to ensure a steady and continuous electrical power output from each joint[8].

Figure 2.6: *The Pelamis P1A-002 on site in Portugal[8].*

2.3.2 Point absorber

Point absorber, which formerly was defined as a WEC with a horizontal extent less than 1/20th of the wavelength of the incident waves, is by EMEC only defined by how the technology work. Thus, EMEC defines PAs as devices with a floating structure at or near the surface, where the relative motion between the floating structure and a base is converted in to energy [30].

The article written by Falnes and Budal from 1975 is highly referenced today, as well as earlier in this text, and introduced point absorbers. To illustrate how a PA work the illustration from this article is shown in figure 2.7[1].

In this illustration a represents the floating structure and d represents the base. The wire s is kept stretched by the auxiliary tank b, where s drives a flywheel f[1]. In this case, one can imagine the flywheel driving a generator, thus creating electricity. The PA illustrated in figure 2.7 is an example of how a PA may take form, but this may differ[30].

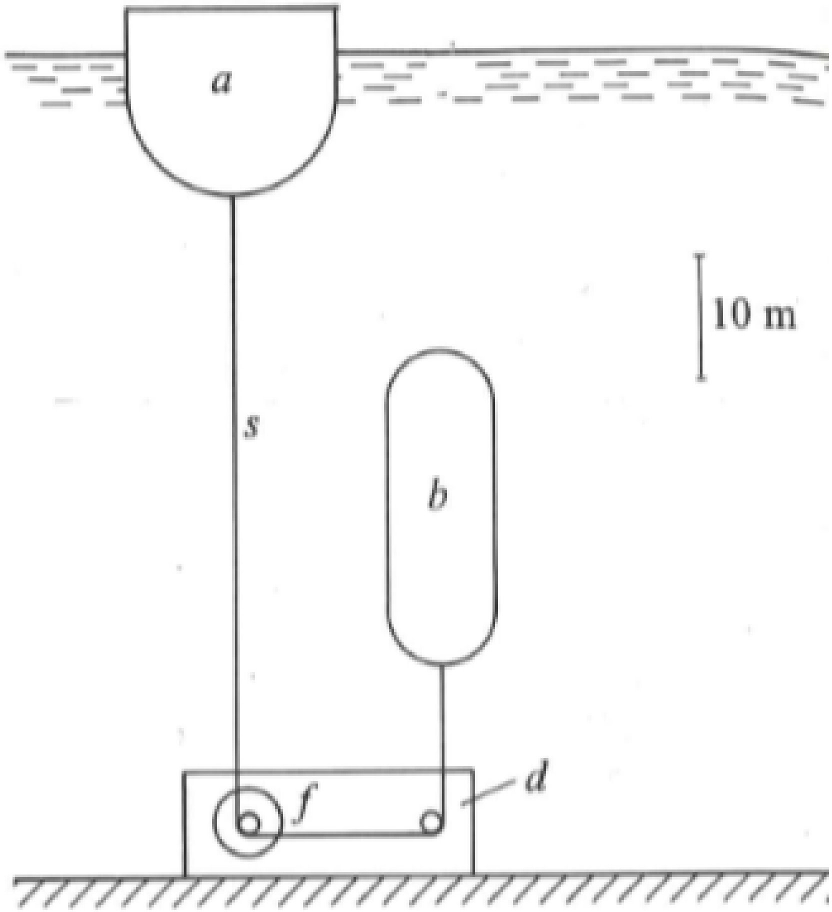

__Figure 2.7:__ Illustration of an example of a point absorber[1].

2.3.3 Oscillating wave surge converter

The Oscillating Wave Surge Converter(OWSC) has an arm, typically a flap, that oscillates and reacts to the oncoming surging waves and the water particles' movements within the waves[13, 30]. A well known example of a oscillating wave surge converter is Stephen Salter's *Nodding Duck*[13].

The *Nodding Duck*, illustrated in figure 2.8, consist of a flap, which shape is shown in (a). This flap obtains an oscillatory motion by the incoming waves. In turn, this motion is converted into electricity by a hydraulic-electric system[13]. This system is comparable to the one Pelamis use, which is explained in section 2.3.1.

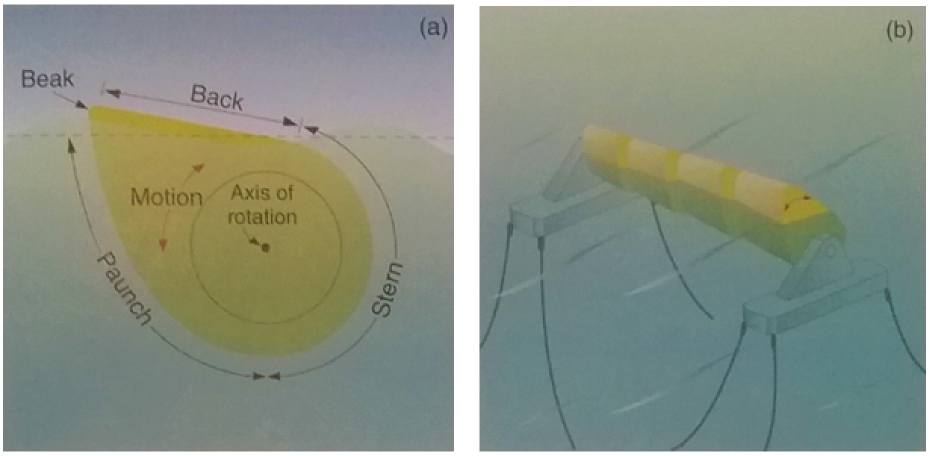

Figure 2.8: *Illustrates Nodding Duck from the side(a) and as an array(b) [13].*

2.3.4 Oscillating water column

The Oscillating Water Column(OWC) is a device consisting of a hollow column. It is partially submerged, where the structure is open to the sea below the water line. Waves causes vertical oscillations of the water column within the structure. At the top of the structure the oscillations causes air to compress and decompress. The air is allowed out through a turbine, that usually can rotate in both directions, where the rotation is used to generate electricity[13, 30].

An example to further illustrate how an oscillating water column device work is the *Limpet* by Voith Hydro Wavegen. This was installed in the year of 2000 on an island in Scotland, and was the worlds first commercial-scaled WEC to be connected to the grid. The Limpet is illustrated in figure 2.9[13].

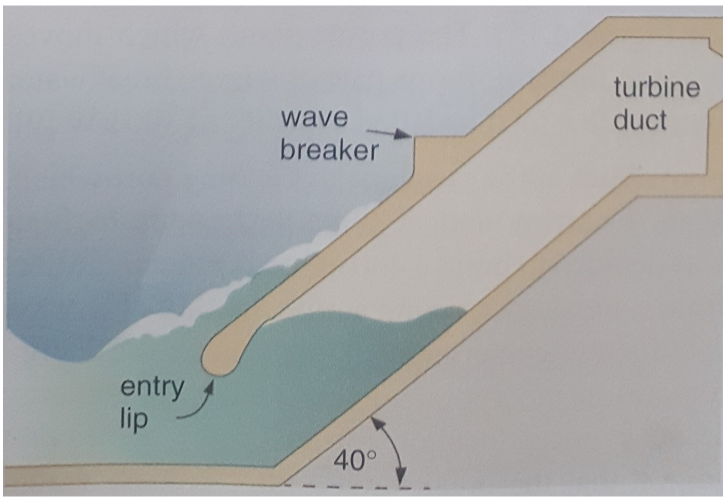

Figure 2.9: *Illustrates the Limpet by Voith Hydro Wavegen[13].*

The *Limpet* allows waves to enter its hollow structure passing an entry lip. Here, the wave faces an inclined ramp. This creates oscillations of the water column within the Limpet. As a result of this the air column above is alternately compressed and decompressed. The air is driven back and forth through a turbine, which rotates in the same direction regardless of the direction of the air flow. Consequently, no moving parts is in contact with the water, which increases the reliability of the device. Furthermore, the turbine is connected to a generator, and this turbine-generator technology is both well tried and tested, yet increasing the reliability[13].

2.3.5 Overtopping/Terminator device

The overtopping WEC captures the energy from waves through directing them into a reservoir, which is located above mean sea level. The potential energy is then extracted by letting the water out passing through a turbine. Special collectors may be used to concentrate the wave energy and increase the water capture [13, 30].

An example of an overtopping device is *Wave Dragon*. An overview of how this device works is illustrated in figure 2.10.

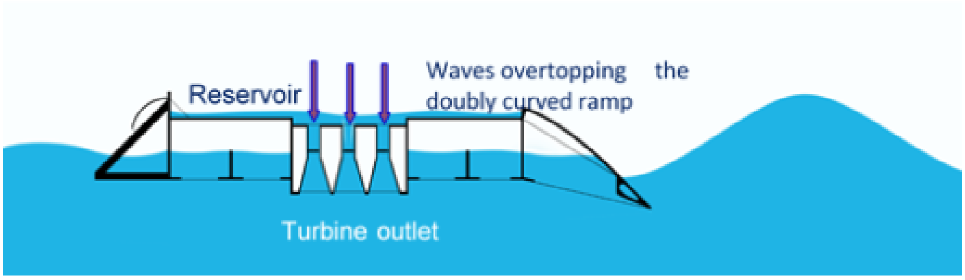

Figure 2.10: *Illustrates how the overtopping technology of Wave Dragon works[31].*

Wave Dragon utilizes two wings to concentrate the wave energy of the incoming waves. The water from the reservoir is let out passing through a number of hydro turbines. These turbines are the only moving parts of the device and are protected by a grating, This will prevent marine debris from inflicting damage on the turbines[31].

2.3.6 Submerged pressure differential

The submerged pressure differential WECs exploits the difference in pressure in the water, caused by the the rise and fall of waves. Hydraulics is applied to generate electricity, by having the alternating pressure pump fluid through a system [13, 30].

2.3.7 Bulge wave

A bulge wave device consist of a rubber tube, which is filled with water. The tube is moored to the seabed and oriented in the same direction as the waves. Water enters in one end and travels through the tube. While passing through, the water in the tube is affected by the passing waves. The waves creates pressure differentials through the length of the tube, then creating a *bulge* of the water within. The bulge grows and gathers energy throughout the tube and is passed out of the tube through a low-head turbine, generating electricity [30].

2.3.8 Rotating mass

The WECs based on rotating mass, uses the movement of heaving and swaying in the waves to capture energy. The devices applies either an eccentric weight or a gyroscope, where the movement described earlier causes precession. Electricity is produced through a generator [30].

2.4 Generating electricity

In section 2.3 a schematic principle of extracting wave energy was presented in figure 2.5. Aforementioned a WEC needs to be able to perform all the principles illustrated in the figure. As the first principle was explained in section 2.2, the following principles will be covered in this section.

The second principle of extracting wave energy, covers the further energy conversion from the captured wave energy, in the form of energy in a working fluid, to mechanical energy. It is important to know that each WEC may handle the conversion of wave energy into electricity in different ways, depending on their design. The *Lifesaver* of Fred. Olsen is an example of a WEC which somewhat skips a step of conversion from the basic schematic of figure 2.2. Their Power Take-Off(PTO) system do not consist of a state where the energy is in a working fluid. Whereas this system will be further explained in section 2.5.1, it is already clear to see that this does not coincide with the schematic principle of figure 2.2. However, as the Lifesaver is an example of how the energy conversion is done may differ immensely, the Pelamis is an example of a WEC which follow the schematic exactly.

The PTO-system is a system which can differ immensely from a WEC to another[13]. Some of the different forms the PTO-systems may take has been described shortly in some of the previously explanations of WECs. Examples of this is the hydraulic system of Pelamis and the compressed and decompressed air of the Limpet, which drives a turbine. These PTO-systems is described in sections 2.3.1 and 2.3.4, respectively.

To further demonstrate how a PTO-system may take form, a basic hydraulic PTO-system is illustrated in figure 2.11. A piston within a hydraulic cylinder(C) moves back and forth due to wave motion. This causes high pressure in the liquid being used, at the right end of the cylinder. The liquid is forced through a control valve(V) and into the high pressure line(HP). Short term energy storage is provided by an accumulator(A), which releases energy in a way that provides steady input to a hydraulic motor(M) and further, an electrical generator(G). The liquid is transferred back to the cylinder through a low pressure line(LP) via the control valve[13].

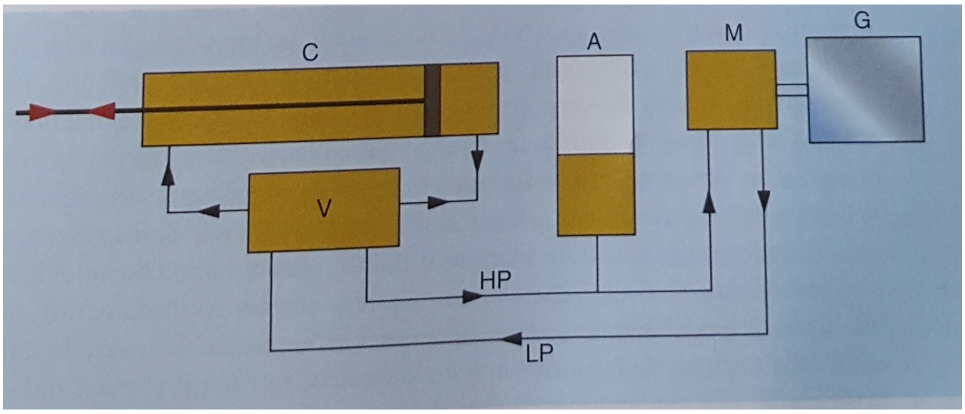

Figure 2.11: *Hydraulic PTO-system[13].*

The last principle of extracting wave energy, based on figure 2.5, is turning mechanical energy in to electrical energy. In terms of figure 2.11, the last principle covers the conversion from M through G. In the same manner as many other aspects of WECs, the type of generator and set up may differ immensely. There are pros and cons about every type of generator, and the designer of the WEC needs to choose based on the need and fit of the WEC. However, every designer needs to consider the integration of its generator to the grid. In order to connect to the grid, the output needs to have the right frequency, voltage and phase corresponding to the grid[13].

Examples of how to deal with this issue, is by a *power converter* and a *transformer* in connection with a synchronous generator. The transformer adjust the amplitude of the voltage. The power converter decouples the rotation speed of the shaft from the frequency of the grid. The alternating current(AC) of the generator is first converted to direct current(DC), and then converted back into AC. This provides separation between the AC of the generator and the AC of the grid. This means that the power converter allows the generator to run at variable speed, which can smooth the transition of the unpredictable wave energy to electrical energy. Furthermore, the power converter can be designed to produce or absorb reactive power. Hence, it can regulate the *power factor* of the grid. Devices such as generators may need or produce reactive power, but most household devices only takes real power. Generally, the grid therefore has a power factor of unity, which means only real power[13].

