**FACULDADE DE ENGENHARIA DA UNIVERSIDADE DO PORTO**

# Tripower UP: Mechanical Design

## Mechanical Transmission of the Wave Energy Converter

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# Resumo

Os oceanos são uma fonte de energia relativamente inexplorada e, entre todas as fontes existentes, a energia dos oceanos (e, em particular, a energia das ondas) são das fontes mais limpas e seguras, sendo relativamente inesgotáveis. Não existe muito trabalho realizado no tópico de conversão de energia das ondas, mas apesar de as tecnologias de aproveitamento da energia dos oceanos estarem pouco desenvolvidas, elas apresentam o potencial para resolver vários problemas energéticos, o que reforça a importância de trabalhos como este.

O objetivo deste trabalho passa pela continuação do trabalho feito anteriormente por um antigo colega, que consistia num conceito para um dispositivo, Tripower UP, que permitiria incorporar três formas de conversão de energia (ondas, vento e correntes) e combiná-las mecanicamente, através de um único veio central. Este dispositivo foi submetido para aprovação de patente.

A conceção mecânica foi feita em colaboração com um atual colega do Mestrado Integrado em Engenharia Mecânica da FEUP, que foi responsável pela estrutura do conversor de energia das ondas.

O dispositivo Tripower UP existente foi estudado, sendo que foram corrigidas algumas complicações conceptuais, tais como a assimetria das cargas nas cremalheiras e a substituição do transmissor de deslocamento elastomérico por uma solução mais eficiente.

Foi feita uma conceção detalhada da transmissão mecânica do conversor de energia das ondas, incluindo alguns cálculos mecânicos. De seguida, a estrutura mecânica do conversor de energia das ondas e a estrutura geral de suporte foram concebidas e estudadas.

Durante o desenvolvimento do projeto, surgiu um novo conceito para um conversor de energia das ondas, Spider UP, que também foi submetido para aprovação de patente.

# Abstract

Oceans are a somewhat unexplored source of energy and, among all listed sources, ocean energy (and, in particular, wave energy) provide for the cleanest, safest and inexhaustible of sources. There is not a lot of work done on the topic of wave energy conversion, but even though ocean energy's harnessing technologies are still underdeveloped, they pose the potential to solve many energy problems, which reinforces the importance of works like this.

The purpose of this work is to follow-up on a previous work done by a former colleague, which consisted on a concept for a device, Tripower UP, that would be able to incorporate three forms of energy conversion (wave, wind and currents) and combine them mechanically, through a single central shaft. This device was submitted for patent approval.

The development of the mechanical design was made in collaboration with a current colleague of the Master in Mechanical Engineering at FEUP, who was responsible for the wave energy converter's mechanical structure.

The pre-existing Tripower UP device was studied, being that some design complications were corrected, such as the rack's asymmetric loads and the replacement of the elastomeric displacement transmitter with a more efficient solution.

A detailed design of the mechanical transmission of the wave energy converter was performed, including some mechanical calculations. Afterwards, the mechanical structure for the wave energy converter and the device's overall support structure were designed and studied.

During the development of the project, a new concept for a wave energy converter arose, Spider UP, being that it was also submitted for patent approval.

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Miguel Eduardo dos Santos Godinho

*"Please do not be cynical. I hate cynicism. For the record, it's my least favourite quality. It doesn't lead anywhere. Nobody in life gets exactly what they thought they were going to get.*

*But if you work really hard and you're kind, amazing things will happen."*

Conan O'Brien

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# 1 Introduction

This introduction explains the context, motivation, goals and structure of the work.

## 1.1 Problem Statement and Motivation

Considering the current paradigm of energy dependence on non-renewable fuels, society is working towards finding viable alternatives. That being said, the oceans are a somewhat unexplored source of energy and, among all listed sources, ocean energy provides the cleanest, safest and inexhaustible of sources [1].

Ocean energy may have diverse sources, which leads to different classification. The most relevant are:

1) tidal energy - caused by the interaction between the Sun's and the Moon's gravitational fields;
2) ocean's thermal energy - direct consequence of the solar radiation;
3) maritime currents energy - originated by the temperature and salinity changes and the action of the tides;
4) wave energy - created by the effect of wind in the surface of the ocean [2].

Although there are concepts for wave energy converters over 200 years old, it was only recently that viable technology for harnessing energy from ocean waves emerged [3]. There has been some testing of prototypes in recent years and many other devices are being developed around the world, with more than one thousand different prototypes developed during the last decades [4]. However, none of the existing wave energy devices has been commercially completed yet, since none have achieved economic viability. This is why wave energy devices are still at an early stage of development [4]. These devices are still in early stages compared to other renewable technologies (solar, wind) and compared to conventional fossil plants, and most importantly, there is still no design outweighing over the rest [5].

Portugal has a wave resource that ranks medium-high worldwide, with an average of 40 kW/m [6]. The northern part of Portugal, where Porto is located, in particular, is a good location for the harvesting of this kind of energy, as there is a potential of 46 kW/m, as shown in Figure 1.

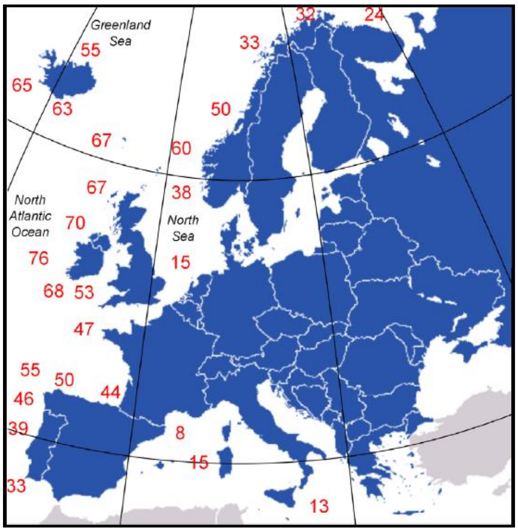



*Figure 1 - European distribution of the annual wave power, in kW/m (or MW/km) of crest length [5]*

However, the main barriers in the development of marine energies are: 1) the early stage of development of the technologies; 2) the uncertainties regarding the coastal and marine impacts of wave farms; and 3) the fact that they are considered uneconomical [7].

Also, one of the main problems with most wind and ocean energy converters (wave, currents, ...) is that they do not provide for a constant energy production due to the inconsistency of the resources they harness. This lead to the conception of hybrid systems such as the Tripower UP device. Because it combines three forms of energy conversion (wind, waves and currents), it provides for a somewhat constant production of energy.

Even though ocean energy's harnessing technologies are still underdeveloped, they pose the potential to solve a lot of energy problems, hereby reinforcing the importance of works like this dissertation.

## 1.2 Context

The work described is a follow-up on a previous work done by a former colleague, Miguel Macieira [8].

His work consisted in developing the concept for a device, Tripower UP, that would be able to incorporate three forms of energy conversion: wave, wind and currents. This device was submitted for patent approval. Concepts for devices such as this already exist (for example, see [9]), but the innovation in this device is mainly due to the fact that the three forms of energy are combined mechanically, through a single shaft.

This work was developed as part of a team of two, along with Diogo Telo Rodrigues, a fellow colleague of the Master in Mechanical Engineering at FEUP, also during the development of his own work [10]. Part of the work was developed together, as the goal was to manufacture a single prototype; another part was developed individually. In this document, it will be identified whether the work described was done as an ensemble or by Diogo Telo Rodrigues exclusively, being that if there is no reference to this, then it was done exclusively by the author.

It should be noted that, in parallel to the work described here, the team applied for a governmental programme ["StartUP Voucher" by IAPMEI (Instituto de Apoio a Pequenas e Médias Empresas e à Inovação)] which aims to stimulate the development of as-of-yet conceptual projects, through diverse support tools. The application was successful and the team was granted a small funding, being that it decided to use it on the construction of the prototype. This is relevant as it has led to a divergence of a previously set design strategy, towards a more quick and efficient one: as the free-wheel (described in subsection 4.3) was the most expensive component and a crucial one at that, and the project funding was limited to the faculty's budget, before being granted the funding the team decided to design a "custom free-wheel" (described in subsection 4.4.1), as it would save costs; after the funding was granted, the design strategy changed, and it was decided to purchase a commercial free-wheel, as it was a more compact and tested solution.

### 1.3 Goals

Since the final product of Macieira's work was an unfinished concept, the current work was focused on narrowing down his broad concept to a specific solution, in order to allow the construction of a functional prototype.

As it was a main objective to build a prototype, some of the main project constraints are related to time, economic and prototype testing factors. The testing of the prototype was intended to take place in the University's wave tank (located at FEUP), which has limited dimensions (emphasis on its depth of 1.3 m), which would mean the prototype could not surpass these measurements. Also, as mentioned in the previous section, there were time and economic factors to consider, so most of the design decisions were made considering the quickest, while still economic, options.

The objective of this prototype is mainly to prove the concept and to narrow down a specific solution. Further studies focused on optimising the solution will be necessary.

### 1.4 Dissertation Outline

This dissertation is divided into six chapters.

After this introduction, in chapter 2, a review of the literature and state-of-the-art on the topic of wave energy and ocean hybrid technologies is presented. The description of the Tripower UP device at the point of start-up is also presented.

A brief overview of the final product of the Tripower UP device's mechanical design is made in chapter 3, while some clarification on the device's subsequent sub classification is presented.

Afterwards, in chapter 4, the detailed design of the Wave Energy Converter's (WEC) Mechanical Transmission that is described. Here, the testing conditions and initial design considerations are presented. The design of the WEC's Mechanical Transmission's components and some mechanical calculations are also explained.

Next, in chapter 5, the WEC's Mechanical Structure and Overall Support Structure subsystems and their components are described.

Finally, in chapter 6 some final conclusions are drawn and some reflections on future works are presented.

# 2 Literature Review

In this chapter, a brief introduction to wave energy technologies is made. At first, some concepts on waves are explained, giving some insight into their characteristics and typical morphology. After this, some design considerations on Wave Energy Converters (WECs) are exposed. Subsequently, WEC technology classifications are clarified, and existing technologies are presented. Thereafter, the environmental impact of wave converters is analysed, and some economic aspects of these technologies are explained. Afterwards, some final remarks are outlined. Finally, the general idea of the Tripower UP system and the design as it was at the starting point is described.

## 2.1 Wave Energy

Wave energy can be considered a concentrated form of solar energy, as it is solar energy that causes winds, by the uneven heating of Earth's surface. Multiple shear and pressure forces, generated by the effect of wind in the sea surface, originate waves. Afterwards, due to environmental and resonance conditions, waves become independent of the wind [11].

Waves located within or close to the areas where they are generated are called storm waves. They form a complex, irregular sea. However, waves can travel out of these areas with few losses of energy to produce swell waves at great distances from the point of origin [3]. The wave's final dimension is determined mainly by 3 factors: wind velocity, wind duration and distance of water over which the wind acts (fetch) [8].

Once created, waves can travel thousands of miles at high sea, with practically no losses in energy. In coastal regions, the waves' energy density greatly decreases through its interaction with the bottom of the sea [12].

As the waves propagate onto the shore, they are modified in a complex way by effects caused by:

1. the bottom of the sea, due to refraction, diffraction, bottom friction and wave breaking;
2. sheltering due to the presence of land (namely headlands and islands) [2].

Due to this, it is common for most models that treat offshore wave converters to assume a somewhat deep-sea bottom, i.e. over 40 m deep, and hence no interaction with the sea bottom [5]. This way one can assume that waves behave as sinusoidal [13].

### 2.1.1 Wave characteristics

As mentioned in the previous section, the shape of a typical wave is described as sinusoidal. In the next paragraph, some standard wave parameters are defined, and then represented in Figure 2.

The difference in height between the peaks and troughs is the height, *H*. The distance between successive peaks (or troughs) of the wave is the wavelength, $\lambda$. The velocity at which the peaks and troughs of the wave move across the surface of the sea is designated as $v$. The time, in seconds, taken for successive peaks (or troughs) to pass a given fixed point is known as the period, *T*. The frequency, $f$, of the wave describes de number of peak-to-peak (or trough-to-trough) oscillations of the wave surface per second, as seen by a fixed observer (and is reciprocal of the period, i.e. $f = 1/T$) [3].

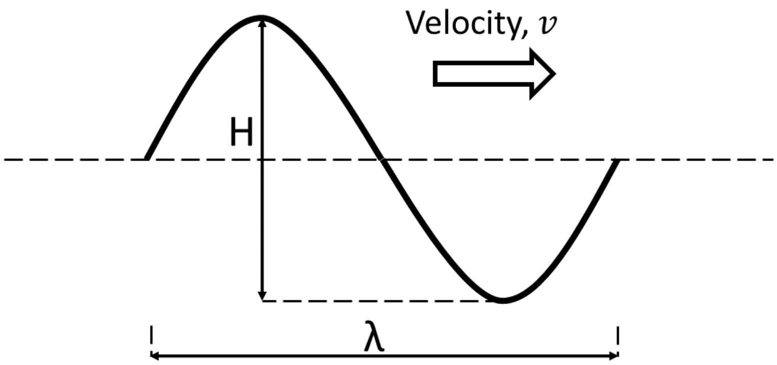



*Figure 2 - Characteristics of an idealized wave*

The power density, $P_d$ (kW/m) of an idealized ocean wave is given by [3]:

$$P_d \approx \frac{\rho g^2 H^2 T}{32\pi}$$

Waves can be separated into three categories, depending on the depth of the location:

1) Deep water waves

If $d > \lambda/2$ (where $d$ is the depth of water) is verified, the velocity of a long ocean wave can be shown to be proportional to period: $v = gT/2\pi$ [3].

This results in the fact that long waves travel faster than shorter waves in deep water.

2) Intermediate depth waves

As the water becomes shallower, the properties of the waves become increasingly dominated by water depth. When waves reach shallow water, their properties are completely governed by water depth.

3) Shallow water waves

As waves approach the shore, the seabed starts to influence their speed. The velocity under these conditions no longer depends on the wave period – it depends only on the water depth [3]. They start to come into contact with the seabed, which elongates the circular motion into a horizontally elliptic shape as the particles flatten and stretch. This in turn amplifies the horizontal movement of the water particles in the near-shore area, creating a strong surge zone [14]. Devices, such as the ones of the Oscillating Wave Surge type (see subsections 2.3 and 2.4), use this in their energy conversion process. This phenomenon is described in Figure 3.

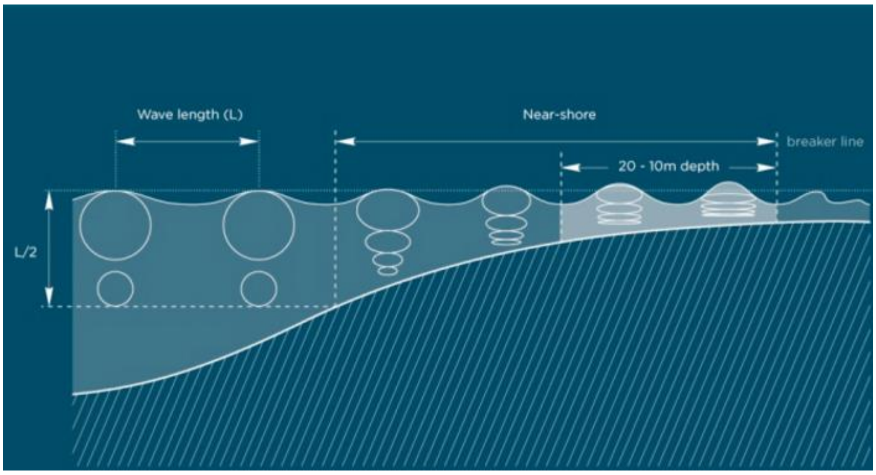



*Figure 3 - Representation of the creation of "surge zones" near-shore [14]*

### 2.1.2 Typical Wave Morphology

A typical sea state is more complex, being usually composed by multiple individual waves such as the one described in subsection 2.1.1, with different properties (i.e. different period, height, direction). As it is impossible to measure all heights and periods independently, an averaging process is used to estimate the total power [3].

The wave energy level is usually expressed as power per unit length [along the wave crest (which refers to the width of the wave) or along the shoreline direction]. Typical values for "good" offshore locations range between 20 and 70 kW/m (annual average) and occur mostly in moderate to high latitudes [2]. Waves of high amplitude (≈ 2 m) and of high period (7 to 10 s) normally exceed the 50 kW per meter of wave front [12].

In Table 1, some typical values for wave parameters in the North Atlantic offshore locations are shown.

*Table 1 - North Atlantic offshore wave conditions*

| | *Period* (s) | *Amplitude* (m) | *Power density* (kW/m) | *Velocity* (m/s) | *Wavelength* (m) |
|---|---|---|---|---|---|
| *Storm* | 14 | 14 | 1700 | 23 | 320 |
| ***Average*** | **9** | **3.5** | **60** | **15** | **150** |
| *Calm* | 5.5 | 0.5 | 1 | 9 | 50 |

## 2.2 Wave Energy Converters (WECs) design considerations

Wave Energy Converter (WEC) is the general designation for devices that convert mechanical kinetic and/or potential energy from waves into electricity. This can be done in several different ways, as described in subsection 2.3, but all of them involve the use of a power take-off mechanism (PTO) which executes the transformation of mechanical energy into electrical energy.

The wave energy absorption is a hydrodynamic process of considerable theoretical difficulty, in which relatively complex diffraction and radiation wave phenomena take place [15]. The physical law of conservation of energy requires that in order to extract energy from the waves, the energy-extracting device must interact with the waves so as to reduce the amount of wave energy that is otherwise present in the sea. The device then generates a wave, which interferes destructively with the sea waves. Hence, "in order for an oscillating system to be a good wave absorber it should be a good wave generator" [16].

Some concepts are more advanced than others, in terms of the complexity of technology and in terms of development progress until today. However, there is a tendency by companies to develop more point absorber type of converters, being that it may indicate that it is less complex and expensive than other technologies [5].

It should be considered as an advantage that practically all the volume, of e.g. a heaving-float system, could be "used to displace fluid and thus to generate outgoing waves". Several proposed wave-energy converters have, however, relatively large proportions of "dead" volume not participating in such wave generation.

An additional difficulty related to the conception of wave energy converters is in the conception of the power take-off mechanism (air turbine, power hydraulics, electrical generator or other) which should allow the production of usable energy. The problem here lies in the variability of the energy flux absorbed from the waves, in several time-scales: wave-to-wave (a few seconds), sea states (hours or days) and seasonable variations. Naturally, the survivability in extreme conditions is another major issue [15].

If the device is to be an efficient absorber, its own frequency of oscillation should match the frequency of the incoming waves, i.e. it should operate at near-resonance conditions.

Hence, one has to regard the system as dynamic, and not as quasi-static (i.e. simply follow the wave surface motion) [2].

In practice, the frequency-matching meets with serious difficulties:

- if the body isn't substantially larger than 10 m, its own frequency of oscillation is too high as compared with typical ocean-wave frequencies;
- real waves are not single-frequency.

## 2.3 Types of technologies for wave energy extraction

As mentioned previously, diverse WECs were and are being developed, with quite different concepts. Hence, the technologies can be classified according distinct characteristics, being the three most common based on: 1) location; 2) size; or 3) working principle.

A brief presentation of each classification method is presented in Table 2, Table 3 and Table 4.

*Table 2 - WEC classification according to its location [5]*

| *Classification* | *Location* |
|---|---|
| *Onshore/Shoreline* | Located in the coast line. |
| *Nearshore* | Located near the coast (10-25 m deep). |
| *Offshore* | Located several kilometres offshore (< 40 m deep). |

*Table 3 - WEC classification according to its size and direction [5]*

| *Classification* | *Characteristics* |
|---|---|
| *Attenuator* | Long structures compared to wavelength, placed in parallel to wave direction.<br>They “attenuate” the amplitude of the wave. |
| *Point absorber* | Diameter significantly smaller than wavelength.<br>Collects energy in all directions.<br>Generates electricity by converting vertical motion of the waves into rotational/oscillatory movements. |
| *Terminator* | Similar to attenuators, but placed perpendicular to wave direction.<br>They “terminate” the wave’s action. |

*Table 4 - WEC classification according to working principle [5]*

| *Classification* | *Characteristics* |
|---|---|
| *Pressure differential* | Oscillating Water Column (OWC) - Using a semi-submerged chamber open at the bottom, the reciprocating movement of the waves raises and lowers the level of water therein, moving the internal air volume. This air flow drives a turbine which rotates always in the same direction, even though the air flow is bidirectional.<br>Archimedes effect converters - Submerged point absorber typically located near-shore and fixed to the seabed; it uses the pressure difference generated between the wave crests and troughs over the device. When the crest of the wave is over the device, this water pressure compresses the air that is inside it, and moves the device down. If it is the through over the device, the water pressure will be reduced and the device rises. |
| *Floating structure* | Floating device. The usable oscillatory movement may be vertical, horizontal, pitch or a combination of them. This movement can be induced either by an absolute motion between the floating body and an external fixed reference, or be the result of a difference of inertia between two or more bodies. |
| *Overtopping devices* | Overtopping systems force water to pass over a structure, filling a reservoir above the sea level, increasing its potential energy, kinetic, or both, and then release the water back to the sea through turbines. |
| *Impact devices/ Oscillating Wave Surge (OWS)* | These converters are flexible structures positioned perpendicular to the wave direction. Electricity is generated by the actuator that moves back and forth due to wave movement. |

## 2.4 Existing technologies

As mentioned previously, there are thousands of concepts for wave energy converters, but only a few reached the testing phase and there isn't any device commercially available yet.

In this section, some WECs will be presented, but this isn't meant to be an extensive list of the existing prototypes of wave converters. Pico's OWC Wave Energy Plant, the Pelamis Wave Power, the Archimedes Wave Swing and the WaveRoller are some of the most significant projects in waves' energy in Portugal; the Powerbuoy device is presented as it is of similar working principle to the device that is the object of this dissertation, and has been successful so far. More on WEC technologies can be found, for example, in [2, 5, 12, 17].

Afterwards, a brief introduction to hybrid energy conversion technologies is also done.

### 2.4.1 Waves systems

1. Pico's OWC Wave Energy Plant

An OWC with a capacity of 500 kW was installed on the island of Pico, part of the Azores, Portugal. It is located on the sea bottom, close to the rocky shoreline, in a slightly sheltered bay which helps to protect it from large storms. The scheme consists of a 12 x 12 m concrete structure built on-site, and equipped with a horizontal-axis turbine-generator capable of producing an average annual output of 124 kW, but rated for a maximum instantaneous output of 525 kW [3].

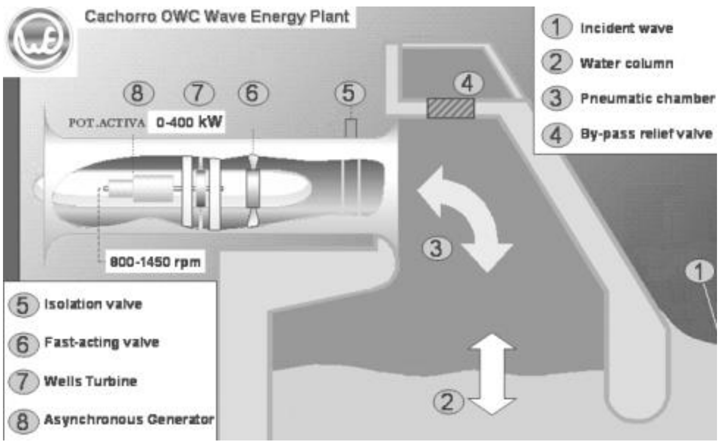



*Figure 4 - Functioning principle of Pico's OWC facility [18]*

The basic functioning principle of the OWC, as shown in Figure 4, is the incident wave motion excites the oscillation of the internal free surface of the entrained water mass inside a pneumatic chamber, which produces a low pressure reciprocating flow that drives the turbine, installed in a duct between the chamber and the atmosphere [18].

On May 10th, 2012, an international campaign titled "Support Wave Energy. Save the Pico Power Plant" was launched to procure funds for maintaining the facility. Even though a little over 50.000 € were collected (being that almost all of it was provided by the Azores' government), a total of 160.000 € were required, meaning that only a few human resources and maintenance costs were covered [19].

2. Pelamis Wave Power

The Pelamis (Figure 5) is an offshore, floating, slack-moored wave energy converter consisting of a set of semi-submerged cylinders linked by hinged joints. Ocean waves perform work on the Pelamis by moving adjacent cylindrical sections relative to each other across two degree of freedom joints [20].

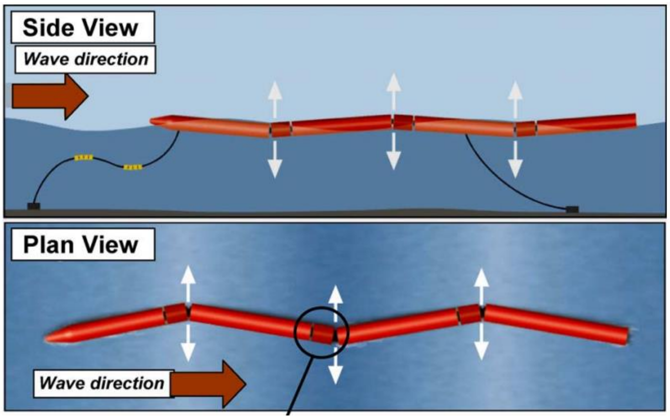



*Figure 5 - Diagram showing Pelamis' working principle [20]*

In 2004, Pelamis Wave Power (developer of the Pelamis device) demonstrated their first full-scale prototype, the P1, at EMEC's wave test site at Orkney (Scotland). The P1 became the world's first offshore wave power converter to successfully generate electricity into a national grid. The device was 120 m long, 3.5 m in diameter and comprised four tube sections. Pelamis' testing at EMEC (European Marine Energy Centre) between 2004 – 2007 led to the development of their second-generation device – the P2 [21].

In 2008, the prototypes were tested in the Aguçadoura wave farm (located in Póvoa de Varzim, Portugal), that hosted three Pelamis devices. This was the first undertaking worldwide as a commercial order of wave energy devices [22]. The machines were entirely built in Scotland to reduce technical and logistic risks during the manufacturing, has the Scottish suppliers had a proven prototype. The assembly took place in the Portuguese Peniche shipyard, after the devices were transported in segments to Portugal [22]. After three months of testing, the prototypes malfunctioned and were returned to the harbour.

Two main technical issues were claimed by Pelamis Wave Power:

- "The first affected the foam buoyancy attached to the subsea quick connection system (not part of the machines), the replacement of which caused a delay to the first machine installation;
- The second involved the cylindrical bearings of the machine where online instrumentation detected a higher wear rate than was expected. This was discovered to be due to faulty lateral movement of the cylindrical bearing face which was subsequently resolved" [23].

In November of 2014, Pelamis went into administration and Wave Energy Scotland now owns their assets and IP. The P2-001 has been dismantled, and the P2-002 machine is in Orkney (Scotland) and is owned by EMEC [21].

3. Archimedes Wave Swing (AWS)

This WEC (see Figure 6) is a cylindrical shaped buoy which is submerged and tethered to the ocean floor.

*Figure 6 - Model of the Archimedes Wave Swing [24]*

Its working principle is based on a pressure differential: when the wave reaches the floater, it moves vertically and generates a reciprocating movement. When the wave's peak approaches, the pressure on the top of the floater increases, which forces the mechanism inside the cylinder downwards, compressing the gas within to balance the pressure. When the wave's trough reaches the floater, the reverse takes place, moving the floater upwards and decompressing the gas inside. This motion engages a hydraulic system or a motor-generator set, hereby generating electricity [24, 25].

The main advantage of this device is that because it only has one moving part, it is more reliable and entails a lesser need for maintenance [25].

4. WaveRoller

This device (Figure 7) operates under an Oscillating Wave Surge (OWS) principle, in a near-shore location (approximately 0.3-2 km from the shore) at depths of between 8 and 20 meters. Depending on tidal conditions it is mostly or fully submerged and anchored to the seabed.

A single WaveRoller unit (one panel) is rated at between 500 kW and 1000kW, with a capacity factor of 25-50 % depending on wave conditions at the project site. Since each device is equipped with an on-board electricity generator, the output from many devices can be combined via electricity cables and a substation [14].

*Figure 7 - Modelling of a WaveRoller wave farm in operation during high tide [14]*

WaveRoller units can float without any external support. This feature makes it relatively cheap and easy to tow the devices to and from the project site. They are then deployed by flooding the ballast tanks with water - causing the device to sink to the seabed where it can commence normal operations [14].

For service or maintenance, air is pumped back to the ballast tanks, so that the WaveRoller unit can rise to the surface. Operators can then access the machine rooms directly on site or tow the device to a suitable location closer for maintenance work [14].

Three prototypes (100 kW) of the WaveRoller have been tested in Peniche, Portugal, since 2012, and a new real-scale device (350 kW) is being planned, after the project was granted 10.000.000 € by the European Investment Bank's (EIB) Horizon 2020 project [26].

5. PowerBuoy

The PowerBuoy (developed by Ocean Power Technologies) is a floating power generation system that can be ranked as a point absorber. A mooring system keeps the structure on station in the ocean. At the surface, a float moves in response to ocean waves along a spar with a reduced response to waves due to a heave plate at its base. Relative motion between the float and spar drives a push rod into the spar. A mechanical actuator converts the linear motion into a rotary action that drives an electric generator [27].

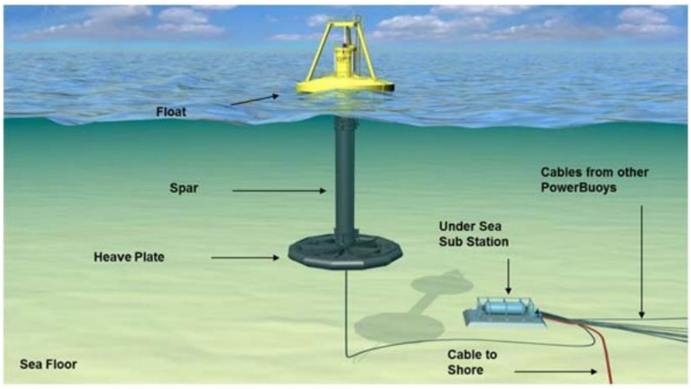



*Figure 8 - Working principle of the Powerbuoy [27]*

Ocean Power Technologies announced, on June 12 of 2017, that its PB3 commercial PowerBuoy, which, at this date, was deployed off Kozu-Island (Japan) as part of a previously announced lease, was meeting all its performance requirements. Its power take-off accelerated life testing, which is conducted at the company's headquarters in New Jersey, reached over 67 million strokes (simulating over 4 years of ocean operation) [28].


*Figure 9 - Photograph of OPT's PowerBuoy deployed off Kozu-Island, Japan [28]*

This is one of the few wave energy converter devices that have reached such an advanced development phase.

### 2.4.2 Hybrid systems

In order to achieve a sustainable development of the offshore energy sectors, it is necessary to optimize the existing resources. As many of the locations that are appropriate for wave energy converters may also be good for wind converters and vice-versa, the use of hybrid technologies may entail a step forward in the energy industry. Not only to maximize power output (and consequently grid input), but also to ensure a somewhat stable (or more stable) power output, as both wave and wind are random to some degree.

Because wave energy technology is not that developed, the technology in the field of hybrids is even less developed. As of the author's knowledge, no prototypes were tested, being that most of the concepts for hybrids are just that: concepts. In Figure 10 and Figure 11 are shown artistic renders of futuristic hybrid converters, by companies that are in the development phase for these technologies.


*Figure 10 - Artistic render of a floating hybrid system, W2Power (by Pelagic Power AS) [29]*

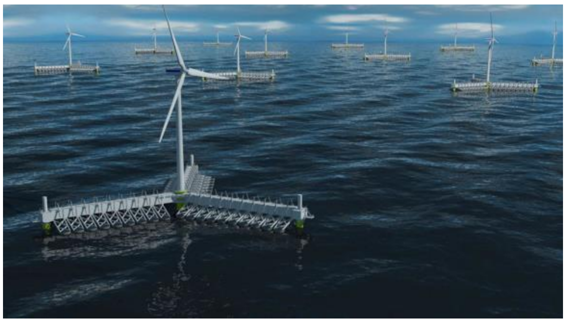


*Figure 11 - Artistic render of a floating hybrid farm (by Wave Star AS) [29]*

These combine floating structures that convert waves' energy with wind turbines.

Floating wave and offshore wind hybrids such as the ones described previously are particularly interesting because of the larger wave resource that exists in deep waters due to the lack of the seabed effects, and lack of water depths suitable for bottom-fixed concepts in several countries with a relevant wave resource, such as Portugal or Spain. Some other concepts of hybrids include: OWWE, by Norway's Ocean Wave and Wind Energy, Ltd.;

Poseidon Floating Power, by the Netherlands' Floating Power Plant AS; Wind Wave Float, by the US Principle Power [54]; and the Offshore Ocean Energy System, by the US Float Inc [29].

## 2.5 Environmental impact of wave energy converters

As WECs are reaching a point of technologic maturation that nears commercialisation, their proliferation in the world's oceans is something that is becoming closer to reality. This means that the environmental impact of these devices and their installation in specific locations should be studied by developers, not only because they are marketed as the "greener technology", but also because there are narrower and narrower legislative constraints that regard sustainability. This environmental concern is more beneficial at an early point of the technology development, allowing the progress to be directed towards a more sustainable solution, saving time and overall costs.

WECs may be among the most environmentally benign of energy technologies because: 1) they have little potential for chemical pollution (any hydraulic oil will be carefully sealed); 2) little visual impact (and no visual impact for offshore technologies); 3) low noise generation (at least concerning humans); 4) low $CO_2$, $SO_2$ and $NO_x$ emissions [3].

But care should be taken in the development, considering themes such as: 1) colonisation patterns (as WEC farms can impose artificial barriers for migration routes); 2) biofouling (undesirable growth of marine organisms on immersed artificial structures, increasing chances of mechanical failure); 3) purposeful artificial reef design (the arraying of WECs can create an artificial reef-like structure, which will alter pre-existing ecosystems); 4) no-take zones (area set aside by the governments where no extractive activity is allowed, to protect ecosystems); 5) marine bioacoustics (underwater noise can pose an issue for the aquatic biosphere); and 6) electromagnetic fields (effects of which can be mitigated by good cable techniques and the burial of cables in the seabed) [30].

## 2.6 Economic aspects

As mentioned in subsection 1.1, one of the main problems in the wave energy development is its uneconomical status in the investing community [7].

The existing models to estimate the costs of a wave energy project are often oversimplified, as it is a lesser developed enterprise, which results in lesser investor confidence, constituting an impediment for the developing of wave energy [7]. But something that is agreed on, is that the key to successful economic implementation of wave energy stations is in reducing operation and maintenance costs [3, 7]. These costs are high mainly because these correspond to facilities in the sea. Nevertheless they are necessary as proper and regular maintenance is fundamental to maintain production capacity over the service life of a wave farm [7].

The cost of the WECs was found to be a very significant part of the overall cost of a wave farm [7]. Indeed, the capital cost per kW of establishing a power station ran by wave energy exceeds that of conventional generation technologies (e.g. gas, coal, ...); also, the load factor (actual annual output divided by maximum possible output) is lower than a conventional station due to the variability of the wave climate [3, 7]. However, these costs can be expected to decrease with economies of scale, as wave farm installations increase; this, combined with the uncertainty of long-term fuel costs for conventional technologies, is leading to an upcoming end of gaps between electricity costs [7].

In what concerns the incomes, the obvious revenues are the sale of the generated electricity. In this regard, current converters have low performances, meaning that improving them would greatly boost their economic viability. Besides these direct sources of revenue, other benefits of wave farms can be quantified, such as the improvement of infrastructures in the area, the rekindling of related sectors, such as the ship industry and allows for the creation of new jobs.

Despite these predictions, a MWh generated from wave power is currently more expensive than its counterparts from conventional sources and most of other renewables, which means that wave power installations can only be economically viable if favoured by subsidies [7, 31]. Despite this, a 2012 study that analysed the cases of Pico's OWC and the Pelamis concluded that, despite the feed-in-tariff (government incentive to boost the production of electricity using renewable energies) that is being applied, these technologies would still not be economically attractive [31]. This leads to the conclusion that these technologies are not yet mature enough to reach economic viability. It should be noted, though, that the technologies that were the subject of the study are somewhat outdated and that since then, other technologies have emerged that may reach those standards of economic feasibility – an economic study on these technologies is yet to be released.

## 2.7 Final remarks

Unlike large commercial wind turbines, the wave energy technologies are quite diverse due, in part, to the multiple ways that wave energy can be transformed into electricity - Table 4 lists at least 5 different devices' working principles. Recent reviews account for dozens of projects at various stages of development, being that the number does not seem to be decreasing as new concepts and technologies replace or outnumber the ones being abandoned [2].