Aforementioned, there are many ways of attaining a good grid connection - the synchronous generator connected to a power converter and a transformer is only one example. Another would be an asynchronous generator connected to a capacitor bank and a transformer. This would have a analogous effect as the previously mentioned synchronous generator example, but often be a more affordable alternative[13].

Moreover, the location of WECs matter in the integration into the grid. Wave energy is an unpredictable source of energy, depending on weather and other conditions. This means that a WEC can experience peaks and lows in power output in a short period of time. This, however, is not something the power companies would be happy about letting on to the grid. There need to be a system in place to smooth the transition. The two examples of generators, may be designed in a way to help this transition. As well as the accumulator in figure 2.11 is a good example of short storage, which also makes this transition smoother. In terms of location it is important to choose a point where the grid is strong enough to handle both the peaks and the lows of the power outputs of the WECs[13].

2.4.1 Reliability

A structure, such as a WEC, consist of several components. When these components is set in a system, which makes up the structure, it can be illustrated by a reliability network - an example of this is illustrated in figure 2.12[4].

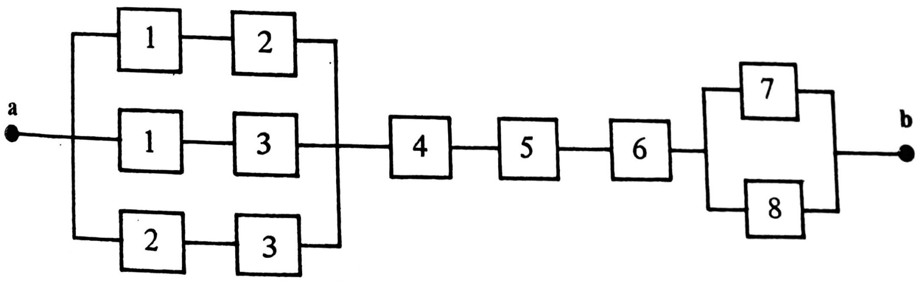

Figure 2.12: *Reliability network[4].*

In order to calculate the reliability of a system, it is necessary to know how to calculate reliability for components in series and parallel. Equation 3 present the reliability for components in series as A_{series}. Here each x represent a component; up to a number of n components[4].

$$A_{series} = x_1 x_2 ... x_n \tag{3}$$

In figure 2.12, components four, five and six represents components in series. Whereas components seven and eight represent a parallel structure. The reliability for components in a parallel is given in equation 4 as $A_{parallel}$[4].

$$A_{parallel} = 1 - (1 - x_1)(1 - x_2)...(1 - x_n) \tag{4}$$

Components one, two and three is, in figure 2.12, placed in a *k- of n-structure*. This means that in such a structure the system only operates when k components out of n is operational. The reliability for this system is given in equation 5. The reliability is represented by P_s, and i equals k - the number of components which at least has to work for the system to be operational. The reliability of the individual components included in the k- of n-structure are represented by p [4].

$$P_s = \sum_{i=k}^{n} \frac{n!}{i!(n-i)!} p^i (1-p)^{n-i} \tag{5}$$

To calculate the reliability for the complete system from component one trough eight, shown in figure 2.12, the aforementioned subdivisions can be counted as components in series. In this case the reliability for the complete system, known as A_S, is found by multiplying the reliability of the k- of n-structure by the reliability of the series-structure and the parallel-structure.

Aforementioned, a WEC consists of several components. The reliability network of a WEC differs depending on their design. Based on the theory presented in this section it is important to understand that if a WEC is designed with all components in series, then a single component error will lead to device failure. In appendix A a list of large-scaled tested WECs is provided. In the column furthest to the right the project outcome is described[16]. Some of these outcomes are examples of how an error in a single component led to failure of the WEC. Again, based on the theory presented above, the WEC would not experience complete failure if the component which suffer fault was connected in parallel[4].

2.5 Wave technology

In the following sections, 2.5.1 to 2.5.5, some wave energy technologies are presented. These are technologies that may be considered some of the most mature wave energy technologies and closest to commercializing. Pelamis and Wave Dragon were mentioned already in 2014 in Paul Lynn's book as some of the more mature and established WECs in his section on case studies of wave energy converters[13]. All of the following technologies are mentioned in Aurélien Babarit's book from 2017[16], except from the CorPower Ocean's WEC. The CorPower Ocean's WEC is incorporated based on the recommendation from EMEC on technologies they considered promising. EMEC also recommended the technologies; the Penguin(by Wello Oy), the Laminaria, the Blue Horizon(by Mocean) and Archimedes Waveswing(by AWS)[20]. These are not included due to inadequate information.

2.5.1 Lifesaver

The company Fred. Olsen has run a wave energy development program since the early 2000s. They are currently working on the BOLT Lifesaver wave energy converter in co-operation with the US navy[25]. The *lifesaver*, shown in figure 2.13, has been tested in real sea conditions, which has contributed to experience and knowledge[14].

In order to be relevant and competitive on the marked, Fred. Olsen has chosen a niche marked. An example of this is their collaboration with the US navy, as one may imagine operates on remote locations.

Figure 2.13: *Lifesaver [14].*

The Lifesaver is a point absorber in context of its working principle, while in the categorization of Falnes it would classify as a PA or a QPA, depending on the wave climate. The specifications of the Lifesaver is shown in figure 2.14[24].

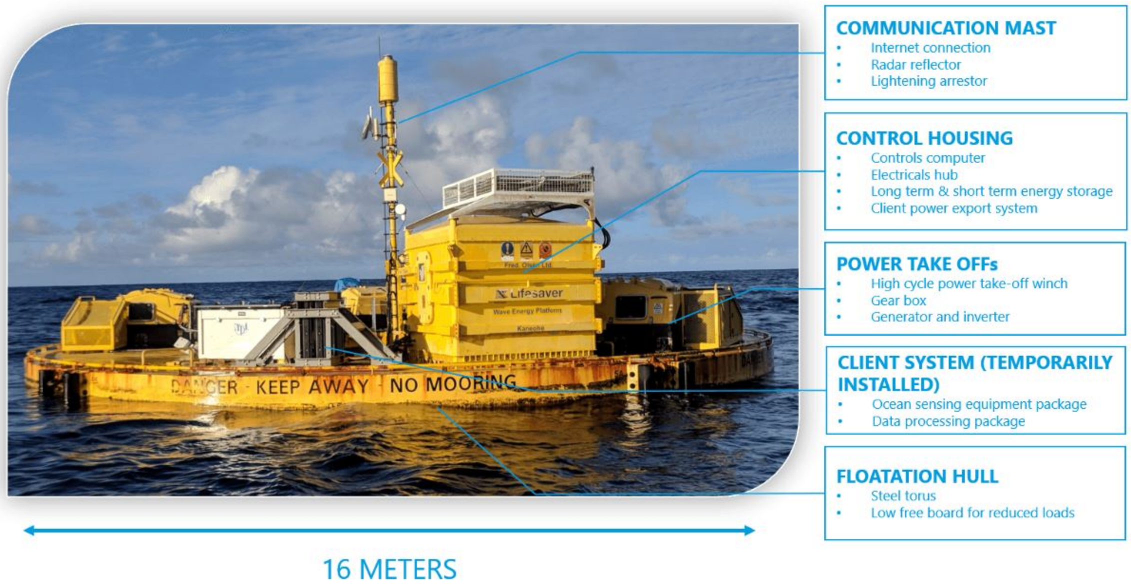

Figure 2.14: *Specifications of the Lifesaver [24].*

The phd *Marine renewable energy conversion* by Jonas Sjolte, amongst other topics, looks at the financial perspective of the Lifesaver. This is presented in table 4.2 and will be further covered in section 4.2. The phd also incorporate a detailed description of the system of the Lifesaver. The WEC consist of a floater, and may contain up to five PTOs. Nonetheless, there were only three PTOs installed. Some key parameters of the Lifesaver are listed in table 2.1[14].

Table 2.1: *Key parameters of the Lifesaver [14].*

Floater outer diameter	16	m
Floater inner diameter	10	m
Floater hight	1.0	m
Mass	55	tons
Water depth	55	m
Number of PTOs slots	5	
Currently installed number of PTOs	3	
Damping force per PTO	100	kN
WEC rated export power	75	kW
Total installed generator capacity	400	kW

Fred. Olsen has operated five WECs in total, at different depths between 30 and 60 meters. They have simulated the WEC at a depth of 1000 meters, and reported that it would operate well. However, the efficiency will decrease with the depth[22]. The

Lifesaver are designed to be able to both be a stand-alone system and a grid connected system. The topology of the grid connected system are shown in figure 2.15. This illustrates how the electricity are made to correspond to the grid and how they are designed to be able to work independently. This makes the system able to smooth the transition and be easy to maintain[14].

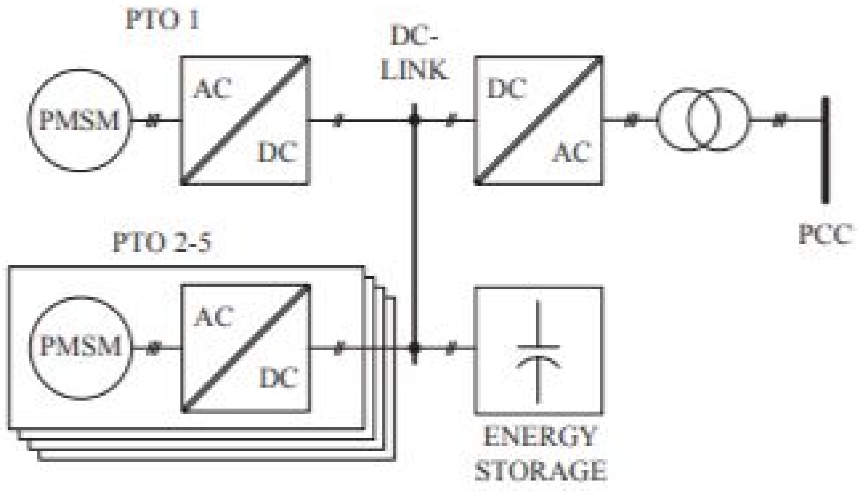

Figure 2.15: *Topology of the grid connected system of the Lifesaver [14].*

The purpose of the PTOs is to convert linear motion in to electrical power. The system is realized through a winch and rope system. A sketch of the principal of the PTO-system is shown in figure 2.16. The system is designed to only produce power during one direction - heaving motion. More specifically the generator will produce power during upwards motion, and work as a motor during the downwards motion in order to wind the rope back on to the drum[14]. Hence, it is the net energy which will be transferred in to electricity.

The drum is connected to a gearbox, which is realized as a belt drive system. This offers a system which is robust against shock loads and operates well with reciprocating motion. The belts are coated in order to be resistant against the highly corrosive environment at sea. The belt drive system is well tested by Fred. Olsen, and the concept has demonstrated excellent performance. It is a flexible system and is easy to exercise maintenance on. The gearbox can carry full load at maximum speed, and therefore has a high power capacity. However, the system has a poor PTO utilization factor due to large speed variations. It is further exaggerated due to only allowing unidirectional production force. The PTO utilization may be doubled if the system would allow bi-directional force production. This is not done due to cost evaluations[14].

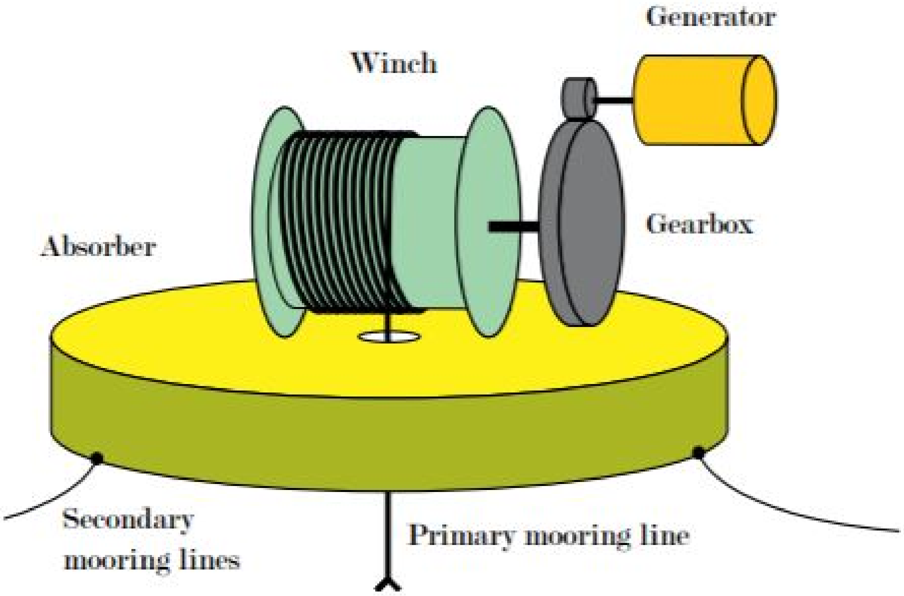

Figure 2.16: *Principal sketch of the PTO of the Lifesaver [14].*

The generator was chosen based on some main parameters including efficiency, cost and torque precision. Fred. Olsen landed on a Permanent Magnet Synchronous Machine(PMSM) from Siemens, which serves as a servo machine. This means that the generator delivers high torque precision and good efficiency. However, the torque precision delivered is much higher than required, which results in an unnecessarily costly system[14].

2.5.2 Pelamis

The working principle of the Pelamis is explained in section 2.3.1, under the explanations of EMEC's categories. In the categorization of Falnes, the Pelamis is a LA. Pelamis was a technology developed in the time between 1998 and 2014. It was considered the leader of its time and "the competitor to overcome". However, Pelamis Wave Power went bankrupt in December 2014. This due to a crisis of confident that the wave power business experienced, starting in 2012, where investors became sceptical and more cautious. There were many projects starting out too optimistic, where the development of the WECs proved harder, longer and more expensive than the initial plan. Several WEC developers were affected by this crisis, leading to downsizing and bankruptcies. The intellectual property of Pelamis now belongs to Wave Energy Scotland. Nonetheless, the technology has been thoroughly tested and highly developed in the active years up to

2014[16].

Pelamis had several pilots, where the last one was Pelamis P2. The P2 had a rated power of 820 kW. It was 180 meters long, consisting of five cylinders, each of 36 meters with a diameter of 4 meters. Aforementioned, in section 2.3.1, the relative motion between the cylinders operated the hydraulic PTO[16]. A cut out of the joint and the PTO-system of the P2 is shown in figure 2.17[8].