None of the existing wave energy devices has been commercially completed yet, which means there are a lot of opportunities in the development of these technologies. Even more so in the development of hybrid concepts, that have the potential to combine the costs of the installation of the offshore structures and double, or triple, the output of electricity, hereby increasing revenues.

Care should be taken during the development process, though, to consider aspects that may yet seem frivolous or accessory at first, but are essential down-the-line in the life of the product, such as its environmental impact, and its economic viability.

## 2.8 Concept presentation of Tripower UP

As mentioned previously, this system was designed by Miguel Macieira [8].

At first, a general description and requirements for the system are presented, to put the project into context. Afterwards, the Tripower UP system, as of January of 2017, will be presented, being that the wave mechanism will be described in more detail, afterwards.

### 2.8.1 General system description

The Tripower UP is an offshore electric energy generation system. The starting point of this device is modelled in Figure 12.

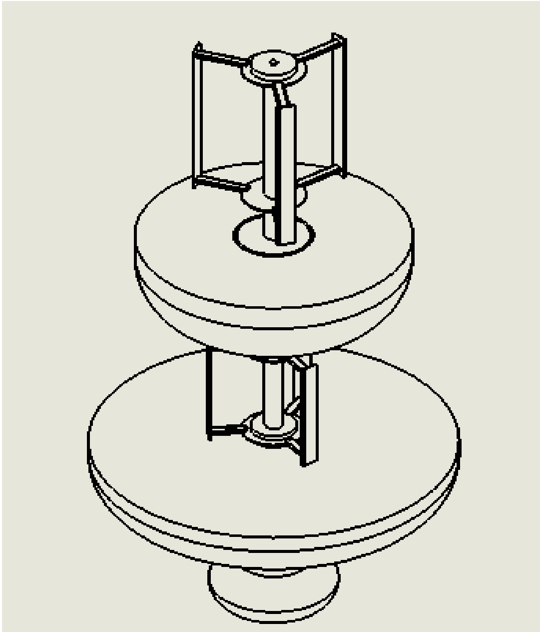


*Figure 12 - Three-dimensional modelling of the Tripower UP system [8]*

The device combines a buoy that serves as a wave energy converter with a couple of turbines: one that is meant to harness wind energy; another that is meant to harness currents energy. This combination is made through a single, central shaft that has an outlet into an electric generator.

This system is to be deployed at high-sea and have little to no maintenance for large periods of time, and it is to provide the grid with a constant energy source. This is because it combines three forms of energy conversion (wind, waves and currents), providing a somewhat constant production of energy.

One point at which this system heavily diverts from existing (conceptual) solutions is in the fact that it combines the multiple kinds of energy mechanically. Existing solutions of devices that combine multiple kinds of energy sources do so by attaching generators to the various converters, and then combining electrically the output. This solution does the combining mechanically, and the resulting output is a single generator, which leads to a more complex mechanical solution.

### 2.8.2 System requirements

In summary, the main requirements for a given offshore wave energy converter are: survivability (the device has to withstand years of the ocean's harsh conditions); easy maintenance (the device should be easily maintained at sea, or easily disconnected and towed); performance (in order to perform well, control is needed, due to sea variability) [32].

The system must float so that it performs regardless of variation in tide caused by sea depth. It has to be towable, in order to be brought on to shore in the event of harsh weather conditions. Also, its mooring should be done in one single point, in order to allow the device to orient itself towards the direction of waves and currents [8]. The system also must be somewhat robust and independent in the sense that it has to endure harsh weather conditions, while needing little to no maintenance for months.

One of the main requirements for this particular system is that it must be modular, so that it can hold different configurations. This means that, in a later phase, the device can be mass-produced (or produced with little changes in its design) and installed in multiple locations, including places in which some modules may not be interesting – e.g. locations with no wind or in which the currents are not significant.

### 2.8.3 Device description

The Tripower UP device can be separated into four main subsystems: the wind turbine; the wave energy buoy; the currents turbine; support components. These are represented in Figure 13.

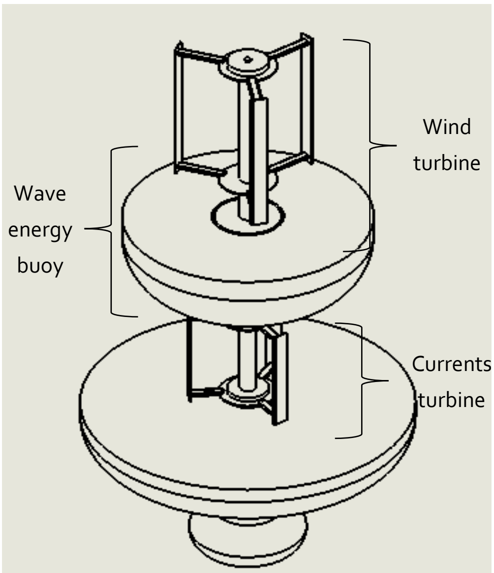



*Figure 13 - Multiple components that compose the Tripower UP device*

In order to ensure structural robustness, a structural tower was designed, on which all systems are assembled (i.e. the wind turbine, the wave energy buoy subsystem and the currents turbine).

The wave energy buoy will be detailed in subsection 2.8.4.

The tower is mounted on a supporting buoy with a general purpose of providing buoyancy. This buoy, which is an enormous hollow volume, has a great upper contact area, immediately below the currents turbine, as it is modelled in Figure 13. As the buoy has a great hollow volume, a buoyancy force with high magnitude directed towards the surface is generated, hereby supporting the weight of the whole system. This buoy acts as the foundation for the system and, due to the fact that it floats, it can increase or decrease its distance to the bottom of the sea to accompany the tides. Its great upper surface area creates a high vertical movement resistance for the structure, granting a higher stability to the system [8].

The system remains unstable, still. Hence there is the need for the installation of a large mass, underneath the supporting buoy. This allows for the weight of the submerged mass, which has a point of application different than the buoyancy force generated by the supporting buoy, to generate a moment that leads the system to verticality [8]. This verticality is crucial for an efficient operation of the device, as it will be explained up next, in subsection 2.8.4.

### 2.8.4 Wave energy buoy

The wave energy converter integrated in the Tripower UP device (Figure 14) is, fundamentally, a rack-and-pinion system that converts the energy provided by the movement of the rack (1), that is attached to a moving buoy (2), that consequently drives a pinion (3), located in a "relatively fixed" tower (4), to rotate a series of gears and shafts so as to rotate the shaft of a generator, in the end of the kinematic chain.

As the more vertical the rack is, the higher the force it transmits to the pinion, verticality must be ensured in order to provide for an efficient system.

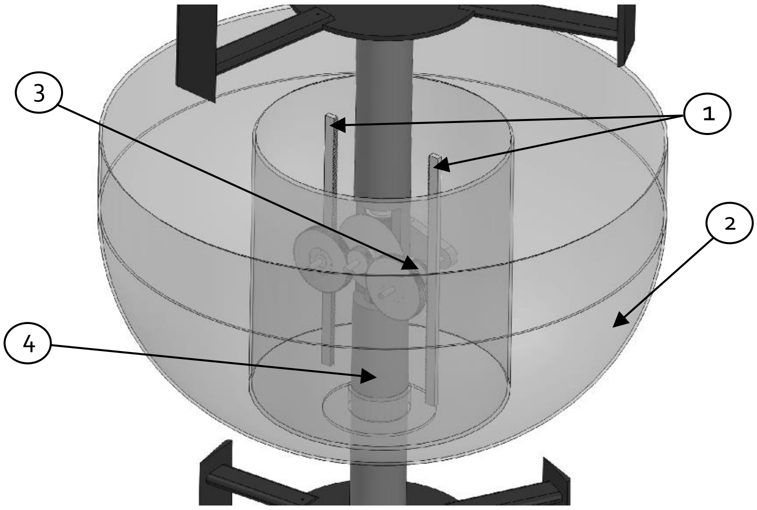



*Figure 14 - Detail of the 3D modelling of the wave energy buoy of the Tripower UP system*

For the present case, two racks drive two pinions, each of which are attached to a shaft that holds another wheel. These wheels are, in turn, connected to a third wheel, which is responsible for turning a shaft that holds a bevel wheel, that connects the movement to the central shaft. This kinematic structure is detailed in Figure 15.

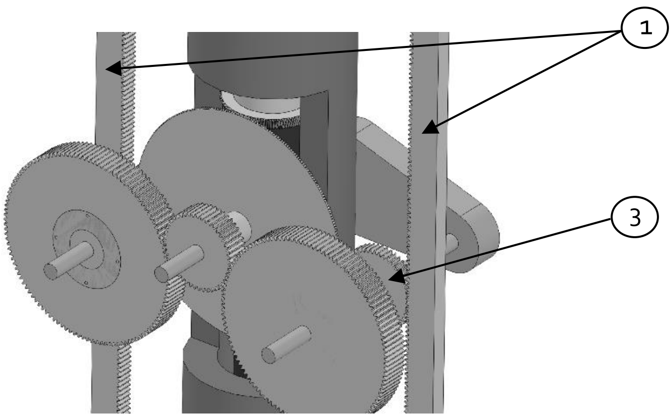



*Figure 15 - Detail of the wave energy buoy's kinematic chain*

It should be noted that one of the racks is responsible for the harnessing of energy in the downward movement, and the other in the upwards movement. This is possible because a free-wheel is installed in the gears.

This free-wheel (Figure 16) enables that once the buoy is in an ascending movement, for example, the wheel that is responsible for the descending movement will not be transmitting power.

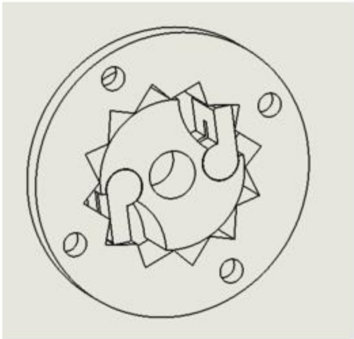


*Figure 16 - Custom free-wheel of the initial Tripower UP device [8]*

The free-wheel is to be installed in every subsystem, as it has a second, essential, function: if one converter (e.g. wind) is clearly generating more energy (than waves, for example), this component will allow for the central shaft to rotate with a higher speed, and hereby disconnecting the other subsystems from the central shaft. In using this component, the highest potential is always reached, prohibiting subsystems that are not generating energy from "slowing down" the central shaft.

The description of the work since done on the Tripower UP project follows on section 3.

# 3 Final device's overview

This chapter is aimed at assisting the reader's analysis of the subsequent chapters, through the presentation of a brief overview of the final product of the Tripower UP device's mechanical design.

In Figure 17, the Tripower UP device is modelled. It should be noted that the sea's medium level is at the WEC's buoy's. The reader should note that the current model does not describe exactly the output of the work on this device. The Wind Energy Converter, the Generator and the Currents Energy Converter were not extensively studied. They are modelled in order to allow a more extensive understanding of the authors' view of the final device.

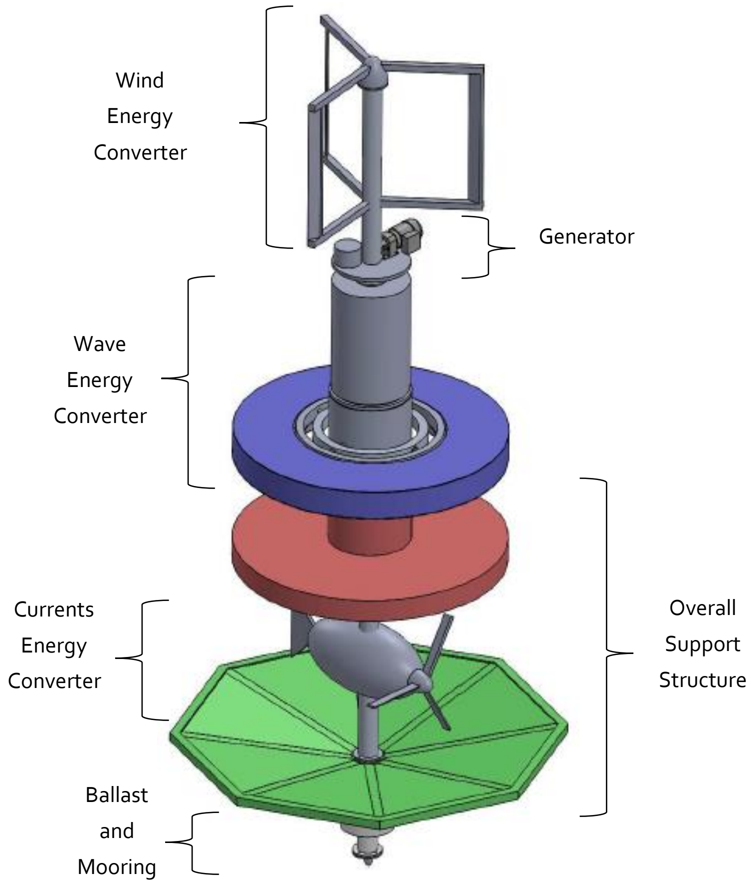



*Figure 17 - Overall model of the Tripower UP hybrid system*

It should be noted that the major part of the work was done on the Wave Energy Converter and the Overall Support Structure – these will be referred to as Overall System from here on out. This is because the necessary turbine-related technology for the wind's and the currents' converters is already somewhat established, and, more importantly, due to the fact that the Wave Energy Converter technology is lesser developed, and could set the design for the rest of the device.

The design description is subdivided into two major groups: 1) the design of the wave energy converter; 2) the design of the overall supporting structure. The latter refers to the structure that is necessary to support all three energy converters: wind, waves, currents.

The overall system, the wave energy converter and the overall system's support structure are modelled in Figure 18; Figure 19 and Figure 20, respectively.

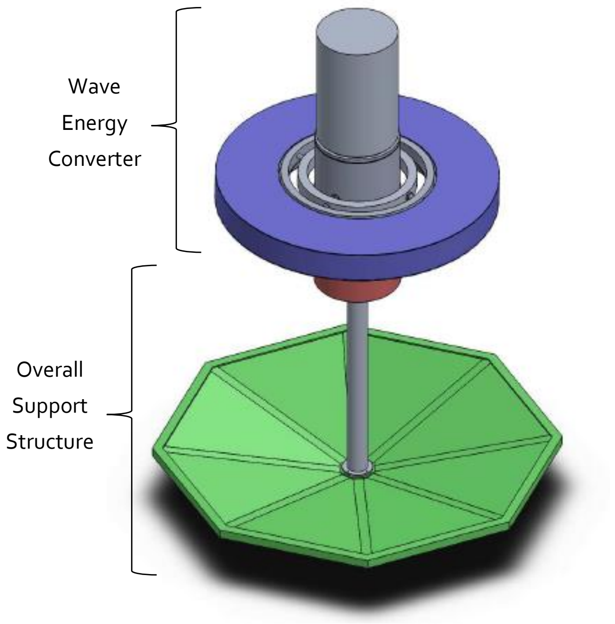



*Figure 18 – Model of the overall system*

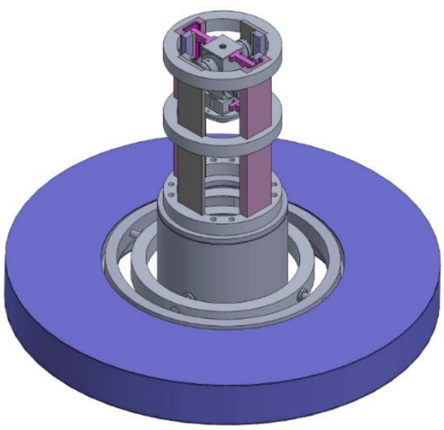


*Figure 19 - Detailed view of the Wave Energy Converter*

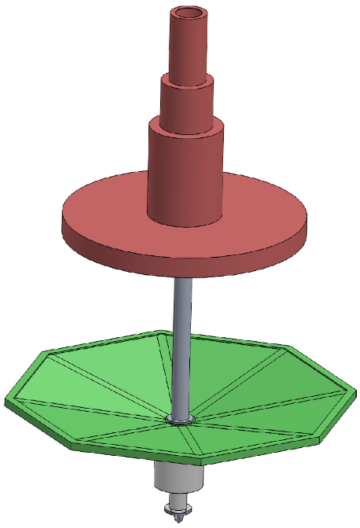
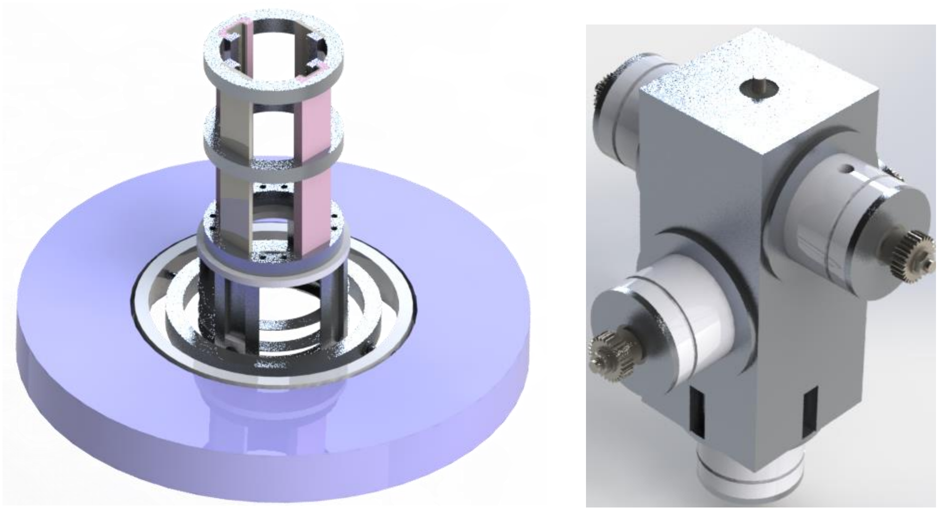


*Figure 20 - Model of the Overall Support Structure*

The Wave Energy Converter (WEC) itself, can be subdivided into two groups: 1) the WEC's Mechanical Transmission; and 2) the WEC's Mechanical Structure. These two components are described in Figure 21.



(a) (b)

*Figure 21 – Rendered models of the WEC's components: i) WEC's Mechanical Structure; ii) WEC's Mechanical Transmission*

The WEC's Mechanical Transmission will be described in detail in section 4 and the WEC's Mechanical Structure in section 5.

To convey the size of the prototype, general device characteristics for the overall system (Figure 18) are presented in Table 5, and described in Figure 22.

*Table 5 – Overall system's characteristics*

| | |
|---|---|
| *Device's mass* [kg] | 442 |
| *Maximum height* [m] | 4.00 |
| *Minimum height* [m] | 3.80 |
| *WEC's buoy diameter* [m] | 1.50 |
| *Inverted parachute's maximum length* [m] | 2.00 |

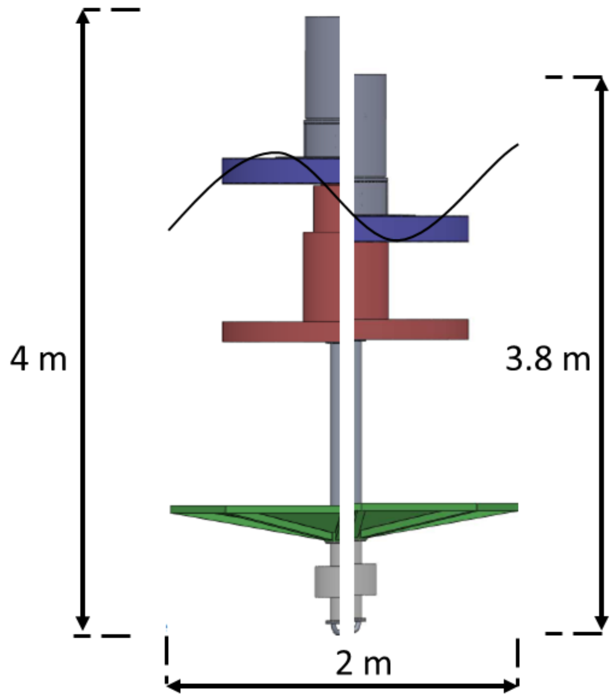



*Figure 22 - Overall system's dimensions*

# 4 Design of the WEC's Mechanical Transmission

In this section, the detailed design of the WEC's Mechanical Transmission will be described.

Firstly, the device's testing conditions will be described. The implications of these conditions and other design considerations (the selection of the main parts – i.e. the rack, gears and generator – and the definition of the gear ratios) are described followingly, in subsection 4.2. Afterwards, the design of the system's free-wheel is described. Thereupon the "wave cassette" concept and design are presented. Subsequently, the wave converter's general transmission's design is outlined. Finally, some mechanical calculations of the WEC's Transmission are described.

## 4.1 Testing conditions

As mentioned previously, the functional prototype to be manufactured is meant to be tested in the Wave Tank located at FEUP, which is 12 m wide, 28 m long and has a maximum height of 1,2 m [33]. This tank is equipped with a wave generating system, composed of two modular units, with eight narrow elements each – this makes the system quite versatile, being able to be moved inside the tank. Each of the units include eight paddles coated with glass fibre, with independent movements, allowing it to generate waves with different directions [33].

*Figure 23 - Wave tank installed in the Hydraulic Laboratory at FEUP [33]*

Considering the initial model for the Tripower UP system, it was necessary to scale the model, and so a scale of approximately 1:100 would be necessary.

The scalability of the design was not studied. Instead, the device was designed for the final conditions, which are the weather (wave) conditions that can be simulated in the wave tank. Attention should be paid, though, during the process of adapting the design of this prototype to another scale, as some variables, such as power and speed, may not be directly proportional.

To perform an initial approach to the design of the system, one must figure out for which kind of conditions the system has to perform well. This being said, the objective of the final system is to be installed in a certain offshore location, so the most efficient converter would consider the specific location's weather conditions, and the design would adapt to it.

It was chosen to design the wave converter to have its highest efficiency for average wave conditions in Matosinhos, Portugal, which is the geographically closest location. This would ease any further tests. Another option would be to test the wave converter in Póvoa de Varzim, as it is a previously studied location at the time of the installation of the Aguçadoura's Wave Farm.

Data was withdrawn from a weather forecast provider, Windguru®, for the period of one year, to provide reliable statistics.

This data, which can be found in Appendix A, lead to the values in Table 6.

*Table 6 - Statistics for wave amplitude and period in Matosinhos, Portugal, between 01/01/2016 and 31/12/2016 (Windguru ®)*

| | *Wave height* [m] | *Wave period* [s] |
|---|---|---|
| **Average** | **1.73** | **11.08** |
| Maximum | 6.10 | 20.00 |
| Minimum | 0.40 | 5.00 |

Hence, as the waves generated by the wave tank are approximately 5 times smaller than the ones from Table 6, it was decided to design the system for the wave conditions set in Table 7.

*Table 7 - Wave amplitude and period for the prototype*

| | Wave height (m) | Wave period (s) |
|---|---|---|
| **Average** | **0.35** | **2.22** |
| Maximum | 1.22 | 4.00 |
| Minimum | 0.08 | 1.00 |

Using the expression from 2.1.1, and assuming the average wave that the tank is to generate, Table 7, one concludes that the waves generate approximately 254 W/m.

## 4.2 Design considerations

After the analysis of the design of the existing Tripower UP design, some frailties came up, such as the unbalance of forces caused by the racks. As each rack is responsible for transmitting power for one separate direction, in each movement there is an unbalance, as the rack generates a force that causes a moment in one direction, causing instability. In order to balance this, symmetry of forces would be need, i.e. a rack with equal movement in both ends of the system. A configuration such as this could be described as a "cross configuration". This situation is described in Figure 24.

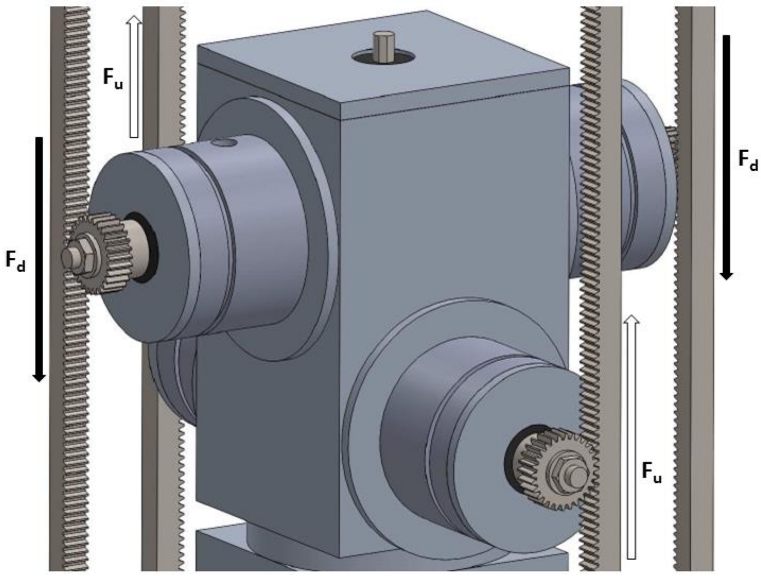



*Figure 24 - Forces applied to the "cross configuration" racks on the ascending movement ($F_u$) and on the descending movement ($F_d$)*

Something that was poorly considered in the design of the first version of the Tripower UP device, was the eventual need for maintenance. The components for the wave energy buoy are of difficult access, which means that during maintenance this could be a problem. This issue was, therefore, considered throughout the design process.

This lead to a different design that contemplated the concept of a "wave cassette". The idea would be to design a subsystem that would be positioned in a central body and arrayed. This would allow for lesser manufacturing and assembly complications, as well as an easier maintenance.

In an attempt to narrow down a solution, there was a need to figure out some design constraints, so as to introduce some system variables. In order to design the kinematic chain, one has to define the diameter of the wheel connected to the rack; gear ratios; and the power of the generator.

In the market, two common values for the module (m) of the gears and racks are m=1 and m=2. As the goal was to manufacture a small prototype, and m=1 would lead to a smaller device [$d=m \times Z$ (being $d$ the pitch diameter and $Z$ the number of teeth)], it was decided to purchase pinions and racks with m=1.

### 4.2.1 Rack

As mentioned previously, it was a main goal to obtain a small prototype, so the selected rack-and-pinion would be of module m=1.

Something that is also relevant for the selection of the rack is its length. As the system must harness the energy from waves with the characteristics of Table 7 (i.e. wave height of 350 mm and period of 2.22 s), the rack must have a length of, at least, that of the height of the wave, 350 mm. Hence the selected rack has a length of 500 mm (see the representation on Figure 25).

*Figure 25 - Selected rack (m=1; length=500 mm) - Supplier: RS*

### 4.2.2 Spur cylindrical wheel

The spur wheel that was selected as the input for the system is represented in Figure 26. This one was selected because it was the cheapest wheel available from the market, made of steel, with a module of m=1. The pitch diameter is hereby defined: 28 mm.

*Figure 26 - Selected spur cylindrical wheel (m=1; d=28 mm) – supplier: RS [34]*

### 4.2.3 Bevel gears

The bevel gears were, during a first iteration of the design, selected with a module of m=1. But when the central shaft was being designed, the central shaft's bevel wheel was causing an interference. This is due to two design constraints: 1) this wheel is geared with two other wheels simultaneously; and 2) the shaft had to be of a minimum diameter due to design restraints towards the end of the shaft. This situation is described in Figure 27.

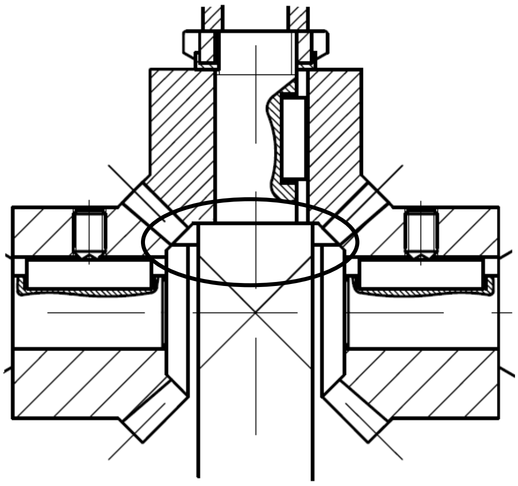


*Figure 27 - Central shaft's possible interference with the bevel gears*

This lead to the use of a wheel with a module of m=1,5, described in Figure 28.

*Figure 28 - Selected bevel wheel (m=1,5; d=30 mm) – supplier: RS [34]*

### 4.2.4 Generator

In essence, a generator is a motor set up to function the other way around. So, one has to select a motor, after figuring out what kind of output is expected at the end of the kinematic chain.

Considering that the input would be in the order of 254 W/m, that the final buoy has the diameter of 1.5 m (see section 3), one has the potential to extract 381 W. As a rough approach, one can assume that throughout the entire system one would have losses that amount to 1/3 of the power. Hence it would be needed approximately 254 W of power input in order to properly drive the generator.

After a market research, a motor/generator was found: a brushless, 250 W motor.


*Figure 29 - Brushless, 250 W generator selected (idle speed=8670 rpm; maximum torque=311 mNm) - supplier: maxon motor [35]*

### 4.2.5 Gear ratios

In order to define the gear ratios, it is necessary to figure out what kind of input and output the kinematic chain admits.

As small brushless motors function with higher efficiency at higher speeds, it is advantageous to have a high speed at the entrance of the generator. Hence, it was decided to target the minimum of 500 rpm as being the output of the system, feeding the generator. Furthermore, as the selected generator has an idle speed of 8670 rpm, a target end velocity of approximately 8670 rpm is set.

In order to define the input for the kinematic chain, one has to calculate the pinion's angular velocity:

The rack's angular velocity ($\omega_r$) is given by a fraction that includes the wave period (and subsequently the rack's), *T*=2.22 s:

$$\omega_r = {}^{2\pi}/_{T} = {}^{2\pi}/_{2.22} \approx 2.84\, rad/s$$

This allows for the rack's linear velocity ($v_r$) to be calculated:

$v_r = A\ \omega = 491\ mm/s$, where *A* is the wave's amplitude

As the pinion has a pitch diameter of *d*=28 mm, the pinion's angular velocity is given by:

$$\omega_p = {}^{v}/_{r} = 35\, rad/s \approx 335\, rpm$$

This angular velocity $\omega_p$ is the input speed.

In order to define the gear ratios, some considerations should be made:

1. The input speed is 335 rpm;
2. The output speed is approximately 8670 rpm;

3. As stated in 4.2.3, the central bevel wheel cannot be smaller; hence a transmission ratio for that gear cannot be superior to 1;
4. As a total transmission ratio of ≈ 25.9 is needed, the most efficient solution would be to have a multiplication box before the generator;
5. Common values for spur gear transmissions are not superior to 4, due to efficiency purposes; bevel gears' transmissions are not superior to 3.

These lead to the solution for gear ratios described in Table 8.

*Table 8 - Kinematic chain's gear ratio values*

| *Gear* | *Gear ratio* |
|---|---|
| *Cassette shaft to central shaft* | 1 |
| *Central shaft to generator's multiplication box's first shaft* | 2.5 |
| *Multiplication box's first shaft to second shaft* | 4 |
| *Multiplication box's second shaft to third shaft* | 2.5 |

This solution leads to an output speed of approximately 8365 rpm.

It should be noted that the design for this generator's multiplication box is not the subject of this work and should be addressed in future works. This multiplication box would have a kinematic chain similar to the one described in Figure 30, with the ratios from Table 8.

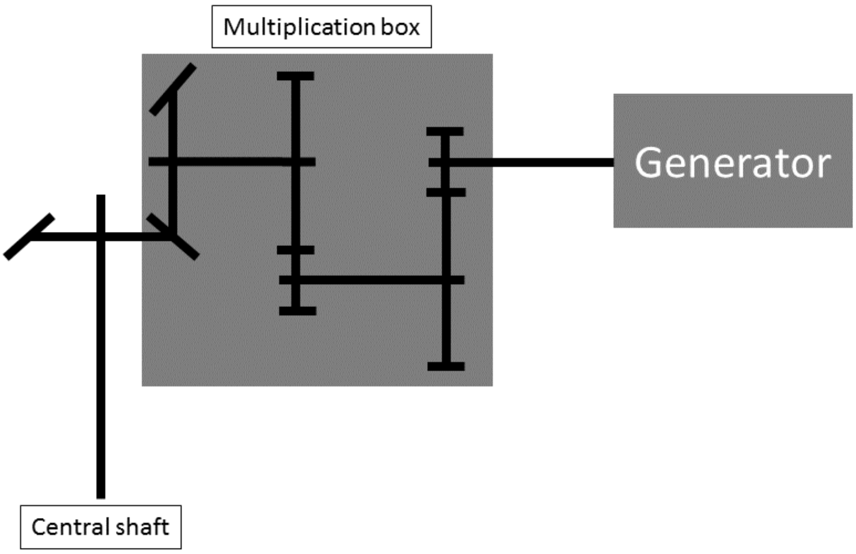



*Figure 30 – Schematic for a possible generator's multiplication box's kinematic chain*

It should be noted, though, that in further stages of development, this multiplication box may no longer be necessary, as generators with higher power values do not require such high figures for speed input.

### 4.3 Free-wheel

This subsection describes the work done as a team between the author and Diogo Telo Rodrigues.

A free-wheel is a component that generally disengages the driveshaft from the driven shaft when the driven shaft rotates faster than the driveshaft.

The free-wheel is a crucial design component in this project, as mentioned in 2.8.4, because it is responsible for: 1) the alternation of power transmission between the ascending and descending movements and 2) the decoupling of the subsystem if it is "slowing down" the device.

If one converter (e.g. wind) is clearly generating more energy (than waves, for example), this component will allow for the output shaft to rotate with a higher speed, and hereby disconnecting the subsystem from the central shaft. In using this component, the highest potential is always reached, prohibiting subsystems that are not generating energy from "slowing down" the central shaft.

Also, it allows that once the buoy is in an ascending movement, for example, the wheel that is responsible for the descending movement will not be transmitting power.

As mentioned in subsection 1.2, as the free-wheel was the most expensive component and a crucial one at that, and the project funding was limited to the faculty's budget, before being granted the funding the team decided to design a "custom free-wheel" as it would save costs; after the funding was granted, the design strategy changed, and it was decided to buy a commercial free-wheel, as it was a more compact and tested solution.

The custom free-wheel's hitching mechanism and the commercial free-wheel are described in subsections 4.3.1 and 4.3.2, respectively. It should be noted that the discardment of the "custom free-wheel" concept means that the custom free-wheel presented is not fully finished: the solution's design was not completed, and it was not validated (neither through calculation nor simulation) and no 3D model was generated. Also, the technical drawing presented is not complete.

### 4.3.1 Custom free-wheel's hitching mechanism

The starting point of the design was that of the wheel represented in Figure 16.

The free-wheel that was designed for the Tripower UP project is loosely based on a mechanism that is currently used to holster sails on sailboats (see Figure 31).

*Figure 31 - Part from a mechanism destined to holster sailboats' sails*

To reproduce this mechanism for the prototype, there were available teeth like the one in Figure 32, which would cause future design restrictions (i.e. this component would set the minimum size for the free-wheel).

*Figure 32 - Tooth from the mechanism destined to holster sailboats' sails*

Something that was heavily considered and lead to multiple design decisions was the need to use as much standardised (i.e. market-available) components as possible, as well as design as much equal parts as possible (since it is easier to manufacture and to assemble). Something that also lead to design restrictions was the need to obtain a somewhat close solution to existing free-wheels, so as to allow for a replacement in later design phases.

This lead to the design of the solution shown in Figure 33 and Figure 34.

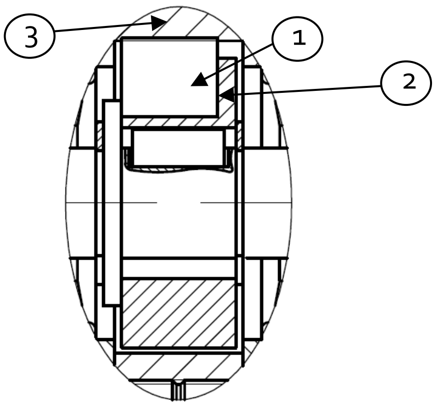



*Figure 33- Custom free-wheel's hitching mechanism - section view*

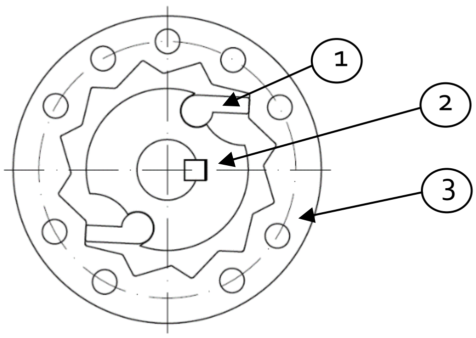



*Figure 34 - Custom free-wheel's hitching mechanism - front view*

It should be noted that part 2 is similar to the part from Figure 31 (without the geared wheel) and that part 1 refers to the teeth from Figure 32.