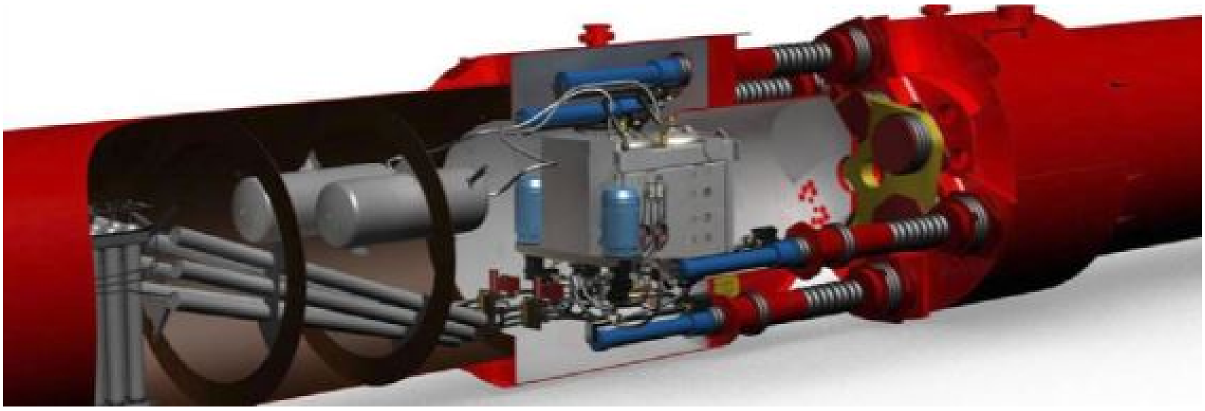

Figure 2.17: *The joint and the PTO-system of Pelamis P2[8].*

The mooring system was consisting of flexible lines and was connected to the first section of the WEC. A fast connection/disconnection of the mooring system lead to it being easy, when necessary, to perform maintenance- and other operations at port[16].

There were made many prototypes of Pelamis - three P1 prototypes and two P2. The WEC evolved from the P1, with 750 kW rated power, to the P2, with 820 kW. The length went from 120 meters to 180[16]. Always developing and improving the technology, lead to an increase in efficiency. This is illustrated in figure 2.18, which shows an comparison between the prototypes of P1 and P2. The total conversion efficiency of the P2 is approximately 70%[8].

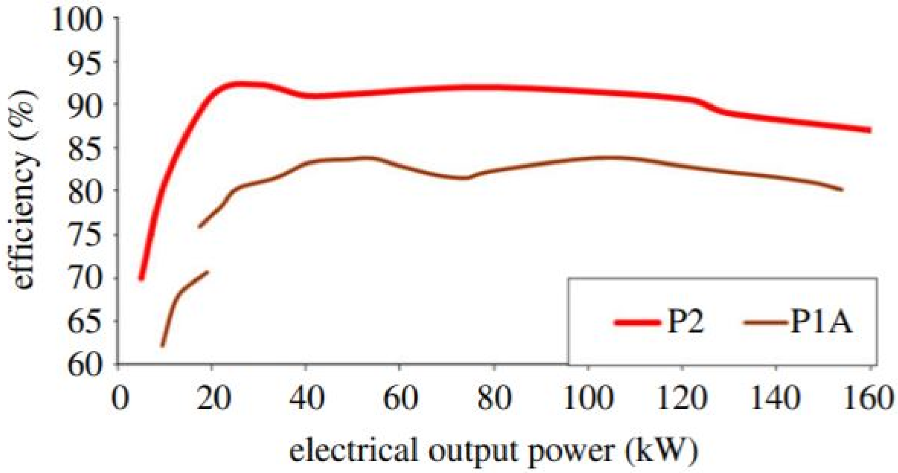

Figure 2.18: *Comparison of efficiency between P1 and P2[8].*

Aforementioned, in section 2.3.1, Pelamis utilizes varied displacement of the motors and short time storage in the accumulators to ensure steady and continuous power output. A prototype of the Pelamis P1 was tested at EMEC in 2007 and delivered electricity to the grid in the United Kingdom. A power record for the first joint of the prototype is shown in figure 2.19. This five minute recording shows the high variation in absorbed power with the smooth outgoing electrical power[8].

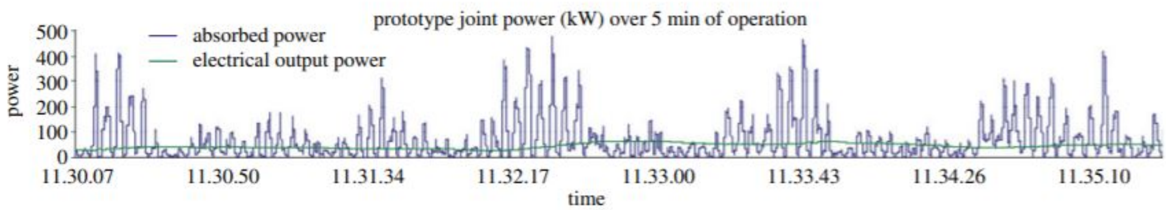

Figure 2.19: *Recording of absorbed power and outgoing electrical power of the Pelamis P1[8].*

2.5.3 Langlee Robusto

Langlee wave power created their WEC based on the key factors listed in table 2.2. Their WEC utilizes the horizontal component of the upper layer of the wave energy. The components used are standard, off the shelf components, in order to reduce cost and avoid any dependency of new developments and unique, specially produced components. The mooring systems are designed to be competitive by basing it on the existing offshore aquaculture mooring models. Competitive installation is achieved by the use of existing, standard towing- and lifting vessels. There will be no need for specially designed ships. Local production is desired because of the cost reduction it would prompt and the because of the work positions it would create and the jobs it would secure. In order to achieve direct energy transfer, the energy conversion is done from wave to wing/flap to generator. This will be further explained below. Lastly, the maintenance program will be executed with simple methods and minimal down time, in order to obtain as continuously as possible grid delivery.

Table 2.2: *Key factors of Langlee Wave Power's Wave Energy Converter[23].*

- Great utilization of the wave energy
- Low cost components
- Competitive mooring systems and installation
- Local production
- Direct energy transfer
- Direct, simple and cost efficient grid connection
- Long lifetime
- Defined and cost efficient maintenance program

Figure 2.20 shows an illustration of the Langlee Wave Power's WEC. The WEC is made of a moored submersible base. This consists of two wings/flaps, which oscillates in the pitch mode. The mechanical energy of the angular motion of the wings is converted to electricity through generators[12]. The WEC classifies as a oscillating wave surge converter by the classification of EMEC based on the working principle. By Falnes' classification the WEC is a LA.

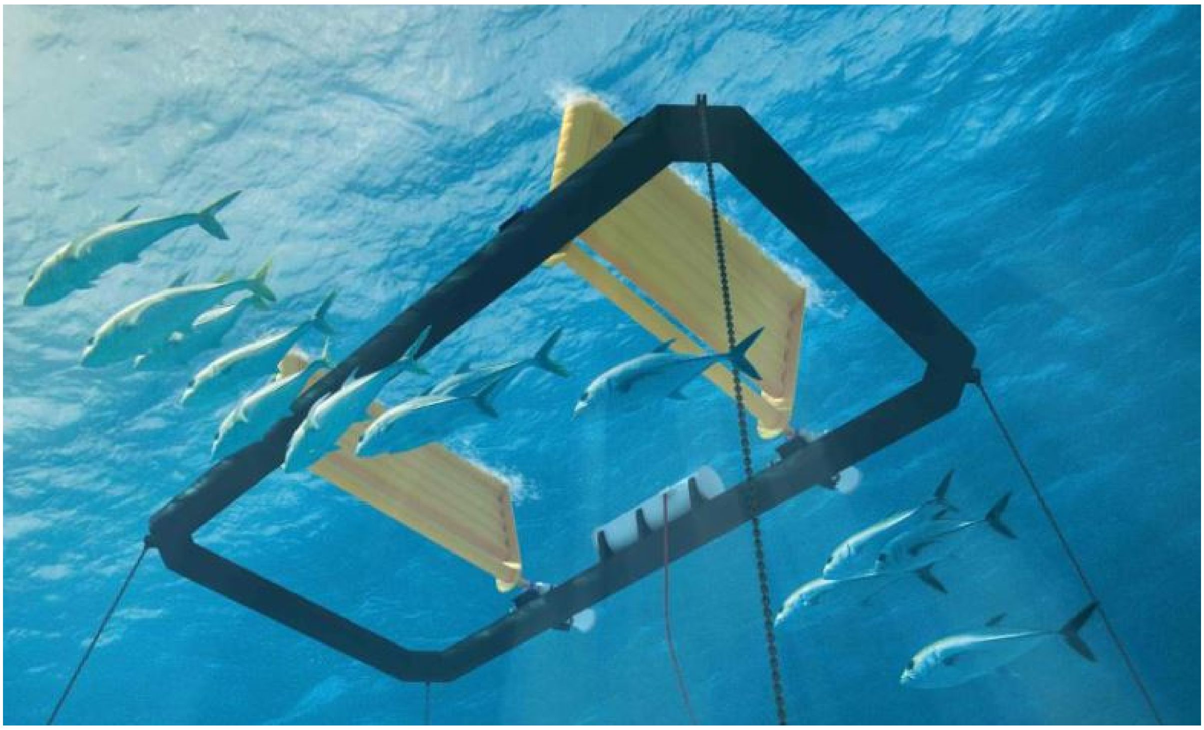

Figure 2.20: *The Langlee Wave Power's Wave Energy Converter[28].*

The wings of the Langlee Wave Power's WEC is equipped with its own PTO-system. The PTO-system is shown in figure 2.21. It shows the direct energy transfer of the WEC. The wave causes an oscillation of the wings. This mechanical energy is directly transferred in to electrical energy via the generator, that in turn is connected to power electronics which ensures good grid connection [6, 28].

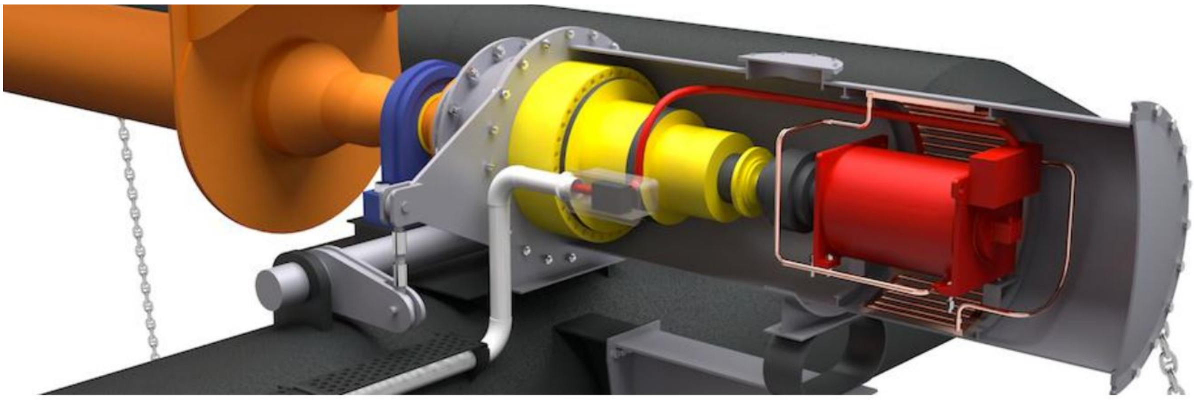

Figure 2.21: *The PTO-system of the Langlee Wave Power's WEC[28].*

The WEC has an installed power of 132 kW and measures 30x50 meters. The normal installation depth is between 40 to 100 meters[28]. The Langlee WEC lack a full-scale test, but has been tested as reduced sized models in wave basins in several experimental studies. These studies all have promising results, where the results indicates good performance and efficiency[6, 10, 12]. The first experimental study establish a wave period of peak performance. This is highly dependent on the design of the WEC. The wave period of peak performance was 1.3 seconds for the model tested at this study. This correspond to a wave length of 2.52 meters, which is twice the length of the model and the distance between the two wings. The enhanced performance at this wave period is due to the two wings moving simultaneously in opposite directions, which leads to a significant counter force to the induced force of the wings[6].

2.5.4 Waveboost

CorPower Ocean has designed a WEC which is considered a point absorber, both with the categorization of EMEC and Falnes. This technology utilizes a phase control to optimize the wave energy absorption[26, 15, 9]. The phase control induces a higher power output, where the highest power output is achieved when the WEC moves in resonance with the incident wave[9]. The schematic overview of the Waveboost is illustrated in figure 2.22.

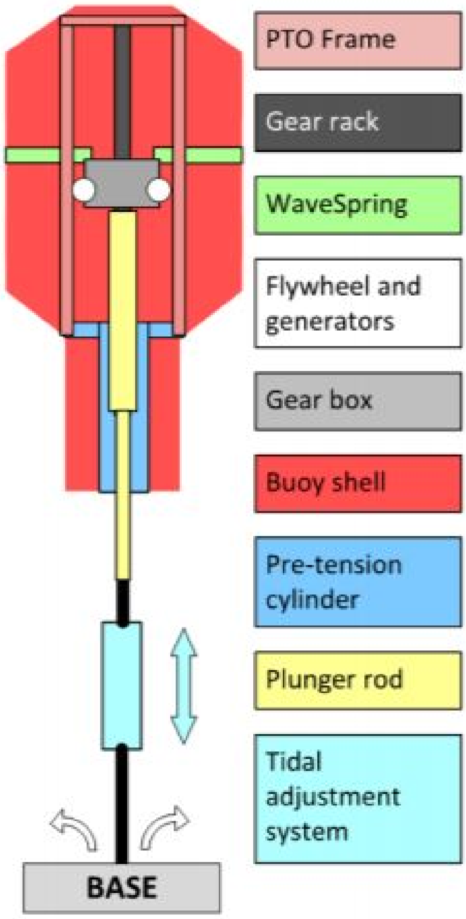

Figure 2.22: *The principal schematic of the CorPower Ocean's WEC [15].*

The phase control, which goal is to obtain resonance, work by locking and unlocking the buoy motion[9]. The phase control technology is called *WaveSpring*, and is marked in green in figure 2.22. The generators and power electronics used for the WEC are well-known and standard components from the wind industry. This ensures good grid connection architecture, due to it being well-tested[15].

The PTO-system consists of a wire that absorb the wave energy through the motion of the buoy. The PTO gearbox convert linear motion into rotating motion and is connected to a set of flywheels and generators. These provide power conversion and short term energy storage. This smooths the transition to the grid, along with the well-known components as mentioned earlier. The PTO also consists of a gas reservoir, which protects the WEC when is encounter large forces[9, 15].
The Waveboost utilizes a pre-tension system, enabling a lightweight system. This means that the mass of the oscillating body is reduced. The use of this technology increases the annual energy capture with 300 percent, and a reduction of required mass by 40 per-

cent[15]. The pre-tension system results in an equal energy production in both downward and upward motion. The WEC absorbs energy from both heave and surge mode[26]. Including the phase control, CorPower Ocean yearns to achieve complete absorption, as explained as theoretically possible in section 2.2.

2.5.5 Wave Dragon

The working principle of the Wave Dragon is previously explained in section 2.3.5. This categorizes the Wave Dragon as a overtopping device, also known as a terminator, in the categorization of EMEC. While Falnes' categorization places the Wave Dragon in the LA group. The structural elements of the Wave Dragon are depicted in figure 2.23.

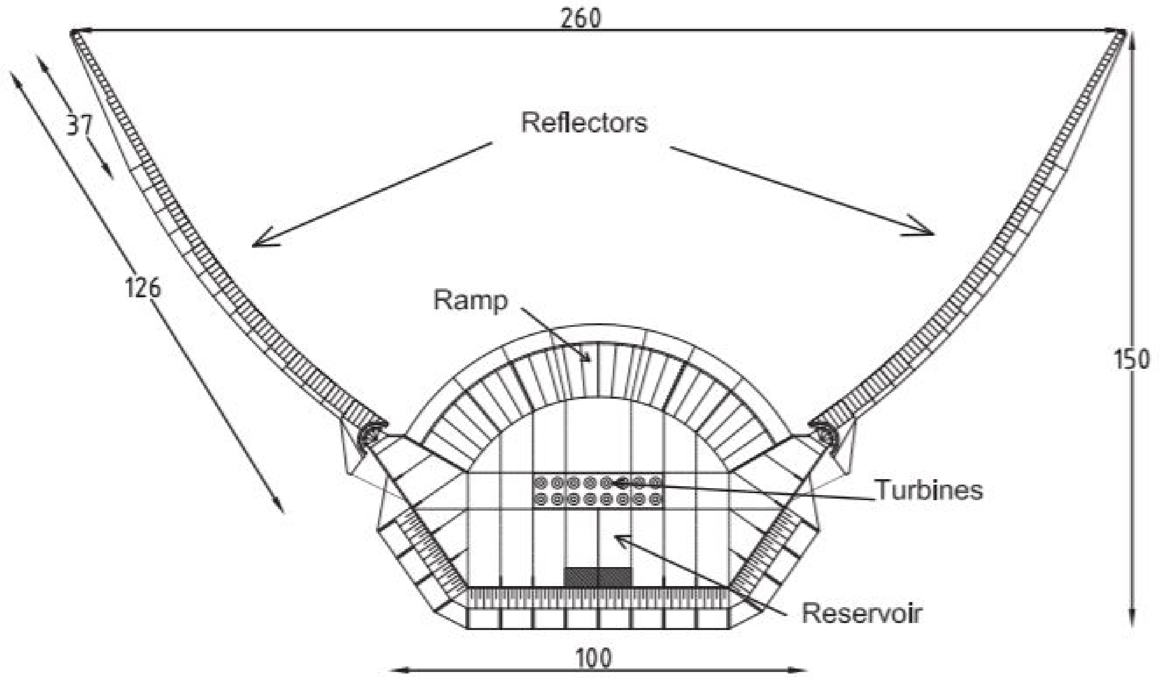

Figure 2.23: *The main structural elements of the Wave Dragon, in meters[7].*

Wave Dragon offers four different sizes on their WEC - 1.5, 4, 7 and 12 MW. They deliver 4, 12, 20 and 35 GWh/year, respectively[27]. In 2017 Aurélien Babarit reffered to the Wave Dragon as the WEC with highest rated power[16]. The grid connection is made smooth with the use of short term storage, in the form of the reservoir. Furthermore, the turbines is directly connected to variable-speed, permanent-magnet, synchronous generators, which subsequently are connected to an electronic power converter[13].

Like Langlee, Wave Dragon lack a full-scaled prototype. However, a scaled prototype located in the large inland sea Nissum Bredning, collected data and experience for more than 20 000 operating hours[13]. Wave Dragon states that the operational and maintenance costs are low, due to the main work being possible to carry out at sea[27]. Furthermore, the turbines are installed in such a way, in parallel, that the electricity production continues even if one turbine fails or is stopped due to a maintenance operation[13].

3 Method

This bachelor has been a mainly theoretical thesis, where the method is based on how to obtain relevant scientific papers. Starting out this bachelor with minimal knowledge of the topics wave energy and wave technology, it was necessary with help to learn where, what and how to search to get hold of relevant theory. The main library at NTNU-Gløshaugen was a great starting point. The books, articles and PHDs attained, at the first visit at the library, contained names of authors and supervisors, which proved smart to contact.

These contacts introduced new contacts and/or led to relevant technology or theory. This additionally made it easier to find more specific keywords, when searching for relevant scientific papers. An example of this is the search for relevant theory describing the working principle of an attenuator. With the keyword "attenuator" the number of hits at the NTNU university library were *40 083*. By changing to advanced search and adding the keyword "wave energy" the number of hits fell to *6 866*. However, this is to many hits to look over, and even the ones notes as most relevant did not include the needed info. Reading obtained relevant theory and talking to some of the contacts with more insight in the wave energy community, learning that the Pelamis in many ways illustrates a conventional attenuator, the search got easier. Only using the keyword "Pelamis" got *4 260* hits. Adding the keyword "concept" got it down to *503* hits, and the first hit, noted most relevant, contained the required material.

Though the search got easier eventually, the most relevant theory has been obtained through personal communication. This due to some reports not being published yet and access to different search engines. The search engines essentially used for this bachelor are *Oria NTNU* and *Science direct*.

The learning curves calculated in this bachelor, are based on Aurélien Babarit's definition of the learning effect, rendered in appendix B. For each learning rate, a learning rate factor was found by subtracting the learning rate from a hundred and divide it by a hundred(e.g. one hundred subtracted by the learning rate of 16.5% makes 83.5, dividing this number by a hundred results in a learning rate factor of 0.835). The initial cost of the WEC is multiplied by the learning rate factor, which generates the new cost of the device when the number of units has doubled. This process is then repeated for the new cost, generating the cost for the device when a new doubling of number of units has been achieved.

4 Results and discussion

Based on the presented information of the five WECs in section 2.5, wave energy technology seems likely to be considered reliable when considering having a working device, producing and delivering electricity to the grid. This section will undertake this consideration further, and analyze the financial perspective of the WECs and comparing them with other energy production technologies.

4.1 Market considerations

The first known patent for wave energy harvesting dates back to 1799. By 2017 there were more than 3000 patents registered for wave energy conversion applications[16]. EMEC lists 253 WECs under development in the world in 2020 - an increase of 53 since 2017[16, 29]. Even though wave energy technology often is referred to as new technology the fore-mentioned facts would suggest otherwise. The number of WECs having undergone large scale testing, listed in appendix A, adds to the claim that wave energy technology has a long history. The WECs listed in this appendix is of the scale between 1/3 and 1[16]. The objective of this bachelor is not to conduct a survey to figure out if wave energy technology is able to produce energy. However, both the information presented on the selected technology of this bachelor, and the historical review of Babarit rendered in appendix A, shows that this is a fact.

It has long been though that wave energy technology would follow a similar *learning curve* that of wind energy technology, and by this obtain a cost reduction[13, 16]. The effect that the cost of a product decreases with a constant rate every time the number of produced units doubles, has been observed in different industrial sectors. This includes renewable energy, where examples are photovoltaic solar cells, biomass and wind-based energy. The rate equaled 35, 15 and 18 percent, respectively. The International Energy Agency(IEA) recommends a rate of 18 percent for new technologies, while the Carbon Trust in the United Kingdom recommends 15 percent. An example calculated in the book of Aurélien Babarit, suggest that a rate of 16.5 percent applied in a learning curve for the wave technology *Oyster*, whould make the technology competitive on the Scottish market when they reach the 70th installed unit. To get to the 70th installed unit would still require a considerable investment[16].

In order to analyse if wave energy is competitive on the market a comparable parameter is needed. The Norwegian Water Resources and Energy Directorate(NVE) reports on the costs in the energy sector. The last report was published in 2019 on the costs of 2018. This numbers are listed in table 4.1. The Levelized Cost of Energy(LCOE) represents the cost of the energy over the lifetime of the technology. NVE has divided the LCOE according to the expenditure; investment, operation and fuel. It should be noted that these numbers are gathered from the Norwegian energy market[34].

Table 4.1: *LCOE in the energy sector[34]*

Technology	**LCOE-investment €/MWh**	**LCOE-operation €/MWh**	**LCOE-fuel €/MWh**
Hydropower (>10MW)	27.61	3.55	-
Hydropower (<10MW)	28.55	6.21	-
Onshore Wind	21.65	8.87	-
Coal	14.95	4.87	37.61
Nuclear	36.32	11.04	6.56

The International Renewable Energy Agency(IRENA) published the report *Renewable power generation costs in 2018*, which contains accurate numbers on the costs of renewable energy. Figure 4.1 shows the global weighted average total installed costs and project percentile ranges for; solar photovoltaic, concentrating solar power, onshore wind and offshore wind. It shows the evolution of costs from 2010 to 2018[18].

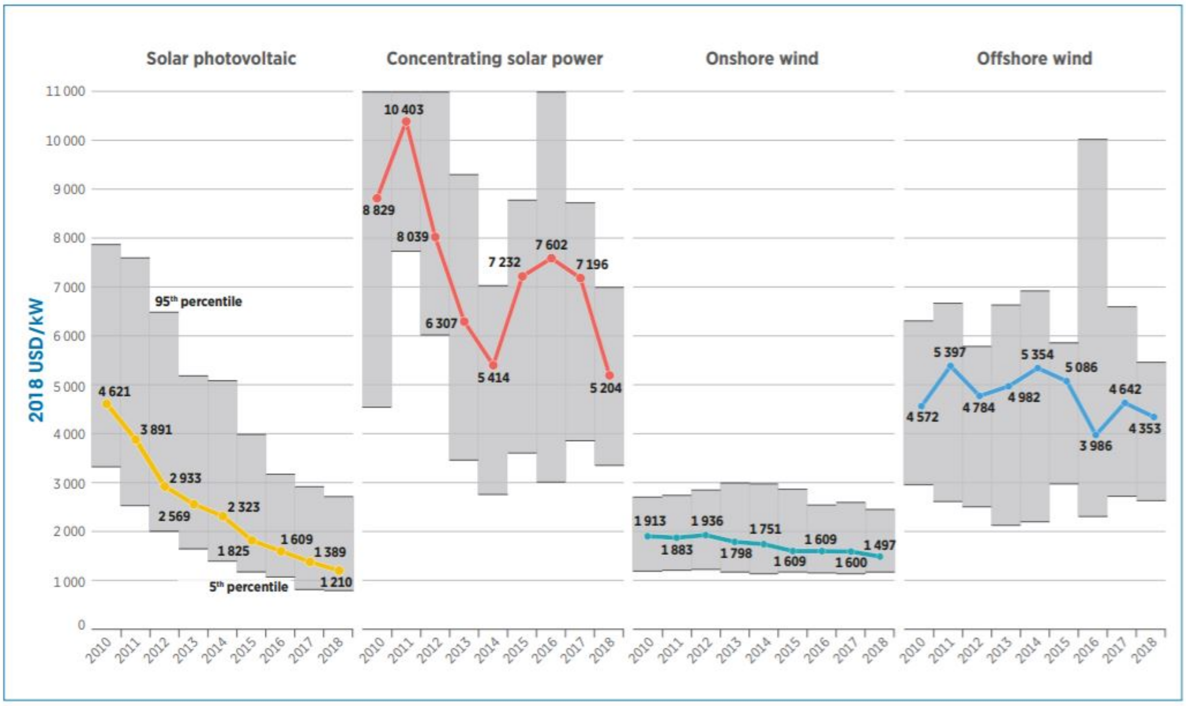

Figure 4.1: *The global weighted average total installed costs and project percentile ranges, 2010-2018[18]*

IRENA states in their report that the cost reduction of solar and wind power technology will continue to 2020 and beyond. Furthermore, they state that it is feasible that, by 2020, onshore wind and solar photovoltaic consistently will offer more economical electricity than the least-cost fossil fuel alternative. By 2020 they predict that offshore wind and concentrating solar power will offer electricity in the range of 0.06 to 0.10 USD/kWh[18].

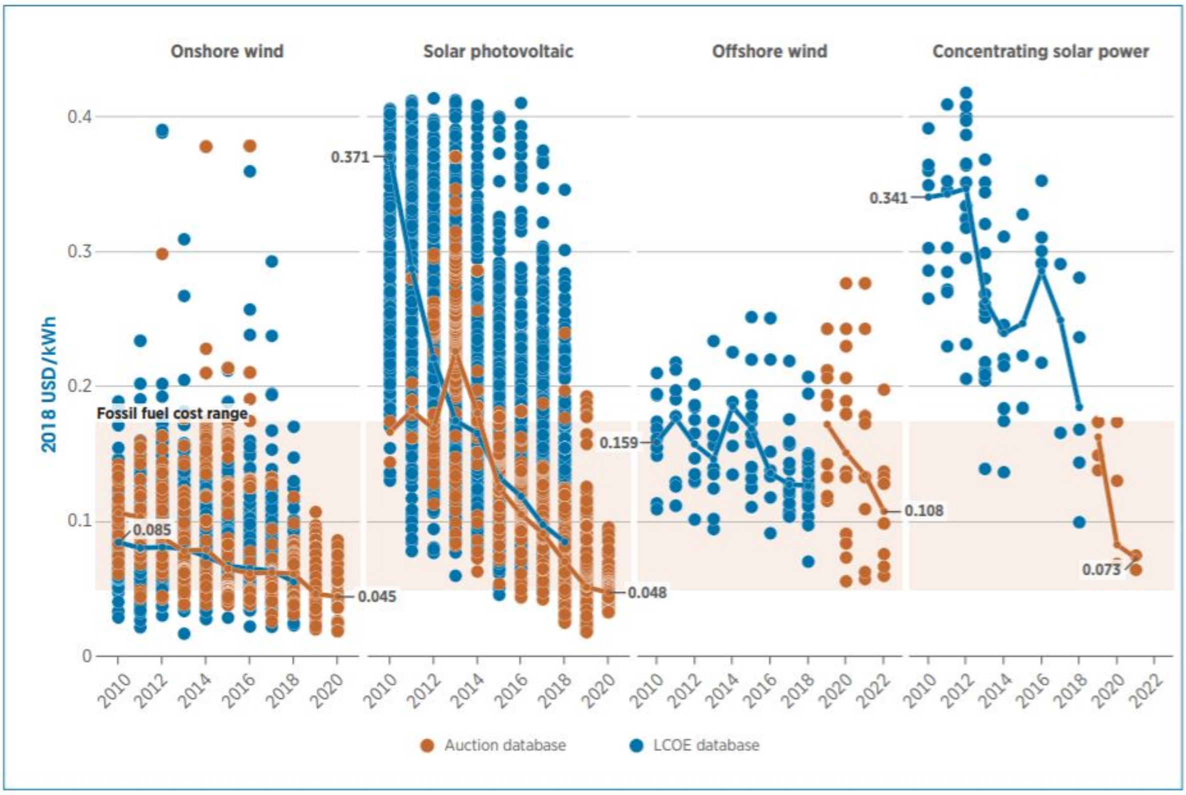

Figure 4.2: *The LCOE for projects and global weighted average values, 2010-2022[18]*

Figure 4.2 shows the LCOE for projects and global weighted average values for; onshore wind, solar photovoltaic, offshore wind and concentrating solar power. It shows both the evolution since 2010 and predicts it up to 2022. Here, each circle represent an individual project or an auction price. The lines are the global weighted average LCOE by year[18].