### 4.3.2 Commercial free-wheel

The free-wheel that was selected for the project can be found in Figure 35.

*Figure 35 – Commercial free-wheel - supplier: Stieber Clutch*

Some of the key features for this free-wheel are detailed in Table 9.

Table 9 - Features for the commercial free-wheel - supplier: Stieber Clutch

| | | | |
|---|---|---|---|
| *Inner diameter* [mm] | 15 | *Maximum Torque* [Nm] | **34** |
| *Outer diameter* [mm] | 35 | *Dynamic Load* [KN] | 7.4 |
| *Nominal Torque* [Nm] | 17 | | |

## 4.4 Design of the "wave cassette"

The initial idea for the free-wheel was to install it inside the gears. This was discarded due to the fact that, because one intended to purchase gears straight from the market, at the least cost available, the free-wheel would not fit in due to minimum size constraints. This meant that it would be necessary to design a system that held supports (i.e. bearings) and mechanical connections to the wheels. This system is designated as "wave cassette".

In subsection 4.4.1, the internal part of the "wave cassette" that would result out of the usage of the custom free-wheel is described; in subsection 4.4.2, the "cassette" that resulted out of the commercial free-wheel.

### 4.4.1 Custom free-wheel solution

This solution is, essentially, composed by two cylinders with an intermediate connector, and held together by two "covers". Inside, there is a shaft that connects one of the movements with the other, through the teethed mechanism, depending on whether the shaft is turning in the right direction (or at the right speed). This is done by the free-wheel's hitching mechanism described in subsection 4.3.1, which gears the intermediate connector's grooves with the teeth. The wave cassette is partly represented in Figure 36.

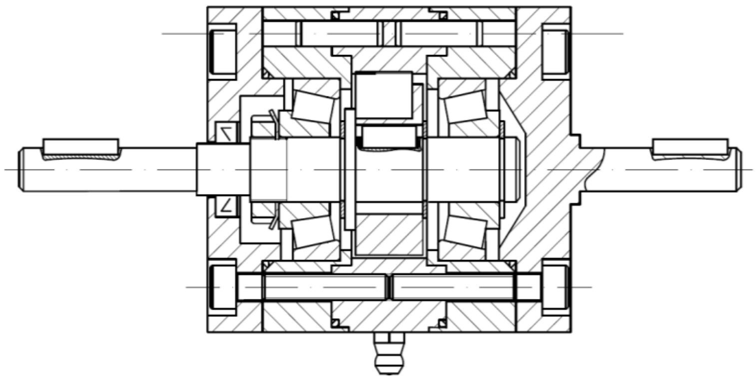


*Figure 36 – Partial "wave cassette" using a custom free-wheel - section view*

This solution is a partial "wave cassette" as it lacks an external supporting body: the external parts rotate, meaning that it lacks bearings and an external carcass to fix it to the central body.

The inner shaft is supported by two tapered roller bearings, arranged in a back-to-back arrangement (Figure 37).

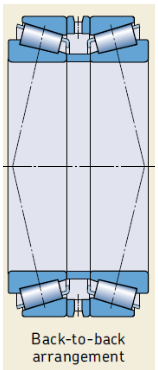



*Figure 37 - Tapered roller bearings back-to-back arrangement (also designated as "O" arrangement) [36]*

This arrangement provides for a relatively stiff bearing arrangement that can also accommodate tilting moments and axial loads in both directions. This solution was chosen for this prototype not because it was hypothesised that there would be great axial loads in the prototype, but because there would be significant axial loads in the final system. Normal ball bearings might have sufficed, but as tapered roller bearings have a somewhat different and more difficult assembly procedure from other kinds of bearings – both the fact that they have two parts and that they require an initial assembly axial load – it was decided to include this solution so as to have a prototype closer to the final system.

It should be noted that the selected lubrication method for this preliminary draft was that of grease. This due to the fact that the shaft rotation speed predictions were relatively low, and because this would provide for an easier maintenance. This decision would have to be validated afterwards.

The full technical drawing for this component can be found in Appendix B.

### 4.4.2 Commercial free-wheel solution

This solution does not differ greatly from the solution presented previously. As represented in Figure 38, there are two main differences: 1) neither shafts are the same part as the covers; 2) there are no longer two cylinders and an intermediate part – instead there is a single part. This is due to the fact that the free-wheel connects two shafts, and does not have an exterior rotating part.

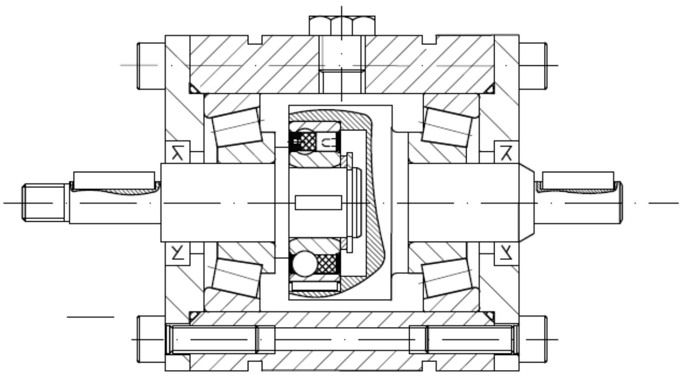


*Figure 38 - Wave cassette using a commercial free-wheel - section view*

The main advantage with this solution (besides the fact that, as mentioned previously, it is a tested solution) is that the only rotating components are the shafts: this means that there is no problem with having a fully liquid lubrication medium (which would have greatly affected efficiency); also, there is no problem with having a fixation using the exterior parts, as these are not moving.

### 4.4.3 Solutions' comparison

In Table 10, one can find the comparison between both solutions, in terms of dimensions.

*Table 10 - Dimensions' comparison between the custom and the commercial free-wheel solutions*

| | *Diameter* | *Maximum length* |
|---|---|---|
| *Custom free-wheel solution* | 110 mm (minimum) | 167 mm |
| *Market's free-wheel solution* | 72 mm | 128 mm |
| *Dimension decrease* | 28 % | 23 % |

It should be noted that the diameter of the custom free-wheel solution was based on the use of the smallest ball bearing of internal diameter of 75 mm (the current solution's external diameter), which is $D$=95 mm. A minimum wall thickness of 7.5 mm for the external supporting body was hypothesised.

It can be concluded that the Stieber Clutch's free-wheel's solution is approximately 25 % smaller than the custom free-wheel's. Due to this, and to the fact that it is a tested solution, the Stieber Clutch's free-wheel leads to a better solution.

## 4.5 Design of the WEC's Transmission

The design of the WEC's Transmission has considered the design restraints mentioned previously, among which the rack's "cross configuration"; the easily accessible system for maintenance assistance; the use of market-available or easily manufactured parts; and the creation of a subsystem that would be positioned in a central body and arrayed.

The result of this approach is the design modelled in Figure 39 and Figure 40.

*Figure 39 - Three-dimensional modelling of the wave converter*

It should be noted that some details are not modelled in Figure 39, such as the racks, the screws and oil plugs. These are detailed in the 2D drawing of the system in Figure 40. A full technical drawing can be found in Appendix C.

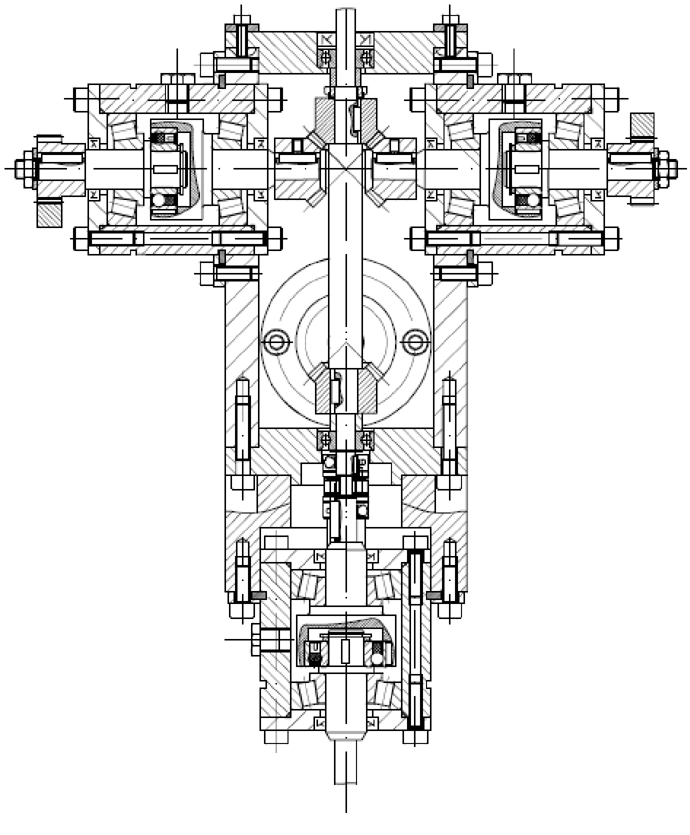


*Figure 40 - Two-dimensional technical drawing of the WEC's Transmission*

In the next subsections, this solution will be explained in detail.

### 4.5.1 Central body

The central body was designed to be easily manufactured, buoyant and to allow the fixation of the "wave cassettes" on its faces. The design process considered two hypotheses: 1) cylindrical body with plane faces where the "cassettes" would fit; 2) squared body, with plane faces. It was chosen the latter, because it would be more easily manufactured. This lead to the solution described in Figure 41.

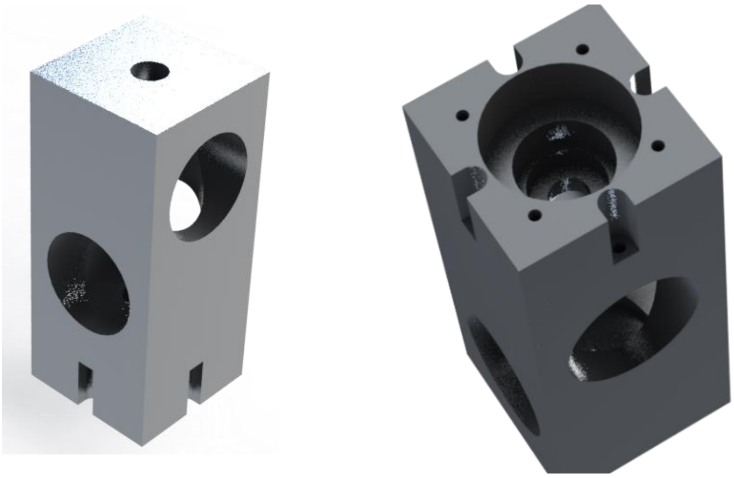


*Figure 41 - Modelling of the wave converter's central body: upper view (left); lower view (right)*

It should be noted that the existence of the cover highlighted in Figure 42 was necessary due to the necessity of having a support (bearing) for the central shaft somewhere – this forced the design of a support (lid) for this bearing.

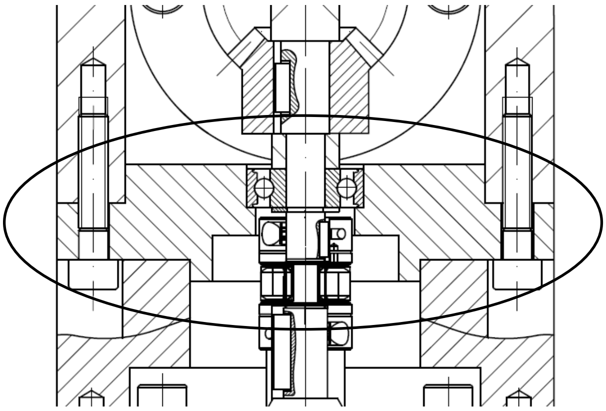


*Figure 42 – Drawing of the WEC's Transmission central body's intermediate cover*

### 4.5.2 Complete " wave cassette"

The "wave cassette" described in subsection 4.4.2, equipped with the parts that enable its fastening to the central body (1); with the rack (2); with the gears (cylindrical – 3; bevel - 4) and its fittings (5) is represented in Figure 43.

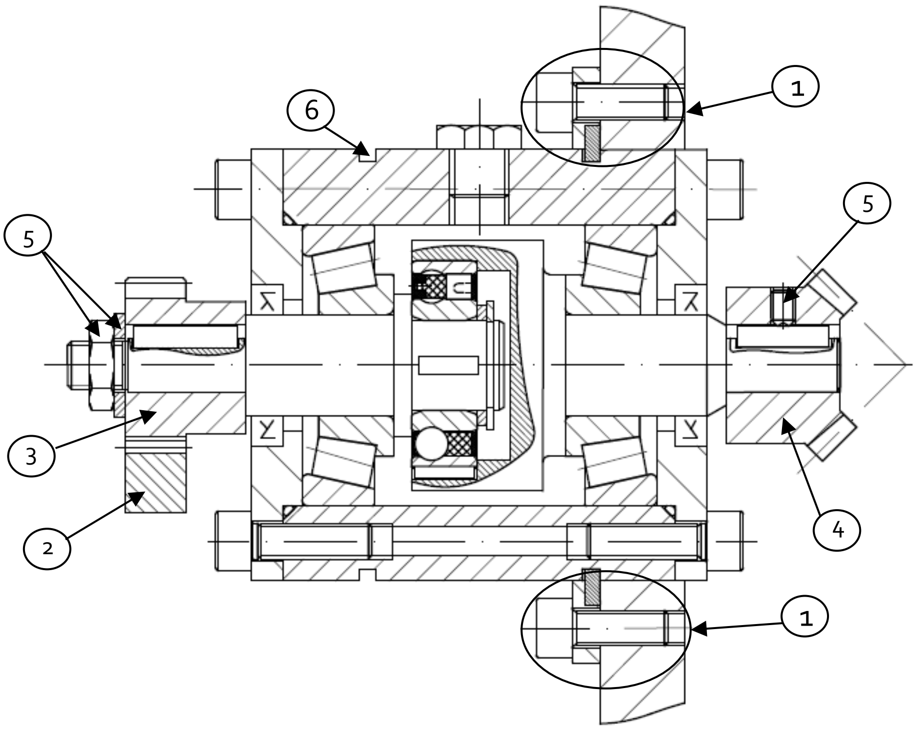



*Figure 43 - Complete wave cassette - section view*

The fixation to the central body (1) is done with a flange-like system, such as seen in Figure 44.

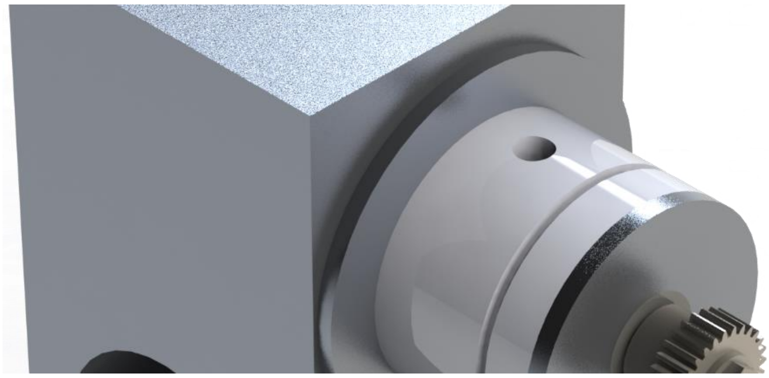


*Figure 44 - Detail of the fastening of the "wave cassettes" to the central body - 3D model*

This is represented in detail in Figure 45.

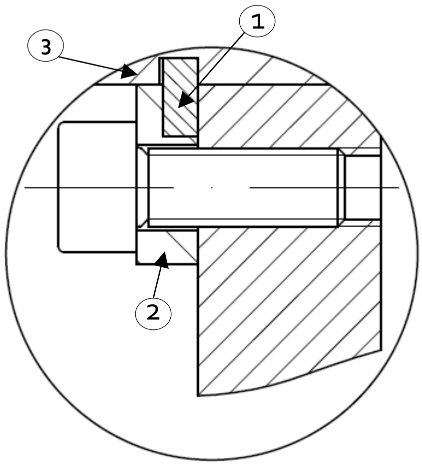



*Figure 45 - Fastening of the "wave cassette" to the central body - flange system*

This fixation method uses the concept of a "faux" flange: the flange is composed by a half-ring (1) that serves as the connection between the flange (2) and the "wave cassette's" body (3). The half-ring will be pressed against the central body, and fixed by the screws.

This method was chosen, instead of a classic flange, because this would allow for a more flexible assembly. Through a careful analysis of the "wave cassette" one realizes that the design allows it to be installed in whichever direction is most convenient, with little alterations to the design (the shafts must be modified, specifically because one would have to switch which one is to be screwed). This is especially important because the direction of the shaft's rotation is fundamental in this project.

### 4.5.3 Central shaft

The central shaft is a critical part of the system as it is responsible for connecting the three energy converters (waves, wind, currents) to the generator.

A significant effort has been made while designing the wave converter to load this shaft as least as possible, and to design it as robust as possible. The final design is modelled in Figure 46.

*Figure 46 - Wave energy converter's central shaft and components*

The load constraints meant that bearings were placed as close to the loads as possible. Also, the shaft was designed to have the larger diameter possible (for bending purposes) and the least diameter reductions/enlargements as possible (to decrease fatigue). Also, to ease assembly, the central unique shaft concept was modified into a shaft separation. There are two shafts which are connected through a coupling, modelled in Figure 47. It should be noted that the elastomeric connector is not modelled.

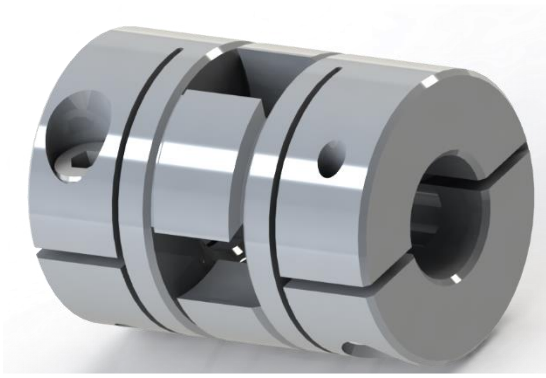


*Figure 47 - Coupling used to connect two central shafts (Ruland's Jaw Coupling)*

A final note concerning the central shaft is that the shaft had to be connected to a free-wheel directed towards the currents. As this free-wheel needed supports, it would be easier to input a similar/equal construction to the one described for the "wave cassette" – this would be referred to as the "currents cassette".