This sections presented the costs of today's integrated energy sources. Furthermore, it presented a prediction of cost reduction for renewable energies from 2018 to 2020 and beyond. This may be considered as an indication of anticipated cost reduction for the wave energy technology, if the technology gets to a point of being integrated on the market. However, as seen by the example of the Oyster by Babarit, it would take 70 produced units to become competitive on the Scottish market. Just to become competitive would require large investment and the assumed learning rate would have to be a precondition. However, this is not guaranteed and this substantial investment may prove hard to come by. Therefore, a lot would have to fall in to place before the technology would reap the benefits of cost reduction when integrated on the market.

Based on the numbers presented in this section, a WEC with CapEx below 5000 €/kW would be in the range of concentrating solar power and offshore wind. These are the most expensive renewable energies on the market today, and by reaching the same costs as these, would be the first step for wave energy technology to become integrated and competitive on the market.

4.2 Financial perspective of presented WECs

Sjolte analyzed and presented the cost level of the **Lifesaver** in his phd. This is rendered in table 4.2 along with Sjolte's projected cost for the next generation device. The numbers in table 4.2 indicates a great cost reduction potential. This is due to the fact that the Lifesaver was primarily built as a prototype. Hence, the WEC was not built for low cost of energy or low operational cost. It was built to gain operational experience, carry out research and maintenance training. The next generation device has a design target of 175 kW rated capacity, with a result of at least 700 MWh per year[14]. The Capital Expenditure(CapEx) is comparable with the aforementioned LCOE-investment and Operational Expenditure(OpEx) comparable with LCOE-operation.

Table 4.2: *System cost for Lifesaver and estimates for next generation device [14].*

Item	Lifesaver	Next generation	Unit
Floater	7.7	1.6	k€/kW
PTO	8.0	2.2	k€/kW
Mooring and auxiliary	7.6	2.1	k€/kW
Installation	-	0.95	k€/kW
Operational cost	5.3	0.38	k€/kW·yr
Sum CapEx	23.3	5.9	k€/kW
Sum OpEx(NPV, 20 yr, 4%)	-	5.2	k€/kW
Sum CapEx + OpEx	-	11.1	k€/kW

Further cost reduction is suggested through the construction of wave farms and reuse of current grid connection structures. Sjolte adds that a full-scale wave farm connected to the grid, at a site such as *Wavehub*, would be the fastest way to large-scale market. The Wavehub site already has structures to connect to the grid, and a launch like this might attract people to invest in wave energy and prove the viability of WECs as a power source. However, to make this profitable there would be a need of an up-scaling of the rated power and along with this - development costs. Sjolte concludes that in order to reach competitiveness in the market, wave energy would need big investments for several years to come. However, he suggests niche markets; remote locations, islands without grid connection etc., for wave energy to become competitive in the market[14].

At the current time of Sjolte's phd the Lifesaver had been operating for more then two years, and in this time supplied significant experience on operation and maintenance of a WEC over time. Some key performance indicators associated with reliability and availability attained over the two+ years are listed in table 4.3[14].

Table 4.3: *Key performance indicators[14].*

Production ours	1468	h
Electrical energy produced	4644	kWh
Mechanical energy absorbed	7192	kWh
Overall efficiency	64.6	%
Average power during production	3.2	kW
Time on site	376	days
One or more PTOs ready for production	234	days
All PTOs ready for production	23	days
Longest continuous production period	24	days
Time available for maintenance	211	days
Availability hull	100	%
Availability communication	98	%
Availability scientific instrumentation	79	%
Availability control dependent instrumentation	100	%
Availability storm moorings	100	%
Availability cooling system	99	%

Pelamis has had several financial studies and case studies. An article from 2010 sums up the overall cost of energy from the previous studies to be between 0.05 and 0.20 €/kWh. The said article's case study resulted in cost of energy varying from 0.16 to 0.62 €/kWh for one WEC, where the lowest cost was on the location in Ireland and the highest cost was on the location in USA. The cost decreased when there were assessed several WECs. The cost dropped till 0.09 €/kWh in the Irish location when five WECs were assessed. When a hundred WECs were assessed the cost of energy varied between 0.05 and 0.2 €/kWh. Lowest cost applied to the Irish location, while the highest cost applied to the American location. The reason for the variation in cost per assessment is the different wave climates on the chosen locations. The cost reduction related to the increase in assessed WECs is related to two factors. A high number of WECs will reduce the costs due to benefits from economies of large scale production, in addition to the cost reduction due to the learning rate. The second factor is the savings related to the cabling, where multiple WECs can share one cable[5].

An article from 2013, *Techno-economic performance of the Pelamis P1 and Wavestar at different ratings and various locations in Europe*, compares the cost of the two WECs; Pelamis and Wavestar. The case study presented in this article ended in results indicating that the Pelamis performed best when located in high resource locations. The device produced the highest energy and economic returns, but has unsatisfactory results at sites with poor resources. Whereas Wavestar had less variation in performance over the different locations, it only performed better then the Pelamis at the sites with poor resources. The cost of energy for the Pelamis from this article varies from 0.21 to 0.40 €/kWh. The lowest cost of energy was observed when located in Ireland[11].

A cost of energy factor for the Pelamis is the end-stop control system. In order to protect WECs from damage and reaching end-positions, it is necessary to install mechanical parts intended to absorb and stop the motion, known as end-stops. However, the end-stops are often fragile and the cause of failure. This is the reason why many WEC designers make control systems to avoid reaching end-stops. This increases the survivability of the WEC, but may result in an under-utilization of the PTO components, and therefore decreasing the energy performance of the WEC. Aurélien Babarit suggests that this may be the origin of the failure of the Pelamis. Developing control strategies with better use of the PTO, would be an important part of the development and cost reduction plan of the Pelamis. Furthermore, a significant increase in energy performance would have been required in order for the plan to be successful. Babarit states that Pelamis would not have been able to achieve the objective of this plan while keeping the risk of reaching the end-stops under a reasonable limit. He specifies that to do so, at least, would not be possible within the budget and timetable of the investors[16].

Langlee Wave Power states that their WEC will be operating 4400 hours per year[28]. The installed power of 132 kW makes the electricity production of on year to be 580.8 MWh. So far Langlee has had investment of a magnitude of 40 million NOK in to the development of their WEC. In order to get their technology to contribute to industrial and commercial development, Langlee claim that no significant investment would have to be provided[23]. The crisis of confident, aforementioned, that struck the wave power business in 2012, affected Pelamis and ended with bankruptcy, and forced Langlee to put their activities on hold[16]. Langlee has plans, locations and deals in place, just lacking sufficient investments. At this point in time Langlee do not wish to specify the costs associated to their WEC. However, they are confident in their bench marking of being cost competitive to onshore wind power[23, 28]. Langlee has some of the same mindset as Fred. Olsen in relations to bringing their technology to niche markets. Their plans of bringing wave energy to the Canaries, where the island is run on diesel generators is an example of a niche market they have in place as a plan[23].

CorPower Ocean received new investments in 2020 and states that they produce reliable and competitive WECs. Their goal is do deliver certified and warranted WECs on the market by 2023-2024[26]. In 2016 an article looking in to the designing of a multi-MW array of WECs, bases the study on the WEC of CorPower Ocean. They examine the different in cost between fewer WECs with higher rated power versus several WECs with lower rated power and of a smaller dimension. Whereas fewer WECs may be beneficial in relations with operational and maintenance costs, a higher number of WECs of smaller dimensions may be beneficial because of the reductions in material costs as compared to power production. Additionally, the smaller WECs makes it possible to utilize small and inexpensive vessels in association to installation, maintenance operations etc. The model used in the case study incorporates the Capital Expenditure estimates for a prototype with 250kW rated power. The case study aims for a 20MW array and the comparison between individual device ratings and locations are shown in figure 4.3[15].

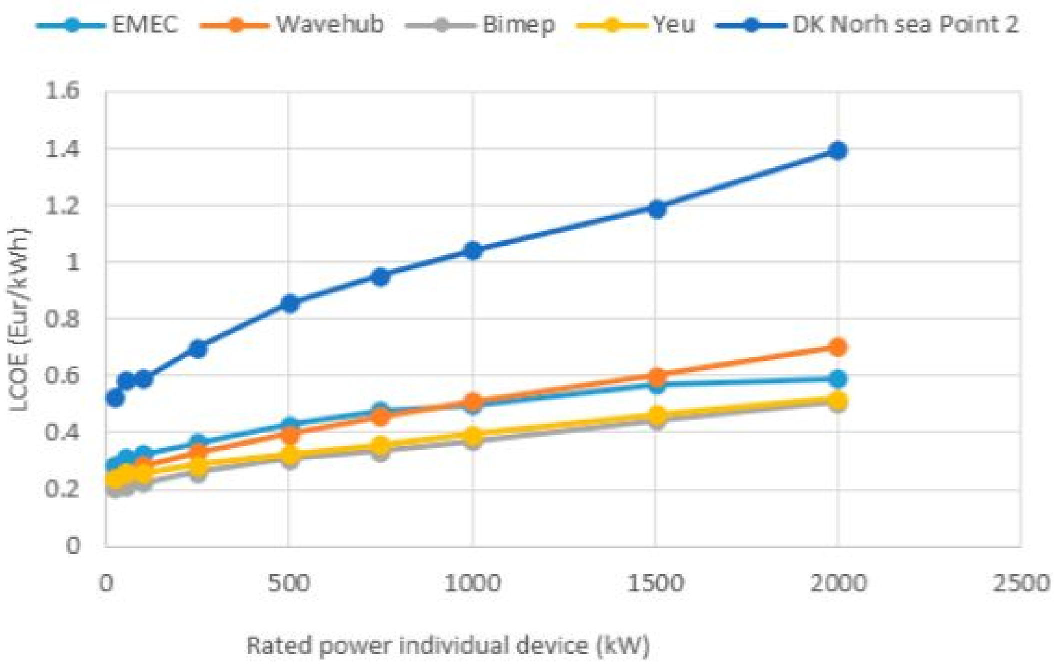

Figure 4.3: *LCOE for different locations and device rating for a 20MW array[15]*

Wave Dragon states to be competitive on the market[19]. The investment cost per kW rated power equals 4000 €/kW for the WEC with rated power of 4 MW, for the first unit. It is suggested that the cost will drop to 2300 €/kW by the deployment of hundreds of WECs[7]. Wave Dragon, a like with Langlee, states to have plans and projects in place, only lacking investments to realize them[19].

The literary study of this bachelor resulted in the accumulation of information on the promising technologies presented in section 2.5. Table 4.4 gives an overview of the most important information collected on these technologies, where the financial perspective of these technologies are presented earlier in this section.

Table 4.4: *Overview of presented technology with financial perspective.*

Name	**Company**	**Type (Falnes/EMEC)**	**Installed Power [kW]**	**Cost [€/kW]**
Lifesaver	Fred. Olsen	PA/PA	175	5900
Pelamis	Pelamis Wave Power	LA/AT	750	1462
Langlee Robusto	Langlee Wave Power	LA/OWSC	132	1269
Waveboost	CorPower Ocean	PA/PA	1000	1890
Wave Dragon	Wave Dragon	LA/OT	4000	4000

Note: In the third column AT is an abbreviation for attenuator and OT an abbreviation for overtopping device.

Reviewing table 4.4 there are several important factors to be aware, these are further explained in appendix D. Regarding Lifesaver, the cost listed is based on a next generation estimation, with reduced cost and higher rated power. This might suggest that the cost is too optimistic. However, the initial cost included expenditures related to research and maintenance training, and this version of the Lifesaver was primarily built as a prototype. Accordingly, a great cost reduction potential seems likely, and therefore the next generation estimations may be assumed as credible.

The cost of energy, listed in table 4.4, for the Pelamis is based on case studies for the Pelamis P1, not the last version of the Pelamis - the Pelamis P2. There were not found case studies with a financial perspective covering the Pelamis P2. However, the article *Pelamis: experience from concept to connection* had graphical comparison of the efficiency of the prototype P1 and the P2, depicted in figure 2.18. This shows a clear increase in the efficiency from the P1 to the P2. A higher efficiency suggest a better and more cost efficient device, indicating that a case study of the Pelamis P2 with a financial perspective, might result in a lower cost of energy, then of that listed in table 4.4.

Furthermore, the cost of energy for the Pelamis is based on a lot of average numbers and assumptions. The case studies which the cost of energy is based on, tested the device at various locations, resulting in the costs varying depending on the location. The reason for this is the different wave climates at each location. An average of all the costs relating to the different locations would represent the overall performance and cost of the Pelamis well. On the other side, the articles presented their results with an interval between the lowest and the highest cost of energy. This means that the average is just based on two numbers - the two extremities of lowest and highest costs. Nonetheless, the average is made more representative when combining the two article's averages in to one total average. Lastly, there were not reported yearly production hours in the articles. Therefore an average between the reported production hours of the Lifesaver and the Langlee Robusto was used in order to get at comparable cost of the Pelamis with the unit €/kW.

In regards to the cost of the Langlee Robusto, the cost was never reported in any scientific papers etc. The cost was only based on a statement that their WEC was compatible with onshore wind power. Therefore, the cost for onshore wind was used for the cost of the Langlee Robusto. This was based on the numbers from IRENA for the year of 2018. Originally, this was listed in USD/kW. To make the number comparable, the exchange rate from 2018 was used to end up with the unit €/kW. The reason for choosing the rate from 2018 was mainly because the listed cost of IRENA was from 2018. Additionally, the exchange rate of today was considered to variable due to the covid-19 situation.