### 4.5.4 Lubrication and sealing

Even though it is only detailed in this subsection, lubrication and sealing were a major cause for concern throughout the project. As mentioned previously, the system is supposed to endure months without maintenance in a maritime environment. Due to this and to the fact that the system is mainly mechanical, lubrication is fundamental for its proper functioning, and sealing is fundamental to protect the system from the outer corroding environment.

1. Lubrication

At first, while the custom free-wheel was being designed, it was hypothesised that it would not be necessary to have oil lubrication, due to low speeds – this meant lesser maintenance, and higher efficiency (the oil would not slow down the moving parts). This is the reason why there is a grease plug in the custom free-wheel drawing.

But afterwards, as there was no longer the need of having a rotating outer structure, and the speeds were higher than previously hypothesised, oil was reconsidered. This is the reason why there is an oil plug in the commercial free-wheel solution's drawing.

In the central shafts wheels' though, as it would be necessary to cover the lower wheels in oil to lubricate the upper wheels, it was proposed to lubricate all of the wheels with grease. This decision is yet to be validated by an experimental approach.

2. Sealing

Throughout the design, it can be noted that there are multiple sealing solutions, being the use of O-rings or the use of rotatory shaft lip seals. As maritime applications are often compromised due to poor sealing, and seals are, generally, the least expensive parts, a design decision was to use as much sealing as deemed necessary. An example for this is the use of double sealing in the "wave cassettes". There are seals on both ends hereby ensuring that the expensive and more critical mechanical parts inside, i.e. free-wheels and bearings, are protected from sand and water.

### 4.5.5 Materials

As mentioned in subsection 4.5.4, the system is supposed to work for months without maintenance in a maritime environment. This means that care should be taken to select materials that excel in this kind of environments, such as polymers. As a high degree of resistance is also necessary, the materials requirements will almost definitely lead us to composite materials. The fibres will provide resistance, and the matrix will provide corrosion resistance.

For the case of the present work, as the main purpose is to prove the concept, using a cheap and quick solution, a metal solution was chosen. In concrete, it was decided to purchase standard parts (i.e. gears, screws, plugs, bearings, ...) as they are provided – steel; any special part that must be machined, such as the bodies and the covers, is to be in aluminium due to its easy machinability.

### 4.6 WEC's Transmission sizing

In this subsection, the calculations validating the mechanical resistance for the critical components will be presented.

The software KISSsoft® was used for the calculation of the resistance of the rack-and-pinion system and the bevel gears. It should be noted that the required service life of 2000 h was selected since this is a prototype destined to prove the concept; hence it is not necessary to enforce a high degree of service life, which would increase its cost. It should also be noted that all calculations were performed considering standard conditions: 1) the wave cassette is lubricated via oil bath, with an ISO-VG 220 oil (standard issue oil); 2) materials' quality is of Q=6, according to ISO 1328.

#### 4.6.1 Rack-and-pinion

In Table 11, the relevant geometry parameters used in the calculation are described; in Table 12, the relevant rating parameters are also described. It should be noted that the material of the pinions and racks from the named supplier is S45C (C45 for DIN), treated with a hardening by induction.

*Table 11 - Relevant geometric parameters in the calculation of the mechanical resistance of rack-and-pinion*

| | | | |
|---|---|---|---|
| *Normal module, $m_n$* [mm] | 1 | *Pinion's face width, b* [mm] | 10 |
| *Pressure angle, α* [°] | 20 | *Rack's face width, b* [mm] | 10 |
| *Rack's height, $H_z$* [mm] | 11 | *Profile shift coefficient, x** | 0.0 |
| *Pinion's number of teeth, Z* | 28 | | |

*Table 12 - Relevant rating parameters in the calculation of the mechanical resistance of rack-and-pinion*

| | |
|---|---|
| *Power, P [kW]* | 0.381 |
| *Speed, n [rpm]* | 334 |
| *Required service life, H [h]* | 2000 |

The results for these calculations can be found in Table 13.

*Table 13 - Results for the mechanical resistance of the rack-and-pinion system (via KISSsoft®)*

| | *Pinion* | *Rack* |
|---|---|---|
| *Root safety* | 1.5720 | 1.6197 |
| *Flank safety* | 1.0285 | 1.3537 |
| *Safety against scuffing (integral temperature)* | 4.4260 | |
| *Safety against scuffing (flash temperature)* | 31.7751 | |

From the analysis of the results one can conclude that the rack-and-pinion system has an acceptable root and flank safety – the pinion's flank safety is not optimal, but still it is over 1. The results for the safety against scuffing are more than optimal – this is most likely because the calculations only consider 2000 h of functioning.

### 4.6.2 Bevel gears

In Table 14, the relevant geometry parameters used in the calculation are described; in Table 15, the relevant rating parameters are described. It should be noted that the material of the pinions and racks from the named supplier is also S45C (C45 for DIN), treated with a hardening by induction.

*Table 14 - Relevant geometric parameters in the calculation of the mechanical resistance of bevel gears*

| | | | |
|---|---|---|---|
| *Mean normal module, $m_{mn}$* [mm] | 1.5 | *Gear's face width, b* [mm] | 8 |
| *Pressure angle, $\alpha_n$* [°] | 20 | *Profile shift coefficient, x** | 0.0 |
| *Gear's number of teeth, $Z_1$* | 20 | *Shaft angle, Σ* [°] | 90 |
| *Gear's number of teeth, $Z_2$* | 20 | | |

*Table 15 - Relevant rating parameters in the calculation of the mechanical resistance of the bevel gears (reference gear wheel is the wave cassette's wheel)*

| | |
|---|---|
| *Power, P* [kW] | 0.381 |
| *Speed, n* [rpm] | 334 |
| *Required service life, H* [h] | 2000 |

The results for these calculations can be found in Table 16.

*Table 16 - Results for the mechanical resistance of the bevel gears (via KISSsoft®)*

| | *Gear 1 (wave cassette's)* | *Gear 2 (central shaft's)* |
|---|---|---|
| *Root safety* | 1.4657 | 1.4657 |
| *Flank safety* | 0.9171 | 0.9171 |
| *Safety against scuffing (integral temperature)* | 4.0587 | |
| *Safety against scuffing (flash temperature)* | 14.4736 | |

The analysis of the results leads to the conclusion that the root safety and safety against scuffing for both gears are not a problem. The flank safety's, though, are below 1, and therefore not acceptable. A way to fix this would be to increase the number of teeth for the wheel. Table 17 presents the results if one would increase the number of teeth from Z=20 to Z=25 (gear also found at the same supplier).

*Table 17 - Results for the mechanical resistance of the bevel gears, with Z=25 (via KISSsoft®)*

| | *Gear 1 (wave cassette's)* | *Gear 2 (central shaft's)* |
|---|---|---|
| *Root safety* | 1.7186 | 1.7186 |
| *Flank safety* | 1.1604 | 1.1604 |
| *Safety against scuffing (integral temperature)* | 4.4175 | |
| *Safety against scuffing (flash temperature)* | 20.9154 | |

One can conclude that the replacement of the wheel would fix the problem. It should be noted, though, that this replacement would entail an increase of 7.5 mm, so the design should be adapted.

### 4.6.3 Shaft's keys

In general applications, the keys that are used are the ones described by the norm DIN 6885. The material selected is CK 45 K (DIN), which is of normal use for keys. This steel has a yield strength of 300 MPa. Also, the typology of the selected keys is type A, as it makes an easier slot manufacturing.

The shaft's resistance considers the shafts' diameter, which defines the keys' width and height. Its length ($l$) is calculated through resistance criteria: 1) shear criterion; and 2) crushing criterion.

1. Shear criterion

This criterion considers the shear stress exerted on the key, which is a result of the moment of torsion ($M_t$), being that it defines the moment of torsion as a function of the maximum admissible shear stress ($\tau_{adm}$).

Hence one has the following [37]:

$$l_{min} = \frac{M_t}{b * d * \tau_{adm}}$$

To note that *b* refers to the key's width and *d* to the shaft's diameter.

2. Crushing criterion

This criterion considers the compression stress exerted on the key during functioning, being also a function of the moment of torsion ($M_t$), defining the moment of torsion as a function of the maximum admissible normal stress ($\sigma_{adm}$).

Hence [37]:

$$l_{min} = \frac{2 * M_t}{d * (h - t_1) * \sigma_{adm}}$$

To note that *h* refers to the key's height and $t_1$ the depth of the key that enters the shaft.

The application of these criteria led to the results on Table 18, admitting a safety factor of 1.75.

*Table 18 - Keys' minimum length to ensure mechanical resistance*

| *Key* | *Criterion* | *Minimum length* [mm] |
|---|---|---|
| *Cylindrical wheel* | Shear | 6.1 |
| | Crushing | 17.6 |
| *Free-wheel* | Shear | 1.5 |
| | Crushing | 4.2 |
| *Cassette's bevel wheel* | Shear | 6.1 |
| | Crushing | 17.6 |
| *Central shaft's bevel wheel* | Shear | 3.1 |
| | Crushing | 8.8 |

In Table 19, the corresponding standard key lengths are presented. It should be noted that the final length to be used before the standardisation of the keys, is the one that includes the width, *b*. This is because the calculated length does not include the rounded ends of the key.

*Table 19 - Keys' length to ensure mechanical resistance*

| *Key* | *Standard length [mm]* |
|---|---|
| *Cylindrical wheel* | 20 |
| *Free-wheel* | 10 |
| *Cassette's bevel wheel* | 20 |
| *Central shaft's bevel wheel* | 12 |

### 4.6.4 Bearings

There are two bearings that require validation: 1) the tapered roller bearings from the "wave cassettes"; 2) the ball bearings from the central shaft. For the validation of the bearings, SKF's Bearing Calculator was used.

1. Tapered Roller Bearing

At first, one must define the radial load for the bearing, which is the axial load of the rack - a function of the power at the rack and the rack's velocity. As defined in subsection 4.2.4, the rack's theoretical power is of 381 W and its velocity is of 491 mm/s. This leads to a radial load of 776 N.

The theoretical axial load for the bearing is approximately zero, but, as this is a tapered roller bearing, a minimal assembly load is necessary – the input will be of zero.

The expected operating temperature is somewhat unknown, as no thermal simulation was made, but as this is an offshore device, to be deployed in the Atlantic Ocean, a temperature of $60^{\circ}$ C was hypothesised.

As one is designing a device that has to endure months without maintenance, the bearing's cleanliness parameters were assumed as being the worst possible.

Also, as in the calculation of the gears' resistance, the selected oil was of ISO-VG 220 oil. The oil bath level was hypothesised as 1/3 of the bearing's height. This is because: 1) for low speeds, the shear stresses are low; and 2) as the oil bath level varies due to the device's oscillation, the oil level should be oversized to guarantee proper lubrication.

In Figure 48, one can find these values inputs.

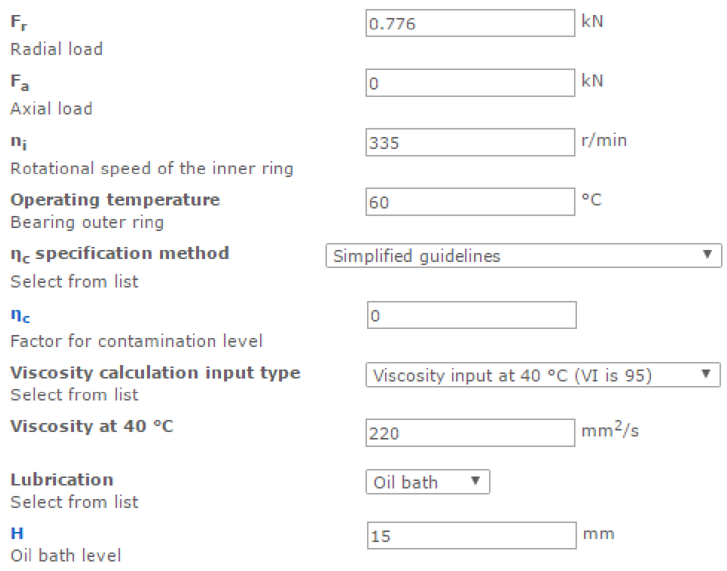



*Figure 48 - SKF's Bearing Calculator input for the tapered roller bearing*

Some relevant results are presented in Table 20.

*Table 20 - Relevant results for the calculation of the tapered roller bearings*

| | |
|---|---|
| *Bearing life* [h] | 781 500 |
| *Minimum radial load* [N] | 560 |
| *Power loss* [W] | 1 |

2. Ball bearing

The calculation for the ball bearing is similar in everything to the tapered roller bearing, with small differences: 1) the bearing's assembly does not require a substantial pre-load; 2) the ball bearing's axial load corresponds to the tapered roller bearing's radial load (assuming no load absorption – which is not realistic, as the tapered roller bearings will absorb most of it); 3) the lubrication method is grease, not oil bath.

Some relevant results are presented in Table 21.

*Table 21 - Relevant results for the calculation of the ball bearings*

| | |
|---|---|
| *Bearing life* [h] | 600 |
| *Minimum radial load* [N] | 10 |
| *Power loss* [W] | 1 |

As presented in Table 21, this ball bearing does not have a life that corresponds to the pre-selected life for the device – 2000 h. The obvious solution for this would be to increase the bearing's size. However, this is the largest bearing that the supplier provides, with an interior shaft of 8 mm. This is important as a change would force to increase the shaft's diameter, disabling the assembly of the central shaft's bevel gear. This detail is something that should be considered in a posterior re-design, as this will force a general scale-up of the device. Despite this, for the purposes of this prototype, 600 h is more than enough to prove the device's concept, so no alterations are in course – especially considering that the calculations account for a perfect power harness by the rack, which is idealistic, and that they do not consider load absorption by the previous bearings, the tapered roller bearings.

# 5 WEC's Mechanical Structure and Overall Support Structure

In this section, the WEC's Mechanical Structure and Overall Support Structure subsystems and their components are described. The general concept was worked on by the author and Diogo Telo Rodrigues, but the detailing of the solution was carried to completion by the latter.

## 5.1 WEC's Mechanical Structure

The WEC's Transmission design set the boundary dimensions and conditions to design the WEC's Mechanical Structure. This system (described in Figure 49) can be subdivided into: 1) Framework; 2) Tilting System; 3) Buoy; and 4) Guidance System.

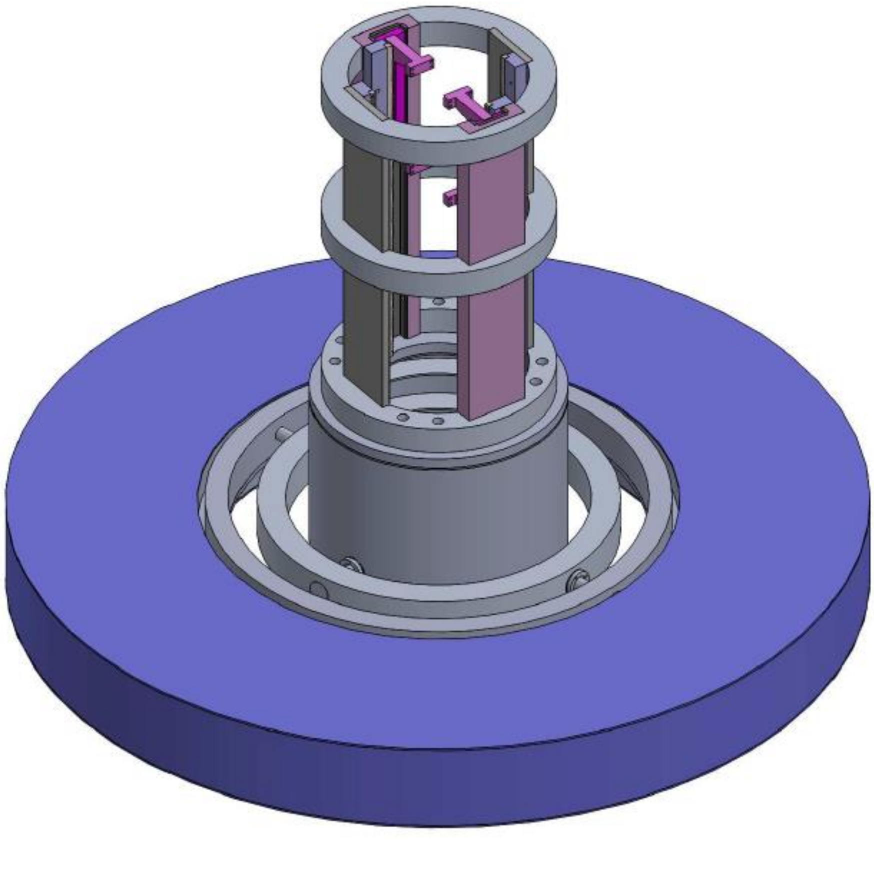
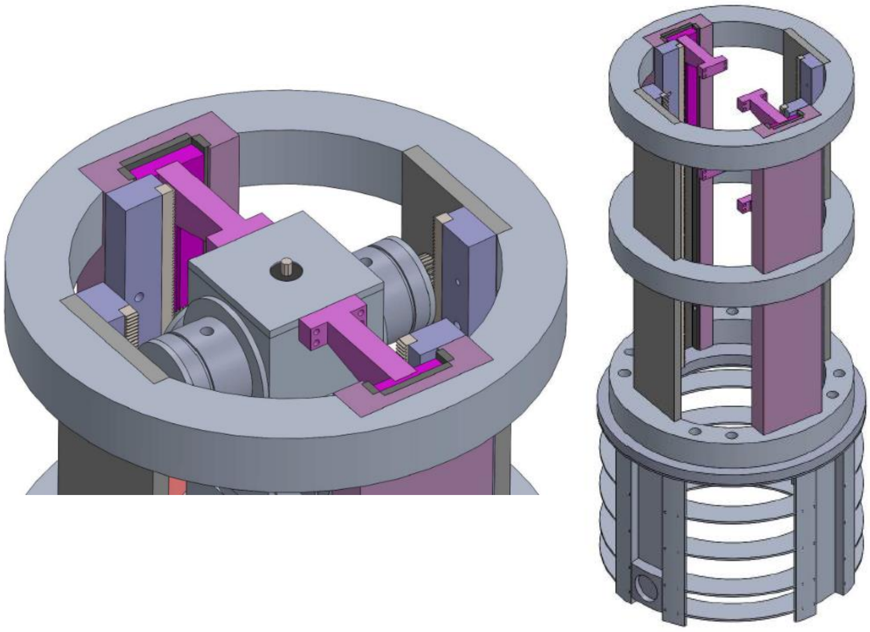


*Figure 49 - Three-dimensional modelling of the WEC's Mechanical Structure*

### 5.1.1 Framework and Guidance System

These structures were designed because: 1) there was the need to support the racks with high stiffness; and 2) the need to guide the WEC's Transmission, enabling only a vertical movement (any horizontal displacement or rotation by any axis would affect the efficiency, as only vertical displacement is harnessed). These structures are represented in Figure 50.



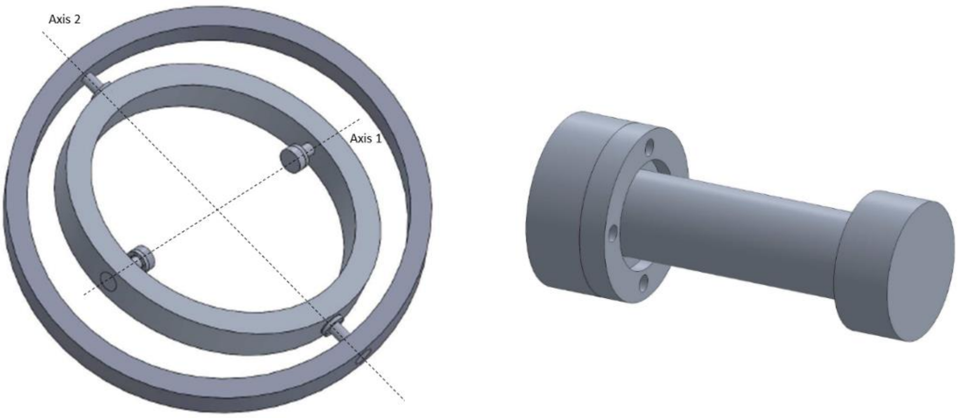
(a) (b)

*Figure 50 – Detailed view of the WEC's Mechanical Structure's guidance system (a) and framework structure (b)*

One of the main advantages for the use of this framework structure is that this allowed for the WEC's Transmission's mechanical parts to be located above the water's level, which would solve any undesirable leakage problems.

### 5.1.2 Tilting system and buoy

The previous Tripower UP's wave energy converter separated the external relative movement from the internal "stationary" movement through the use of an elastomeric cylinder, which surrounded the internal part. This solution would not be efficient at absorbing horizontal forces, while transmitting vertical forces, which advanced the need to the search for a better one - the tilting system, described in Figure 51.




(a) (b)

*Figure 51 - Model of the tilting system (a) and detail on a tilting system's arm (b)*

This system, inspired by a gyroscope's support, allows for a 360° rotation, hereby fully separating the external buoy's (Figure 52) horizontal movement from the interior – the only movement transmission would be the vertical one. The wave causes the upwards force ($F_u$) and the system's weight the downwards force ($F_d$).

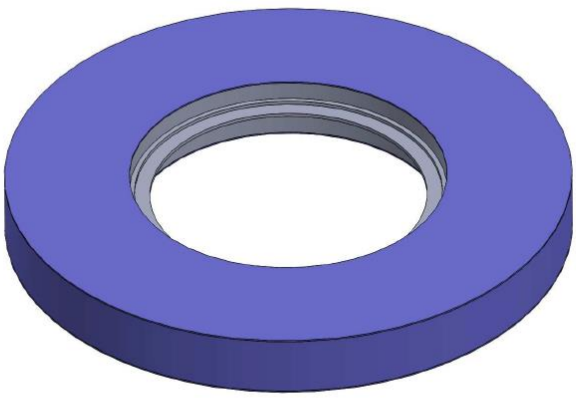


*Figure 52 - Model of the WEC's buoy*

## 5.2 Overall Support Structure (OSS)

The Overall Support Structure (OSS) was designed to support the entire Tripower UP system, which includes the three energy converters. This system, in turn, is subdivided into 4 components: 1) the Overall Support Structure's Buoy; 2) the Inverted Parachute; 3) the Mooring Hook; and 4) the Ballast. These, which are detailed in Figure 53, are further explained in the following subsections.

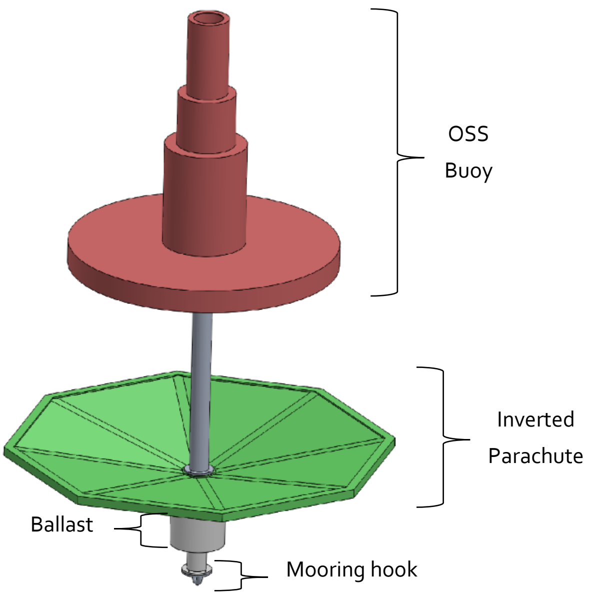



*Figure 53 - Model of the Overall Support Structure and its components*

### 5.2.1 Buoy and inverted parachute

The buoy and the inverted parachute (see Figure 54) have somewhat opposite functions.

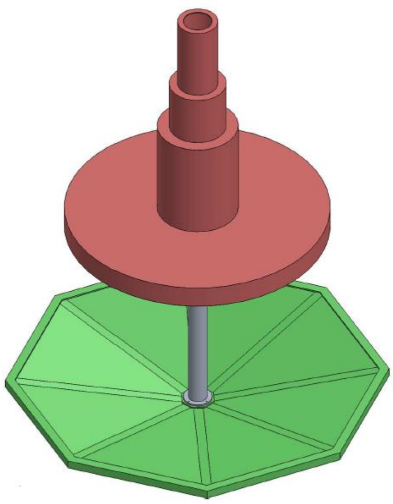


*Figure 54 - Model of the OSS's buoy and the inverted parachute*

The buoy was designed in order to increase the buoyancy of the system, in order to increase floatability, while also providing support for the WEC's Transmission. Considering that it is meant to provide buoyancy, the buoy, which is comprised of four cylinders, has one cylinder with a greater diameter than the previous ones – this is because buoyancy is a function of volume, and volume increases by the squared with the diameter, and is only linear with height.

The inverted parachute was designed to generate a drag force that would create a relative movement between the WEC's Transmission and the WEC's Mechanical Structure buoy – otherwise their movement would be solidary, and the rack would not engage the pinion.

### 5.2.2 Mooring and Ballast

In Figure 55, the ballast and the mooring hook are represented.

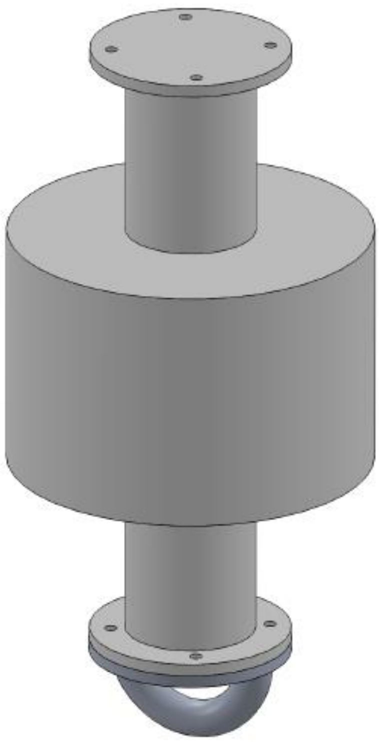


*Figure 55 - Model of the ballast and the mooring hook*

The ballast is used to provide stability to the structure by providing a righting moment that counter-acts the tilting moment. Therefore, it should be placed as low as possible, lowering the structure's centre of mass.

The mooring hook, which is a part of the mooring system, allows for the installation of a cable that moors the structure through a single-point mooring. This is advantageous because it provides for a certain degree of movement for the structure and because it is the least costly mooring method.

Further information on the components described in this section and on the stability and simulation studies that were made can be found in [10].

# 6 Conclusions and Future Works

This chapter summarizes the dissertation's main conclusions and reports the main developments on the design for the Tripower UP device. After these, some considerations on future work on this topic are outlined.

## 6.1 Conclusions

From the analysis of the existing literature, one can conclude that there is not a lot of work done on the topic of wave energy conversion. Most of the literature refers to wave energy as a footnote, being that only the most recent literature regards wave energy with some detail. However, the existing literature allows for the conclusion that the wave energy resource, as well as most ocean energy resources pose an issue, which is its randomicity and seasonality.

Something that can also be concluded from the analysis of the existing literature is that there are not yet many floating wave energy converter solutions, despite the fact that these entail a lesser cost. In addition, most of the existing solutions use indirect power take-off (PTO) mechanisms, which can implicate a higher power loss.

Also, wave energy converters are not extensively studied, which entails benefits for whomever venture in this field of research. Despite the general lack of efforts on this topic, the ocean energy conversion presents an immense potential, something that has been already perceived by the Scandinavian countries, which are the current leaders in this field. Portugal should continue and further its investment in this kind of energy, especially considering the medium-high wave resource potential it has, and the size of its maritime area.

The pre-existing Tripower UP device was studied, being that some design problems emerged from its analysis. The rack asymmetry posed a stability issue, which was solved using a cross rack configuration. The elastomeric connection between the outer buoy and the inner structure was replaced with a gyroscope-inspired tilting system, which would allow for better horizontal forces absorption and vertical forces transmission.

It was concluded, during the design process of the custom free-wheel, that the market currently includes solutions that are quite compact for shaft movement separation. The conceived solution posed a bigger and probably less robust solution (as the sail's holstering mechanism had some sharp indentations, which entail a high stress concentration factor).

It was concluded that, even though the most suitable material for maritime applications are not standard metals like steel or aluminium, but instead composites with polymers in their composition. For the purpose of prototype building, the earlier ones can replace the latter, considering that they are less expensive and easier to manufacture with.

During the analysis of the critical mechanical components' resistance, it was concluded that the rack-and-pinion would not be a problem, for the prototype's testing conditions. Bevel gears, due to poor flank resistance though should be replaced with ones with higher number of teeth. The bearings can resist the efforts, but the ball bearings can only withstand a functioning of 600 h, if the hypothesis on the power losses are correct.

It was concluded that the device could no longer fit in the wave tank, due to design constraints, such as the ones that resulted from the study of the buoyancy forces and the stability. This means that it must be tested elsewhere, preferably a wave tank where the same design conditions can be simulated.

One of the main advantages of the Tripower UP device is that it is not a massive construction, like some WEC's that were tested, which means it is of a lesser cost. Even though it does not involve high values of energy harnessing, this device can be replicated, and wave farms can be created based on this concept. As the replication takes up, the device's cost lowers, and the output increases. Care should be taken, though, when setting up wave farms, in order not to disturb the maritime ecosystems and fauna migration.

It was also concluded that during the creative process, more than one idea for the solution of a specific problem can come up, like the SPIDER UP concept. Even though it was not pursued, the concept was submitted for patent approval and may lead up to new endeavours in the field of wave energy converters.

## 6.2 Future Works

A lot of work is yet to be performed on this device, as well as on the fields of wave energy conversion and hybrid technologies.

As noted during the literature review, there are already some existing concepts for wind-wave hybrid systems. An interesting study would be on the possibility of the integration of currents' technologies on these hybrid systems, being considering wind-wave-currents configuration (which corresponds to the Tripower UP device's configuration) or even wave-currents/wind-currents hybrids.

### 6.2.1 Tripower UP

Also, there are several aspects of work to be done on the Tripower UP device:

- The mooring system is yet to be fully studied, as it will require a somewhat dynamic mooring, which could mean functioning and maintenance issues;
- The device's natural frequency and its resonance with the waves is yet to be studied, in order to figure out the optimal floating WEC's dimensions;
- The implementation of sensors for maintenance alerts are of high importance, especially as the concept of wave farms may lead to hundreds of devices being deployed in several hundred square kilometres farms;
- The device's lubrication is not optimal, as there are wheels that have to be lubricated with grease due to their lack of oil accessibility – this leads to poor efficiency and a high degree of maintenance problems;
- The generator's multiplication box is yet to be designed;
- The device's actual testing is yet to be studied. In order to figure out the best parameters to analyse and the actual expected output of the experimentation, a further study on this is to be done;
- A concept that come up that aims at storing additional energy would be to implement a flywheel at the entrance of the generator. Another idea would be to use an actual gyroscope, and use it for both energy storage and for structure stabilisation.

### 6.2.2 Spider UP: An Alternative Concept

During the phase of project analysis for the Tripower UP device, another concept for the wave energy converter came up. This concept is loosely based on the idea of a carnival carrousel, and its requirements are the same as the Tripower UP device. It is meant to be a valid substitute to the wave energy buoy described in 2.8.4.

The mechanical system is constituted by multiple "arms", responsible for the conversion of waves' potential energy into kinetic energy.

An "arm" is composed of a buoy, connected, through beams, to two bevel wheels. These wheels are, in turn, geared to another bevel wheel, which is located on a shaft that holds another wheel that transmits the power to a central, common bevel wheel. This is represented in Figure 56.

Both the two initial gears, and the final gear (that gears with the common bevel wheel) have installed a free-wheel, which, in similarity with the Tripower UP device, are 1) responsible for the alternation of power transmission between the ascending and descending movements and 2) responsible for the decoupling of the subsystem if it is "slowing down" the device.

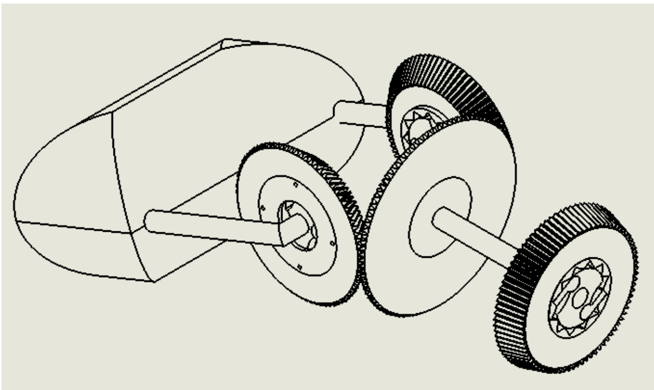


*Figure 56 - Detail of a SPIDER UP's "arm"*

Each arm works independently, transmitting the kinetic energy towards a common bevel wheel which, in turn, rotates a shaft that will engage an electrical generator. The connection between the arm and the central, common, bevel wheel is represented in Figure 57.

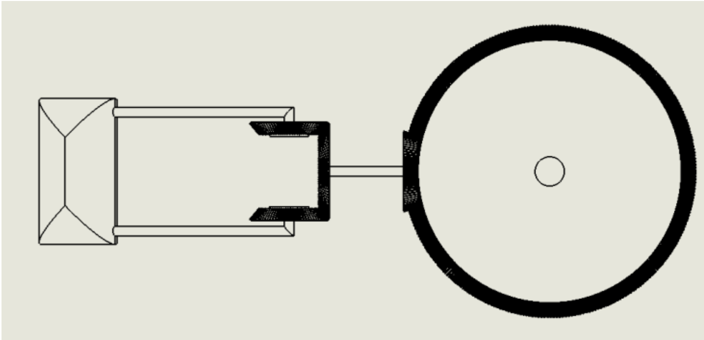


*Figure 57 - View of an ensemble composed of a SPIDER UP's arm and the central wheel*

This system is modelled in Figure 58.

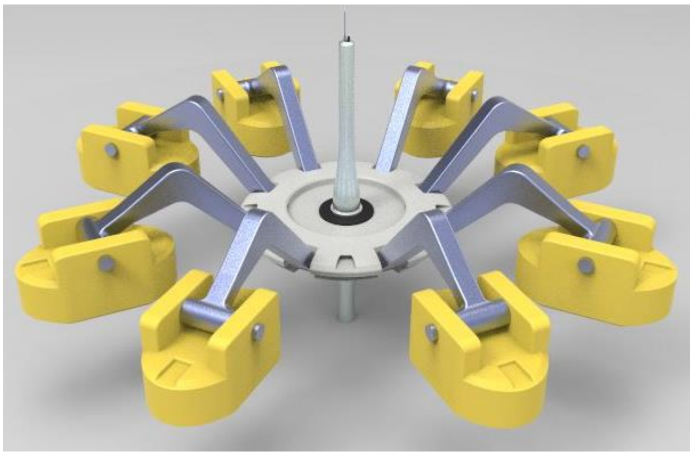
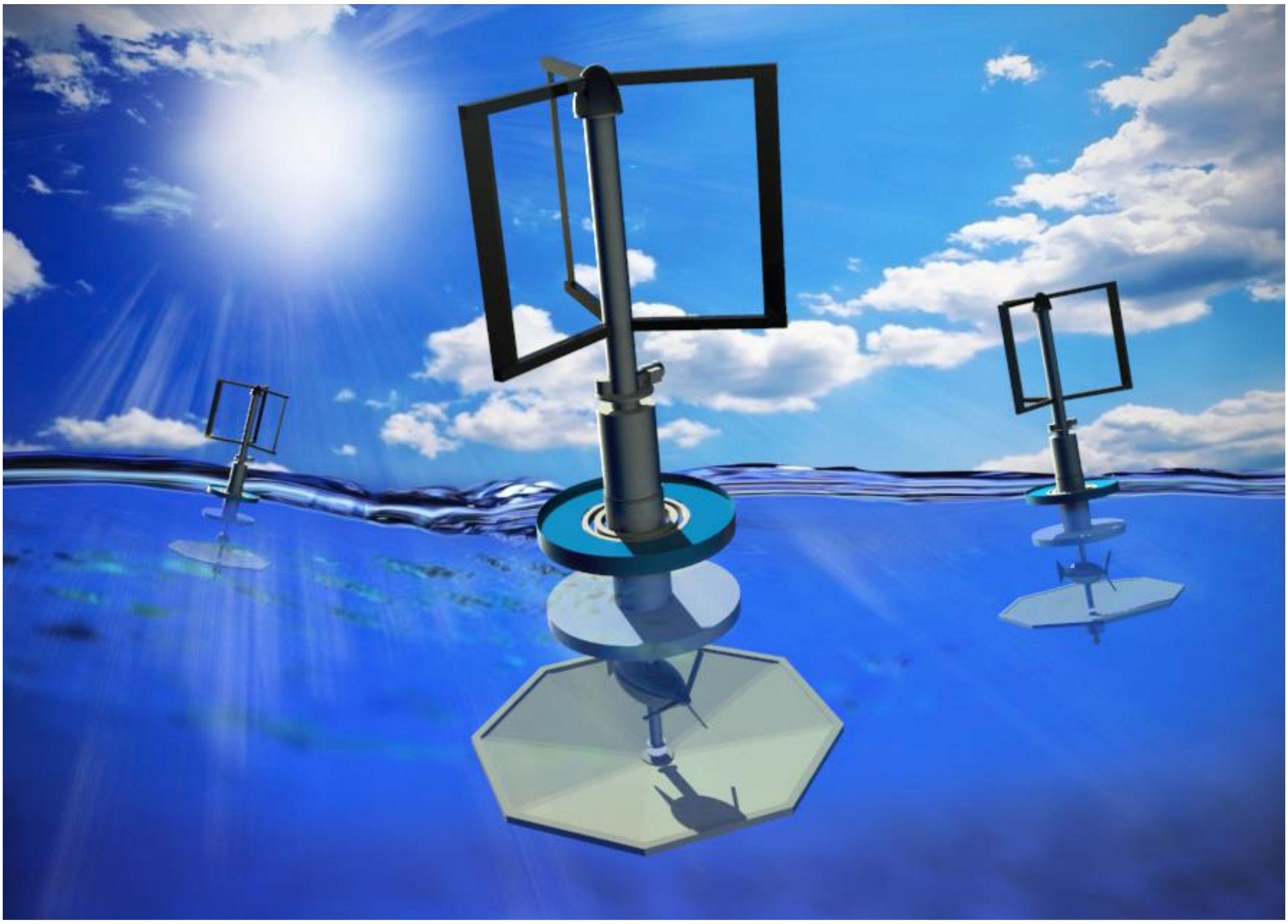


*Figure 58 - Three-dimensional artistic modelling of the SPIDER UP system (courtesy of Vasco Canavarro)*

The concept lead to a patent approval request, which is described in Appendix E.