The most important thing to note in regards to the listed cost of the CorPower Ocean WEC, is that the cost estimate is based on an 20MW array. Even if the LCOE is given for the rated power of individual devices, the cost presented in table 4.4 assumes that a number of twenty devices is built. This differs from the costs listed for the other technologies, which is only based on a single device. Additionally, the same assumption of production hours as the Pelamis is used.

Table 4.5: *Comparable numbers of cost of energy of different energy sources[18, 34]*

Norway		
Hydropower(>10MW)	0.028	€/kWh
Hydropower(<10MW)	0.029	€/kWh
Onshore Wind	0.022	€/kWh
Coal	0.015	€/kWh
Nuclear	0.036	€/kWh
World		
Solar photovoltaic	1026	€/kW
Concentrating solar power	4411	€/kW
Onshore wind	1269	€/kW
Offshore wind	3689	€/kW

Table D.2, in appendix D, illustrates the costs of the presented technologies represented with the unit €/kWh. When comparing these cost with the costs of energy on the Norwegian market, listed in table 4.5, none of the WECs comes close to being competitive. The two technologies that are nearest to be competitive are the Pelamis and the Langlee Robusto. They have costs of 0.348 and 0.288 €/kWh, respectively. Worth mentioning in regard to this comparison and table D.2, is that the same assumptions about yearly production hours as when calculating the costs of table 4.4 are used.

When looking at the costs in table 4.4 and comparing them with the world average costs for other renewable energy sources listed in table 4.5, all technologies except for the Lifesaver is competitive with concentrating solar power technology. The Pelamis, Langlee Robusto and Waveboost all are competitive with offshore wind. However, none of the five technologies shows to be competitive with solar photovoltaic technology. This technology is the cheapest of all of the renewable energies. It experienced a significant cost reduction in the years between 1985 and 1995, with a learning rate of 38%. So far the wave power technology has not experienced such a cost reduction.

This section presented comparable costs of the energy market today and the presented WECs. To obtain these comparable costs many assumptions were made, all mentioned above and in the appendices. With the amount of assumptions one might argue that the costs are too uncertain. On the other side, the same assumptions were repeated, thus, reducing the total amount. Furthermore, the assumptions were mainly based on average numbers of reported yearly production hours or costs of energy from two or more different sources. This might reduce the uncertainty related to the presented numbers. However, a more transparent wave energy sector could have resulted in more reliable numbers.

During the time this bachelor was written the world experienced a global pandemic - the covid-19 virus. This affected the world greatly. One way, worth mentioning, the pandemic in turn affected this bachelor, is the sudden absence of contact with people. Aforementioned in section 3, contact with people has been an important factor of getting hold of relevant theory. In contact with the European Marine Energy Centre, a recommendation of contacting several companies with wave technology, which they considered relevant, was made. These are mentioned in the beginning of section 2.5 as; the Penguin, the Laminaria, the Blue Horizon and Archimedes Waveswing. However, despite attempts of contacting them and obtaining relevant theory through the available search engines, the theory were inadequate and no contact was achieved. Including these technologies would have made a clearer picture of the status of wave energy technology today. However, the lack of obtained theory without the help of people establish in the industry or within the companies, speaks of a technology with poor transparency. The wish of Langlee Wave Power to not specify their cost is an example of this. On the other side, this wish was also based on the fact that the crisis of confident of 2012 has forced the company to reduce their activities and the investors to pull away. Therefore, the calculations of cost that they have is based on conditions from several years ago, and they consider them as insufficient at this time.

More transparency throughout the wave energy sector might have led to costs of energy with less uncertainty. Furthermore, it might have led to more openness of the costs related to the WECs. In turn, this might have resulted in a more representative and certain presentation of the promising wave energy technologies. On the other side, openness of known costs may involve presenting outdated costs. However, if the costs were kept up to date, the concrete numbers of cost of energy for a WEC might result in more investments. The rationale for this is that the element of uncertainty will disappear when the statement of being competitive on the market is backed up by a proven cost of energy.

4.3 Learning curves

Figure 4.4 shows the estimated learning curve of Lifesaver, based on the next generation cost estimations of Jonas Sjolte. The calculations and assumptions are further explained in appendix B. The learning rate used in figure 4.4 is 16.5%, and is based on an average of recommended learning rates from the IEA and the British Carbon Trust.

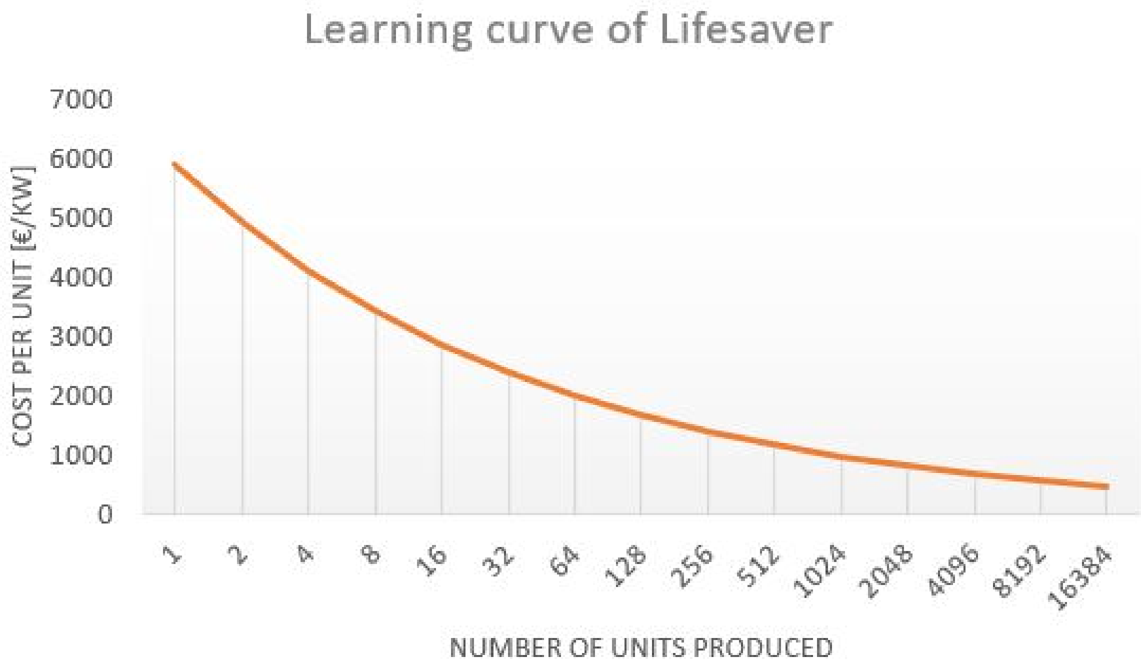

Figure 4.4: *Learning curve of Lifesaver.*

Figure 4.4 shows the expected cost of the Lifesaver with a set learning rate. When this cost is compared with the costs of other renewable energies, it only gets to be competitive when considering a high number of units. This is further illustrated in figure C.2 in appendix C. However, when comparing with other WECs, the Lifesaver would for example be competitive with the current cost of the Waveboost by between 128 and 256 produced units. To illustrate this comparison, all the presented technologies' cost reductions, with a learning rate of 16.5%, are shown in figure 4.5. In this figure the average cost of renewable energies, from 2018, published by IRENA has been added for comparison. Further explanations of calculations related to figure 4.5, are to be found in appendix E.

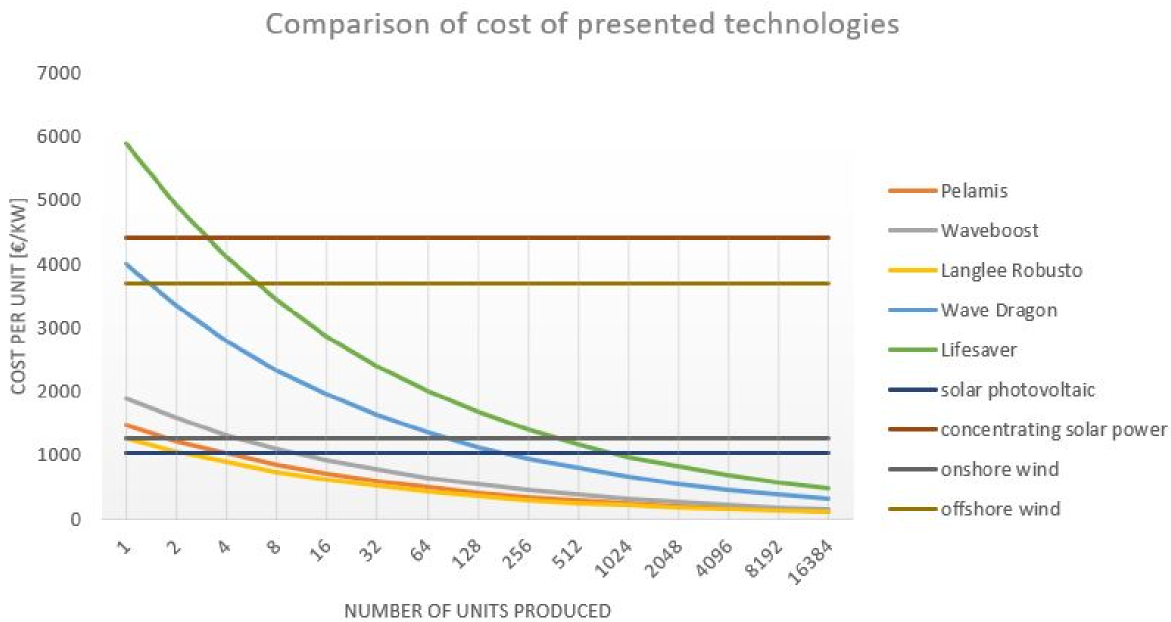

Figure 4.5: *Graphical representation of learning curve effect with different technologies*

It should be noted that for the Wave Dragon device, the learning rate of 16.5%, is more optimistic then their own estimation of cost after hundreds of produces units. However, this learning rate was used for all of the presented technologies, since it is considered most conceivable when taking into account the recommended learning rates for new technology and ocean technology.

Both Wave Dragon and Lifesaver stand out as the most expensive technologies. The three other can be seen as competitive with onshore wind by the 4th produced unit, and competitive with the world average solar photovoltaic technology by the 16th produced unit. However, to get to the 4th and 16th produced unit would still require significant investments, and even then the learning rate is not guaranteed.

Figure 4.6 shows the learning rate of figure 4.4, 16.5%, in comparison with learning rates experienced by other energy technologies. For clarification, the WEC used for this comparison is the Lifesaver, as in figure 4.4. The additional learning rates are 15, 18 and 35 %. Learning rates experienced by biomass, wind and solar energy, respectively. The calculations of figure 4.6 are further explained in appendix C. Figure C.2 in appendix C includes illustrative lines of the cost of other renewable energies, in order to better visualize the comparison.

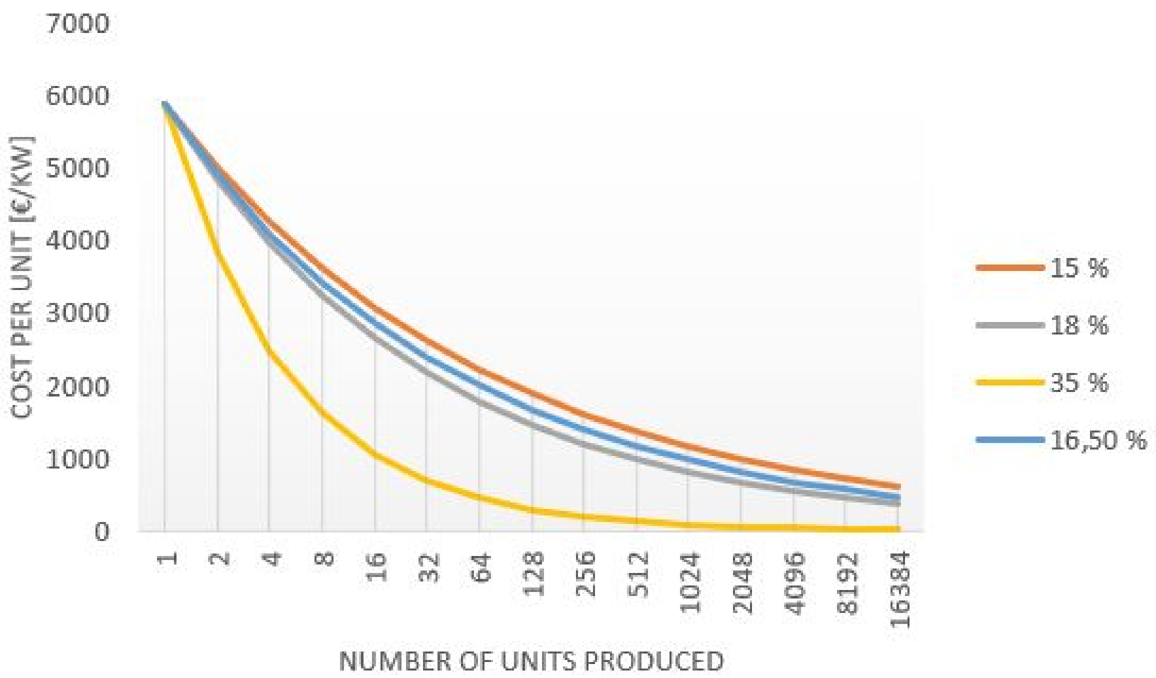

Figure 4.6: *Learning curve of Lifesaver with different learning rates.*

Aforementioned, all of the presented technologies except for the Lifesaver, are competitive with concentrating solar power today. All of the learning rates used for figure 4.6 makes the Lifesaver competitive with concentrating solar power by the fourth unit. The learning rate of 35% makes it competitive by the second unit. Realistically, being competitive with concentrating solar power is not enough to be considered being competitive on the market. Furthermore, the competitive cost needs to be reached within a reasonable number of produced units. The reason for this is to not require a too substantial investment to realize this cost. Offshore wind is made competitive by the eighth unit produced, for all learning rates. Solar photovoltaic technology and onshore wind power only gets competitive withing a, close to, reasonable number of produced units with the highest learning rate of 35%. Nonetheless, this would still require 16 produces units and a large investment.

Noticeably, it is likely that the other renewable energies would have some sort of cost reduction in the same period of time. This is predicted by IRENA, as mentioned in section 4.1. However, this is not considered for the comparisons made here. The examples with learning rates is mainly done for the Lifesaver device. This is the most expensive of the five presented technologies, as can be seen in table 4.4. This suggest that the other technologies may have better results in regard to cost reduction with the learning effect. However, in figure 4.5 it can be seen that none of the presented technologies are competitive with all of the other renewable energies before reaching a high number of produced units. Not until the 1024th unit produced is this aim reached.

The objective to figure out if the wave energy technology is mature and competitive on the market has been discussed throughout section 4. It is shown that the technology may obtain this objective with a learning rate of 16.5% and a high number of units produced. The first problem with this, is that it requires substantial investments to produce the number of units to obtain the costs that are competitive. When presenting the technologies, all but one technology, the Waveboost, reports that they struggle with investments. The second problem is that a cost reduction of wave energy technology, based on the learning effect, has been expected for decades without this happening. An example of this, is the fact that several of the technologies that are considered as promising today, are the same that was considered promising in 2017 and in 2013. This, despite that one of them, the Pelamis, went bankrupt in 2014. The question then becomes; why would this learning rate occur now? Historically, crisis in the energy delivery sector causes a venture into new technologies. Wave energy technology has benefited on this before. Furthermore, this brings into question if the recommended learning rate of the IEA is fitting, since it is recommended for new energy technologies, which it can be argued that wave energy is not.

Previously mentioned, the global pandemic, covid-19, affected the world greatly. The consequences it has had on the climate is worth mentioning in context of this bachelor. The world has seen a positive effect of industries shutting down. This has led to a greater aspiration in the world to do something about the climate change. Both the general world view of the climate crisis and the extra push to do something about the climate changes, delivered by the covid-19 crisis, may be considered enough incentive to cause a venture in to wave energy technology. On the other side, the virus crisis has resulted in a poorer world economy, and may proceed to make investors more cautious and the companies developing the technology economically insecure.

A way of being considered as competitive on the market, is to move into niche markets. An example of a technology that has done this, is the Lifesaver with their collaboration with the US navy, to apply to remote locations. Furthermore, Langlee displays similar mindset by trying to bring wave energy to the Canaries. However, Langlee's plan is not realized due to, amongst other things, lack of investments. Furthermore, Fred. Olsen's collaboration with the US navy, is just that - a collaboration, a project. This suggests that the technology is not yet competitive on that niche market, due to no commercializing of the technology still.

The last topic up for discussion is the reliability of the presented WECs. The two technologies that appears simplest, consisting of fewest components and easiest working principle, are the Lifesaver and the Langlee Robusto. The theory presented in section 2.4.1 suggests that the fewer components the system consist of, when the components is placed in series, equals higher reliability. The key performance indicators of the Lifesaver, presented in table 4.3, corroborate with the suggestion that this technology obtains a high availability. However, there are no reported numbers of availability for the Langlee technology. On the other side, the reported yearly production hours of the Langlee Robusto are higher then that of the Lifesaver. These are 4400 and 4000 hours, respectively (the calculation of the yearly production hours of the Lifesaver is explained in appendix D). This might suggest that the Langlee Wave Power's WEC has at least as high availability as the Lifesaver.

Despite that the other presented technologies are more complex and consisting of more components, their costs include estimations of costs related to maintenance, and are considerable lower than that of the Lifesaver. This suggest that the complexity of the technology may not always result in poorer availability. On the other side, the complexity of the working principle of the Pelamis, e.g. with the need of end-stop control, is suggested by Babarit to be the origin of failure for the technology.

5 Conclusion

The purpose of this bachelor is specified in the introduction as:

> *"(...) to take a new look at wave energy, to see how far the technology has gotten. How mature has the research and technology on wave energy become, and is it at this point competitive with current energy production technologies?"*

It is established that wave energy technology has been able to achieve production of electrical energy from the waves in decades. Based on this, the conclusion that the technology work and that it is no longer considered as a new technology is drawn. In regards to the reliability of the WECs, it is concluded that the number of components is important. However, the complexity of the device is also a critical factor of reliability.

The technology proves mature enough to be reliable in relation to producing electricity. However, considering the Norwegian energy market, the presented WECs are far from competitive. When comparing with the world average costs of other renewable energies, the WECs presented in this bachelor is only competitive with concentrating solar power technology on the market today. Furthermore, the conclusion that it would require substantial investments to get the technologies on the market, and even larger investments to make the technologies competitive on the market, is made. Nonetheless, a potential is observed in the niche markets of Fred. Olsen and Langlee Wave Power. It would still require substantial investments to commercialize the technologies on these markets, but less to make them competitive.

Moreover, the conclusion that the learning rates tested in this bachelor may be considered too optimistic is drawn. This is due to the lack of proven cost reduction in the last couple of decades.

Although the findings of this survey shows no indications of WECs being competitive on the market today, substantial investments, a new venture into the wave energy due to climate change etc., may change that. Lastly, it is concluded that a more transparent wave energy sector would benefit the companies developing and producing WECs. Additionally, this would have resulted in a more representative and certain presentation of the WECs presented in this bachelor.

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Appendices

A List of large-scaled tested WECs

The lists in appendix A are rendered from Aurélien Babarit's book *Ocean wave energy conversion* from 2017. The tables can also be found by *www.iste.co.uk/babarit/ocean.zip*[16]. The sign * indicates rated power at scale 1.

Name	**Country**	**Principle**	**Installed Power (kW)**	**Scale**	**Period**	**Deployment Time (years)**	**Produced Energy (MWh)**	**Project Outcome**
Wave motor	US	OWC	?	1	1898-1910	12	?	Decommissioned in 1910
Bouchaux-Pracéique	FR	OWC	1	1	1910-?	?	?	?
Hydraulic Ram	FR	OWC	?	1	1926-?	?	?	Destroyed by a storm
Navigation Buoys	JP	OWC	1	1	1945-?	>20?	?	Marketed
KAIMEI	JP	OWCA	?	1	1978;1979	?	?	Decommissioned
Cockerell Raft	UK	≈HBA	1	1/10	1978-?	?	?	Decommissioned
IPS buoy	SE	HB	?	1?	1980;1981	<1	?	Decommissioned
Point-Absorber	NO	HB	500*	1/10	1981;1982;1983	<1	?	?
Pendulor I	JP	OWSC	5	1	1983-1985	2	?	Destroyed by a storm
New Pendulor	JP	OWSC	5	1	1985-1989	4	?	?
TAPCHAN	NO	OD	385	1	1985-1989	3	?	Destroyed by a storm
Kvaerner column	NO	OWC	500	1	1985-1989	3	29	Destroyed by a storm
Trivandrum OWC	IN	OWC	125	1	1990-?	?	?	?
Sakata OWC	JP	OWC	60	1	1990-?	?	?	?
Islay OWC	UK	OWC	75	1	1991-2000	9	?	Replaced by Limpet
OSPREY	UK	OWC	2000	1	1995	0	0	Lost during installation
McCabe Wave Pump	IRL	≈HBA	?	1	1996	?	?	Hydraulic circuit failure
Mighty Whale	JP	OWCA	110	1	1998-2000	2	84	Decommissioned in 2000
Pico OWC	PT	OWC	500	1	1999; 2006-2016	9	>84	Turbine fault in 1999 Operational from 2006 to 2016
LIMPET	UK	OWC	500	1	2000-2012	12	?	Stopped
AWS	PT	≈HB	1000	1	2001;2002; 2004	?	?	Lost following a pump breakdown
3kW OWC	CN	OWC	3	1	<2001	?	?	?
20kW OWC	CN	OWC	20	1	<2001	?	?	?
100kW OWC	CN	OWC	100	1	<2001	?	?	?
5kW BBDB	CN	OWC	3	1	<2001	?	?	?

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Name	**Country**	**Principle**	**Installed Power (kW)**	**Scale**	**Period**	**Deployment Time (years)**	**Produced Energy (MWh)**	**Project Outcome**
8kW Pendulum	CN	OWSC	8	1	<2001	?	?	?
30kW Pendulum	CN	OWSC	30	1	<2001	?	?	?

Table A.1: *List of WECs having undergone large scale testing up to 2001[16].*

Name	**Country**	**Principle**	**Installed Power (kW)**	**Scale**	**Period**	**Deployment Time (years)**	**Produced Energy (MWh)**	**Project Outcome**
Pelamis P1	UK	≈HBA	750	1	2004-2007	3	?	Decommissioned
Buldra	NO	HBA	?	1/3	2005	<1	?	Decommissioned
Oceanlinx Mk1	AU	OWC	500	1	2005-2009	>4	?	Power take-off failure repaired? Prototype abandoned
PB40	US	HB	40	1	2005-2006; 2007-2008; 2009-2011	>1	?	Decommissioned
CETO1	AU	HB	?	1?	2006	<1	?	Decommissioned?
CETO2	AU	HB	?	1?	2006;2008	<1	?	Decommissioned?
Seabased	SE	HB	?	1	2006-?	>1	?	Operating?
Waveroller	FI	OWSC	?	1/2	2006-2008	>1	?	Decommissioned
Oscillating body	CN	HB	50	1	2006	<1	?	Lost after breakdown in a shaft
Pelamis P1 (3x)	PT	≈HBA	750	1	2007	<1	?	Mooring system failure
Aquabuoy	US	HB	?	1	2007	<1	?	Lost after breakdown of a pump
Oceanlix Mk2	AU	OWC	?	1/3	2007	<1	?	Decommissioned?
PB40	ES	HB	40	1	2008	<1	?	Decommissioned?
P37	DK	≈OWSCA	50	1/2.5	2009;2010; 2012-2013	<1	?	Decommissioned
Oyster 1	UK	OWSC	315	1	2009	<1	?	Decommissioned
Bolt	NO	HB	?	1	2009;2010	<1	3.36	Decommissioned
Wavestar	DK	HBA	110	1	2009; 2010-2013	>3	?	Decommissioned in 2016
Oceanlinx Mk3	AU	OWC	?	1/3	2010	<1	?	Lost after rupture of the mooring system
WavEL-buoy	SE	HB	?	1	2010	<1	?	Decommissioned
D100t	IT	≈OWSC	?	1	2010	?	?	Decommissioned
Pelamis P2 (2x)	UK	≈HBA	820	1	2010-2014	>1.5	>250	Decommissioned
CETO3	AU	HB	80	1	2011	<1	?	?

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Name	Country	Principle	Installed Power (kW)	Scale	Period	Deployment Time (years)	Produced Energy (MWh)	Project Outcome
Oyster 800	UK	OWSC	800	1	2011-2015	3	?	Hydraulic circuit breakdown Still installed, folded flap
Mutriku	ES	OWSA	259	1	2011-?	>5	>1300	Operating
PB150	UK	HB	150	1	2011	<1	?	Decommissioned
Y25t	IT	≈OWSC	?	1	2011	<1	?	Decommissioned?
Oceanus 1 (x3)	UK	HB	?	1	2011; 2012-2013	>1	?	Decommissioned
Wello Penguin	UK	≈OWSC	500	1	2011;2012;2013 2014-2016;2017	>1?	?	In operation?

Table A.2: *List of WECs having undergone large scale testing between 2001 and 2011[16].*

Name	Country	Principle	Installed Power (kW)	Scale	Period	Deployment Time (years)	Produced Energy (MWh)	Project Outcome
Power Wing	IL	HB	10	1	2012-?	>1?	?	Decommissioned?
SQUID	UK	≈OWSCA	7.5	1	2012	<1	?	Decommissioned
Waveroller	PT	OWSC	300	1	2012	1?	?	Decommissioned
Lifesaver	UK	HB	400	1	2012-2013	1	4.64	Decommissioned
Surge WEC	US	OWSC	30	1	2012-2013	<1	?	Decommissioned
Sharp Eagle 1	CN	≈OWSCA	10	1	2012-2014	>1?	?	Decommissioned?
Azura	US	≈OWSC	20	1/2	2012;2015-?	>1	?	?
WAVE PIONEER	BE	HB	?	1/2	2013	<1	?	Decommissioned
R115	IT	≈OWSC	150	1	2013-2014	1?	?	Decommissioned?
Sharp Eagle 2	CN	≈OWSCA	30	1	?	?	?	?
Green WAVE	AU	OWC	1000	1	2014	0	0	Lost during installation
CETO	FR	HB	?	1	2014	<1	?	Destroyed by a hurricane
M3 Wave	US	≈OWSC	?	1?	2014	<1	?	Decommissioned
Hyberbaric WEC	BR	HBA	100	1	2012-2014	>1	?	Decommissioned
SQUID(3x)	UK	≈OWSCA	7.5	1	2014	<1	?	Decommissioned
H-WEC	NO	?	200	1	2014-2015	<1	?	Decommissioned
CETO 5(3x)	AU	HB	240	1	2014-2016	>1	?	Decommissioned
Oceanus 2	UK	HB	162	1	2014-2015;2016-?	>1	?	Operating
W1	ES	HB	200	1	2014-?	>1	?	In operation?
PH4S version 1	FR	≈OWSC	1.5	1	2015-2016	>1	?	Decommissioned
Atmocean(5x)	PE	HB	?	1/3	2015	<1	?	Decommissioned
Sharp Eagle Wanshan	CN	≈OWSCA	100	1	2015-?	>1	>30	In operation?

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Name	Country	Principle	Installed Power (kW)	Scale	Period	Deployment Time (years)	Produced Energy (MWh)	Project Outcome
ISWEC	IT	≈OWSC	100	1	2015-?	>1	?	In operation?
BioWAVE	AU	OWSC	250	1	2015-?	>1	0	Electric cable breakdown repaired in 2016 Activation in progress
Juju island	KR	OWC	500	1	2015-?	>1	?	In operation
SQUID (6x)	UK	≈OWSCA	7.5	1	2015;2016-?	>1	?	Power take-off failure
PH4S version 2	FR	≈OWSC	5	1	2016-2018	>1	?	In operation
GSIRE	FR	≈OWSC	?	1	2016-2018	>0.5	?	In operation
OBREC	IT	OD	2.5	1	2015-?	>1	?	In operation
Seabased (36x)	SE	HB	30?	1	2016-?	>1	?	Pilot farm
Lifesaver	US	HB	400	1	2016-?	>1?	>18	Power take-off failures repaired as they occurred
PB3	US	≈HB	3	1	2016-?	>1?	?	In operation?
Gibraltar	UK	HBA	100	1	2016-?	>1?	?	In operation?
H24-50	IT	≈OWSC	?	1	2016-?	>1?	?	In operation?
REWEC3	IT	OWCA	?	1	2016-?	>1?	?	In operation?

Table A.3: *List of WECs having undergone large scale testing between 2012 and 2016 [16].*

B Calculations of learning curve effect on Lifesaver

The calculations is based on the definition of the learning effect given by Aurélien Babarit in *Ocean Wave Energy Conversion*[16]:

"The learning effect assumes that the cost of a product decreases with a constant rate every time the number of units produced doubles."

The estimates of the cost of the next generation Lifesaver by Jonas Sjolte is used as a base. Hence, the cost of energy of the first unit is set at 5.9 k€/kW[14]. Further assumptions is a learning rate of 16.5 percent. The assumed learning rate is an average of the recommended learning rates given by the IEA and Carbon Trust. The learning rate recommended by the IEA is intended for new energy technologies, and the rate recommended by the Carbon Trust is intended for ocean energy in general[16].

Learning curve calculation for Lifesaver

Assumed Learning rate:	16,5	%	Average of recommended rates of Carbon Trust and IEA
Cost of energy, first unit:	5,9	k€/kW	Estimated cost of next generation Lifesaver

Number of units produced: n		Learning rate factor:	0,835
Estimated cost of unit by learning effect: c			

n	c
1	5900
2	4926,5
4	4113,6
8	3434,9
16	2868,1
32	2394,9
64	1999,8
128	1669,8
256	1394,3
512	1164,2
1024	972,1
2048	811,7
4096	677,8
8192	565,9
16384	472,6

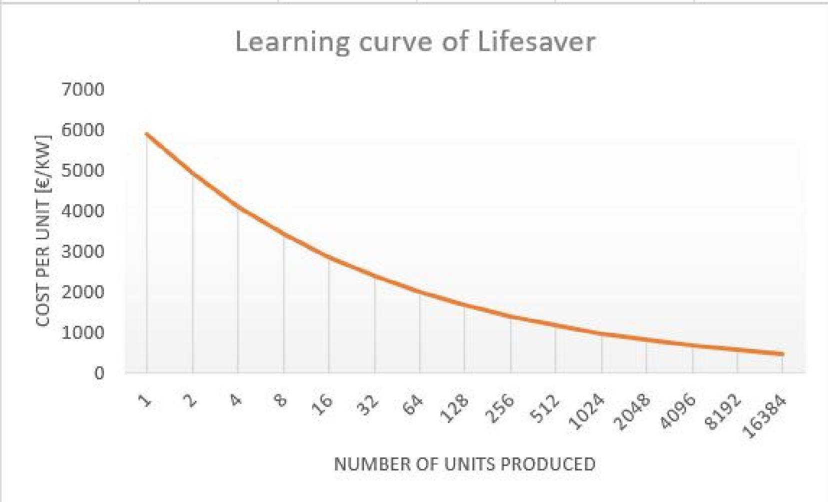

Figure B.1: *Snapshot of excel sheet.*

C Calculations of learning curve effect on Lifesaver with several learning rates

The calculations in this appendix is based on the same definition of learning effect as in appendix B[16].

The learning rate at 15% is based on the recommendation of the Carbon Trust in the United Kingdom for ocean energy. The IEA recommends a learning rate of 18% for new energy technologies. Furthermore, 18% was the learning rate of wind-based energy in Europe in the time interval of 1980 to 1995, while 15% was the learning rate of biomass in the same time interval. The learning rate of 35% is included due to the photovoltaic solar cells' experience between 1985 and 1995[16]. These learning rates are used in comparison to the learning rate of 16.5% of appendix B.

For the learning rates of 15, 18 and 35 %, the learning factors are 0.85, 0.82 and 0.65, respectively.

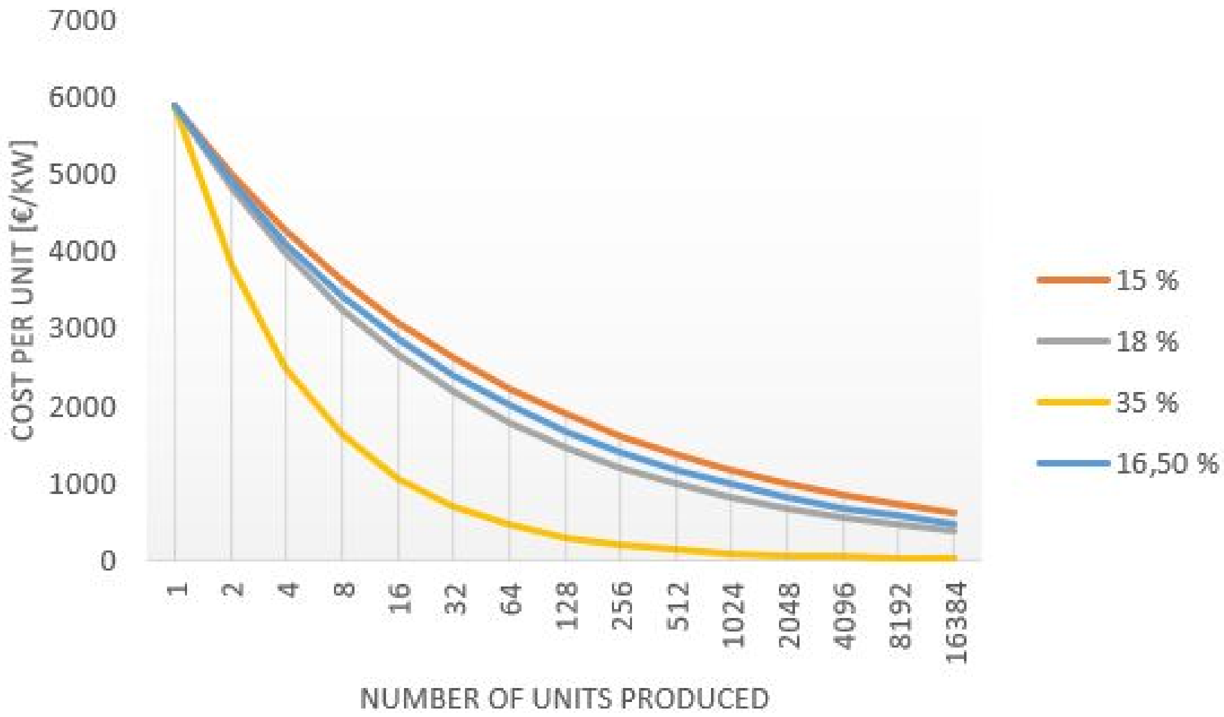

Figure C.1: *Graphical representation of learning curve effect with several learning rates*

To illustrate the comparison of the cost of the Lifesaver with the cost of other renewable energies, these are incorporated in figure C.2. The costs of the renewable energies are the numbers of IRENA from 2018.

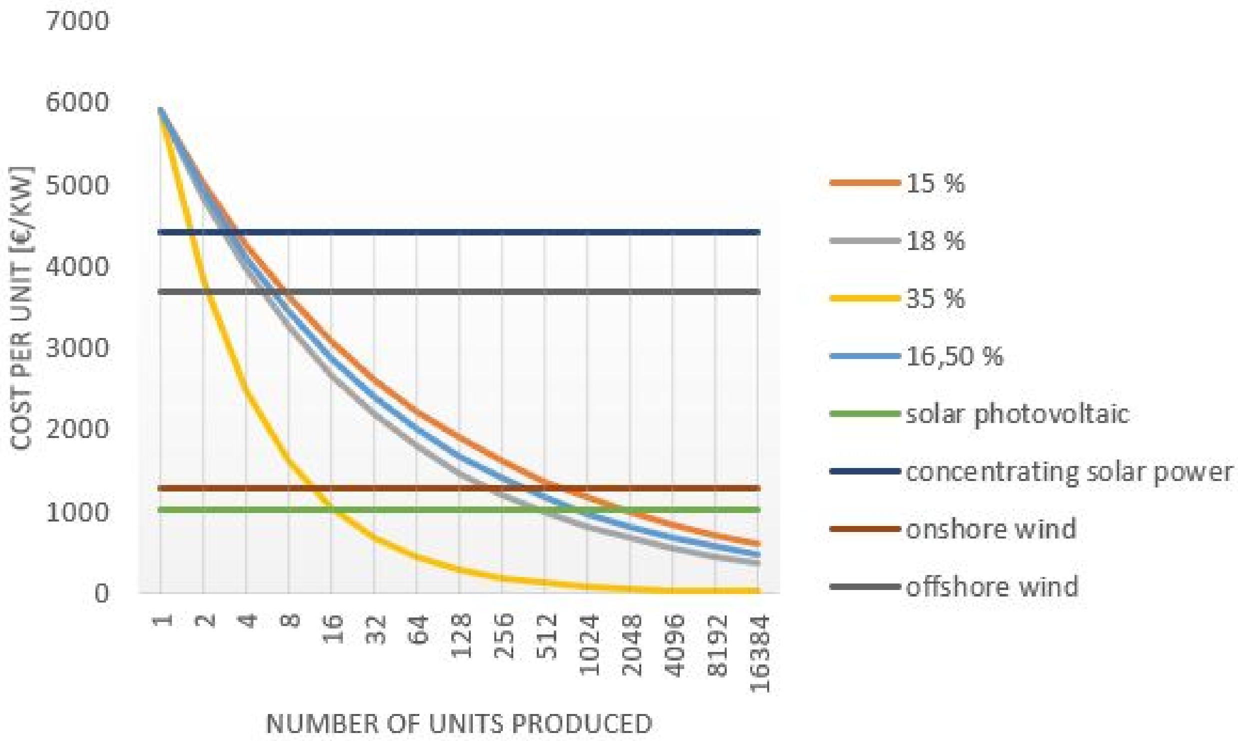

Figure C.2: *Graphical representation of learning curve effect on the Lifesaver with several learning rates and comparison with other renewable energies.*

D Calculations to make costs of energy comparable

In order to calculate costs of energy, which were comparable to each other, some assumptions were made. These are specified below and the reason for each assumption is explained.

The cost of energy for the Pelamis was based on the average €/kWh from the two articles from 2010 and 2013[5, 11], and the average of these two. The numbers are shown in table D.1. The average of the average from the two articles was then multiplied by 4200 hours. This resulted in a cost of energy of 1462 €/kW. 4200 hours were chosen based on an average of the documented production hours of the Lifesaver and the Langlee Robusto. They had production hours of 4000 and 4400, respectively. The yearly production hours of the Lifesaver are obtained based on Sjolte's suggestion that a next generation device of 175 kW will produce 700MWh per year[14].

Article	**Average [€/kWh]**
2010 [5]	0.390
2013 [11]	0.305
Both	0.348

Table D.1: *Average numbers of cost of energy for Pelamis*

Langlee Wave Power did not specify a cost of energy for their WEC, but expect to be competitive with onshore wind power. Based on this, the cost of energy for onshore wind was used for the Langlee Robusto. IRENA's number for cost of energy for onshore wind from 2018, was 1497 USD/kW, based on a global average[18]. This was depicted in figure 4.1, in section 4.1. For this number to be comparable with the other numbers of cost of energy, the exchange rates from USD to Euro of 2018 was used. This is reported to be 0.847541[36], which results in a cost of energy for Langlee of 1269 €/kW.

The financial perspective of the CorPower Ocean's WEC is based on a study of a 20MW array. The LCOE of the DK North sea Point 2 location stands out, and is therefore neglected. The average rated power of 1000 kW is chosen, where the average LCOE is graphically found to be 0.45 €/kWh. The same average production hours, 4200h, of the Pelamis is assumed. This makes for a cost of energy of 1890 €/kW. It should be noted that this assumes an array of twenty devices.

To visualize the comparison with the Norwegian energy market table D.2 lists the costs correlating to the presented wave energy technologies in €/kWh. The same assumptions as above, of yearly production hours, are made when calculating the cost with unit €/kWh. This means that the technologies that had there costs reported in €/kWh, are either divided by their relating yearly production hours or the average of 4200 hours.

Name of technology	**Cost [€/kWh]**
Lifesaver	1.475
Pelamis	0.348
Langlee Robusto	0,288
Waveboost	0.450
Wave Dragon	0.952

Table D.2: *Cost of energy for the presented technologies, given in €/kWh*

E Graphical comparison of costs with learning rate 16.5%

The same process as for Lifesaver in appendix B, was used for each presented technology. The same learning rate of 16.5% was used. The initial cost for each technology is presented in table 4.4. The assumptions made to find these costs are specified in appendix D. The same comparable costs for renewable energies as in appendix C are used in figure E.1.

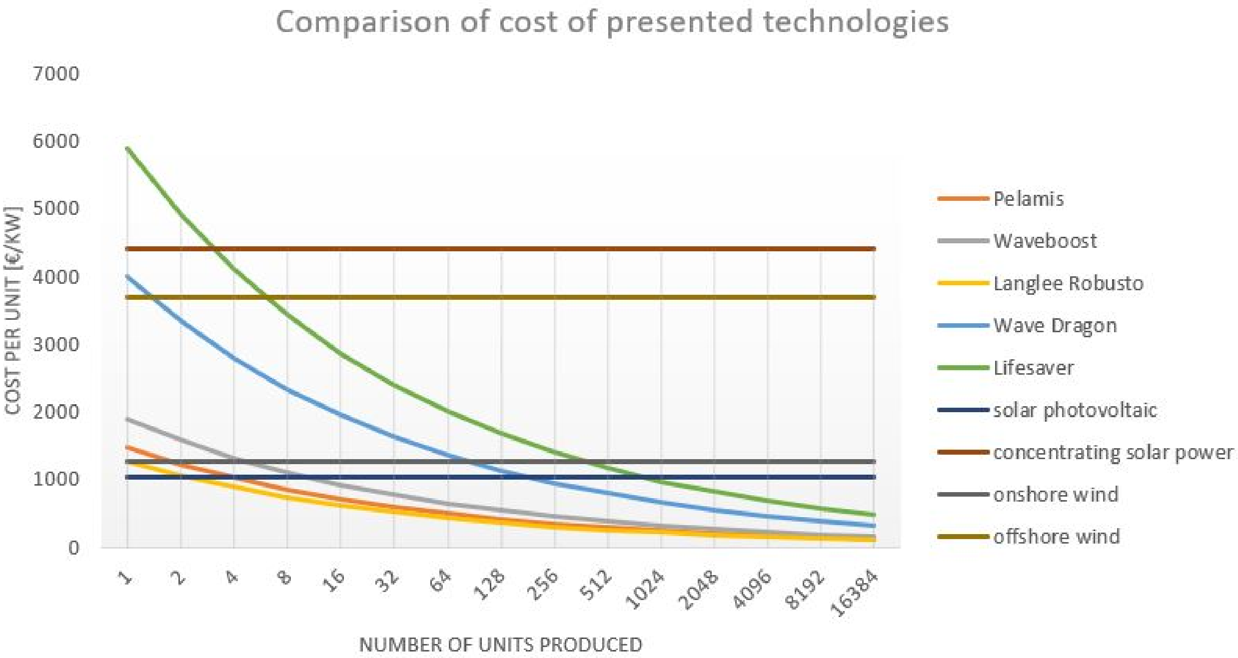

Figure E.1: *Graphical representation of learning curve effect with different technologies*