It should be noted that because at the time that the work was beginning, the Tripower UP design was, by far, more developed, the team chose to focus on the Tripower UP device, and strive towards finishing the project.

# Tripower UP



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# Appendix A

Measurements for wave amplitude and period in Matosinhos, Portugal, between 01/01/2016 and 31/12/2016 – provided by Windguru®

| Date | Waves [m] | | | | | | | | Wave period [s] | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 00h | 03h | 06h | 09h | 12h | 15h | 18h | 21h | 00h | 03h | 06h | 09h | 12h | 15h | 18h | 21h |
| **31.01.2016** | 2,9 | 2,9 | 2,9 | 2,9 | 2,9 | 2,9 | 2,9 | 2,9 | 14 | 14 | 13 | 13 | 13 | 13 | 13 | 13 |
| **01.02.2016** | 2,8 | 2,7 | 2,7 | 2,6 | 2,5 | 2,5 | 2,6 | 2,8 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 |
| **02.02.2016** | 3,1 | 3,5 | 3,7 | 3,7 | 3,5 | 3,3 | 3,2 | 3,1 | 14 | 18 | 17 | 17 | 16 | 16 | 15 | 15 |
| **03.02.2016** | 3 | 2,9 | 2,9 | 2,9 | 2,7 | 2,6 | 2,5 | 2,4 | 15 | 14 | 14 | 14 | 14 | 13 | 13 | 13 |
| **04.02.2016** | 2,3 | 2,1 | 2 | 1,8 | 1,7 | 1,6 | 1,5 | 1,4 | 13 | 12 | 12 | 12 | 12 | 12 | 12 | 12 |
| **05.02.2016** | 1,3 | 1,3 | 1,2 | 1,1 | 1 | 1 | 0,9 | 0,9 | 12 | 12 | 12 | 12 | 11 | 11 | 11 | 11 |
| **06.02.2016** | 0,9 | 1 | 1,2 | 1,5 | 1,8 | 2,5 | 3,4 | 3,8 | 11 | 11 | 14 | 13 | 12 | 8 | 8 | 10 |
| **07.02.2016** | 3,9 | 4,2 | 4,3 | 4,3 | 4,2 | 4 | 3,9 | 3,8 | 12 | 13 | 14 | 14 | 15 | 15 | 14 | 14 |
| **08.02.2016** | 3,6 | 3,5 | 3,4 | 3,4 | 3,3 | 3,6 | 4,4 | 5,1 | 14 | 14 | 14 | 14 | 14 | 14 | 19 | 20 |
| **09.02.2016** | 5,1 | 4,9 | 4,6 | 4,5 | 4,5 | 4,5 | 4,3 | 4,1 | 19 | 18 | 17 | 17 | 16 | 15 | 15 | 14 |
| **10.02.2016** | 3,9 | 3,7 | 3,7 | 3,7 | 3,7 | 3,6 | 3,5 | 3,4 | 14 | 14 | 13 | 13 | 13 | 13 | 13 | 13 |
| **11.02.2016** | 3,2 | 3,2 | 3,1 | 3 | 2,9 | 2,8 | 2,7 | 2,6 | 13 | 13 | 12 | 12 | 12 | 12 | 12 | 12 |
| **12.02.2016** | 2,6 | 2,8 | 2,9 | 3 | 3,1 | 3,2 | 3,4 | 3,6 | 12 | 11 | 11 | 11 | 11 | 10 | 11 | 11 |
| **13.02.2016** | 3,8 | 4 | 4,2 | 4,3 | 4,3 | 4,4 | 4,5 | 4,7 | 11 | 15 | 16 | 15 | 15 | 15 | 14 | 14 |
| **14.02.2016** | 4,7 | 4,6 | 4,8 | 5,8 | 6,1 | 6,1 | 6,1 | 6,1 | 14 | 14 | 13 | 13 | 13 | 13 | 14 | 14 |
| **15.02.2016** | 6,1 | 5,9 | 5,4 | 5 | 4,7 | 4,3 | 3,9 | 3,5 | 14 | 14 | 14 | 14 | 14 | 14 | 13 | 13 |
| **16.02.2016** | 3,1 | 2,7 | 2,5 | 2,3 | 2,1 | 1,9 | 1,8 | 1,7 | 13 | 13 | 12 | 12 | 12 | 12 | 13 | 13 |
| **17.02.2016** | 1,7 | 1,7 | 1,7 | 1,8 | 2 | 2,3 | 2,7 | 3,1 | 13 | 13 | 13 | 13 | 13 | 15 | 15 | 16 |
| **18.02.2016** | 3,3 | 3,4 | 3,5 | 3,4 | 3,3 | 3,2 | 3,1 | 3,1 | 15 | 14 | 14 | 14 | 14 | 14 | 14 | 14 |
| **19.02.2016** | 3,2 | 3,2 | 3,2 | 3,1 | 3,1 | 3 | 2,9 | 2,7 | 14 | 14 | 14 | 15 | 15 | 15 | 15 | 14 |
| **20.02.2016** | 2,6 | 2,4 | 2,3 | 2,3 | 2,3 | 2,4 | 2,4 | 2,4 | 14 | 14 | 13 | 13 | 13 | 13 | 13 | 13 |
| **21.02.2016** | 2,4 | 2,3 | 2,2 | 2,1 | 2,1 | 2,1 | 2,1 | 2,2 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 14 |
| **22.02.2016** | 2,3 | 2,3 | 2,3 | 2,4 | 2,4 | 2,4 | 2,4 | 2,3 | 16 | 15 | 15 | 15 | 14 | 14 | 14 | 14 |
| **23.02.2016** | 2,3 | 2,2 | 2,2 | 2,1 | 2 | 1,9 | 1,9 | 1,8 | 13 | 13 | 13 | 13 | 13 | 13 | 12 | 12 |
| **24.02.2016** | 1,8 | 1,9 | 2 | 2,2 | 2,3 | 2,4 | 2,7 | 3 | 12 | 12 | 12 | 12 | 12 | 11 | 11 | 11 |
| **25.02.2016** | 3,1 | 3 | 2,7 | 2,4 | 2,2 | 2 | 1,8 | 1,7 | 12 | 12 | 12 | 12 | 11 | 11 | 11 | 10 |
| **26.02.2016** | 1,6 | 1,6 | 1,6 | 1,8 | 1,8 | 2 | 2,4 | 3 | 10 | 10 | 9 | 8 | 8 | 8 | 8 | 8 |
| **27.02.2016** | 3,3 | 3,5 | 3,7 | 3,8 | 3,8 | 3,9 | 4,2 | 4,3 | 9 | 10 | 10 | 11 | 12 | 12 | 12 | 11 |
| **28.02.2016** | 4 | 3,6 | 3,2 | 3 | 2,9 | 2,8 | 2,8 | 2,7 | 11 | 11 | 11 | 11 | 11 | 11 | 11 | 11 |
| **29.02.2016** | 2,5 | 2,3 | 2,1 | 1,9 | 1,8 | 1,7 | 1,7 | 1,6 | 11 | 11 | 11 | 11 | 11 | 11 | 11 | 11 |
| **01.03.2016** | 1,6 | 1,5 | 1,5 | 1,4 | 1,4 | 1,5 | 1,6 | 1,7 | 10 | 11 | 11 | 12 | 15 | 14 | 14 | 14 |
| **02.03.2016** | 1,7 | 1,7 | 1,8 | 1,8 | 1,9 | 2 | 2 | 2,1 | 13 | 13 | 13 | 13 | 13 | 13 | 12 | 12 |
| **03.03.2016** | 2,2 | 2,4 | 2,6 | 2,7 | 2,6 | 2,5 | 2,4 | 2,3 | 13 | 18 | 16 | 15 | 15 | 14 | 14 | 13 |

| | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 04.03.2016 | 2,1 | 1,9 | 1,9 | 1,9 | 2,2 | 2,6 | 3 | 3,3 | 13 | 12 | 12 | 12 | 11 | 11 | 10 | 11 |
| 05.03.2016 | 3,6 | 3,7 | 3,8 | 3,7 | 3,5 | 3,3 | 3,2 | 3 | 12 | 13 | 15 | 15 | 15 | 15 | 14 | 14 |
| 06.03.2016 | 2,9 | 2,7 | 2,5 | 2,4 | 2,2 | 2,1 | 1,9 | 1,8 | 13 | 13 | 13 | 12 | 12 | 12 | 12 | 11 |
| 07.03.2016 | 1,8 | 2,1 | 2,6 | 2,9 | 3 | 3 | 2,9 | 2,7 | 11 | 11 | 8 | 9 | 10 | 10 | 10 | 11 |
| 08.03.2016 | 2,5 | 2,2 | 2 | 1,9 | 1,8 | 1,7 | 1,7 | 1,7 | 11 | 11 | 11 | 11 | 11 | 11 | 12 | 12 |
| 09.03.2016 | 1,6 | 1,6 | 1,6 | 1,9 | 2,4 | 2,6 | 2,8 | 2,9 | 12 | 15 | 18 | 17 | 17 | 16 | 15 | 15 |
| 10.03.2016 | 2,8 | 2,7 | 2,6 | 2,5 | 2,4 | 2,2 | 2,2 | 2,2 | 14 | 14 | 13 | 13 | 13 | 12 | 12 | 12 |
| 11.03.2016 | 2,2 | 2,1 | 1,9 | 1,8 | 1,7 | 1,6 | 1,7 | 1,7 | 12 | 12 | 11 | 11 | 11 | 11 | 14 | 14 |
| 12.03.2016 | 1,7 | 1,6 | 1,5 | 1,4 | 1,3 | 1,3 | 1,3 | 1,4 | 14 | 14 | 13 | 13 | 13 | 13 | 13 | 14 |
| 13.03.2016 | 1,4 | 1,4 | 1,4 | 1,4 | 1,3 | 1,3 | 1,2 | 1,1 | 14 | 13 | 13 | 13 | 12 | 12 | 13 | 13 |
| 14.03.2016 | 1,1 | 1 | 1 | 1 | 1 | 1,1 | 1,3 | 1,5 | 13 | 13 | 13 | 12 | 12 | 18 | 17 | 16 |
| 15.03.2016 | 1,7 | 1,7 | 1,8 | 1,8 | 1,7 | 1,7 | 1,7 | 1,7 | 15 | 15 | 15 | 15 | 14 | 14 | 14 | 13 |
| 16.03.2016 | 1,7 | 1,7 | 1,6 | 1,6 | 1,5 | 1,5 | 1,4 | 1,3 | 13 | 12 | 12 | 12 | 12 | 11 | 11 | 11 |
| 17.03.2016 | 1,2 | 1,3 | 1,5 | 1,8 | 2,1 | 2,2 | 2,2 | 2,1 | 11 | 12 | 18 | 17 | 16 | 16 | 15 | 15 |
| 18.03.2016 | 2 | 2 | 1,9 | 1,9 | 1,9 | 1,9 | 1,9 | 1,8 | 14 | 14 | 13 | 13 | 13 | 12 | 12 | 12 |
| 19.03.2016 | 1,7 | 1,7 | 1,7 | 1,6 | 1,6 | 1,5 | 1,4 | 1,4 | 12 | 12 | 11 | 11 | 11 | 11 | 11 | 11 |
| 20.03.2016 | 1,3 | 1,3 | 1,2 | 1,2 | 1,1 | 1,1 | 1,1 | 1,1 | 11 | 11 | 11 | 11 | 10 | 10 | 10 | 10 |
| 21.03.2016 | 1,1 | 1,2 | 1,2 | 1,1 | 1,1 | 1 | 1,1 | 1,1 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 |
| 22.03.2016 | 1,1 | 1,1 | 1 | 0,9 | 0,8 | 0,8 | 1 | 1,1 | 9 | 10 | 10 | 10 | 10 | 10 | 10 | 8 |
| 23.03.2016 | 1,1 | 1,1 | 1,1 | 1,1 | 1,2 | 1,5 | 1,8 | 2,1 | 8 | 7 | 8 | 8 | 9 | 16 | 15 | 15 |
| 24.03.2016 | 2,3 | 2,3 | 2,2 | 2,1 | 2 | 1,9 | 1,8 | 1,7 | 14 | 14 | 14 | 13 | 13 | 13 | 12 | 12 |
| 25.03.2016 | 1,5 | 1,4 | 1,3 | 1,3 | 1,4 | 1,6 | 1,7 | 1,9 | 12 | 12 | 11 | 11 | 11 | 11 | 11 | 14 |
| 26.03.2016 | 2,2 | 2,3 | 2,5 | 2,6 | 3 | 3,3 | 3,5 | 3,8 | 15 | 15 | 14 | 14 | 17 | 16 | 15 | 15 |
| 27.03.2016 | 4 | 4,2 | 4,2 | 4,2 | 4,1 | 4 | 4,1 | 4,2 | 15 | 14 | 14 | 14 | 15 | 15 | 15 | 15 |
| 28.03.2016 | 4,4 | 4,7 | 4,8 | 4,7 | 4,5 | 4,2 | 3,8 | 3,6 | 15 | 15 | 15 | 14 | 14 | 14 | 14 | 13 |
| 29.03.2016 | 3,3 | 3,2 | 3 | 2,9 | 2,8 | 2,7 | 2,5 | 2,4 | 13 | 13 | 13 | 12 | 12 | 12 | 12 | 12 |
| 30.03.2016 | 2,3 | 2,3 | 2,2 | 2,3 | 2,5 | 2,9 | 3,4 | 3,4 | 12 | 11 | 11 | 11 | 12 | 12 | 11 | 11 |
| 31.03.2016 | 3,6 | 3,6 | 3,2 | 2,8 | 2,6 | 2,5 | 2,4 | 2,2 | 9 | 9 | 12 | 12 | 12 | 12 | 12 | 12 |
| 01.04.2016 | 2 | 1,8 | 1,6 | 1,5 | 1,4 | 1,3 | 1,3 | 1,5 | 11 | 11 | 11 | 11 | 10 | 10 | 14 | 15 |
| 02.04.2016 | 1,8 | 2,1 | 2,3 | 2,4 | 2,4 | 2,6 | 2,7 | 2,7 | 14 | 13 | 13 | 13 | 13 | 13 | 13 | 13 |
| 03.04.2016 | 2,8 | 3 | 3,1 | 3,4 | 3,8 | 4,1 | 4 | 3,7 | 15 | 14 | 14 | 14 | 13 | 14 | 14 | 13 |
| 04.04.2016 | 3,4 | 3,1 | 2,8 | 2,7 | 2,9 | 3 | 3 | 3 | 13 | 13 | 12 | 12 | 12 | 12 | 12 | 12 |
| 05.04.2016 | 2,9 | 2,8 | 2,6 | 2,5 | 2,4 | 2,4 | 2,3 | 2,2 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 |
| 06.04.2016 | 2,2 | 2 | 1,9 | 1,9 | 1,9 | 1,9 | 2,1 | 2,4 | 12 | 12 | 12 | 12 | 12 | 12 | 13 | 19 |
| 07.04.2016 | 2,7 | 2,9 | 3 | 3 | 2,9 | 3,1 | 3,2 | 3,2 | 18 | 17 | 16 | 16 | 15 | 15 | 15 | 15 |
| 08.04.2016 | 3,1 | 2,9 | 2,7 | 2,5 | 2,3 | 2,2 | 2,1 | 2 | 14 | 14 | 14 | 14 | 14 | 13 | 13 | 13 |
| 09.04.2016 | 1,8 | 1,7 | 1,6 | 1,7 | 1,8 | 1,9 | 2 | 2 | 13 | 13 | 12 | 12 | 12 | 13 | 13 | 13 |
| 10.04.2016 | 2,2 | 2,4 | 3 | 3,7 | 4,2 | 4,5 | 4,7 | 4,7 | 12 | 12 | 12 | 12 | 13 | 14 | 17 | 17 |
| 11.04.2016 | 4,5 | 4,2 | 3,9 | 3,6 | 3,5 | 3,6 | 3,7 | 3,4 | 16 | 16 | 16 | 15 | 15 | 14 | 14 | 13 |
| 12.04.2016 | 3,2 | 3 | 3 | 3 | 3 | 3,1 | 3 | 2,9 | 13 | 13 | 12 | 11 | 11 | 11 | 11 | 11 |
| 13.04.2016 | 2,8 | 2,6 | 2,5 | 2,4 | 2,4 | 2,3 | 2,4 | 2,4 | 10 | 10 | 10 | 9 | 9 | 9 | 9 | 9 |

| | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **14.04.2016** | 2,8 | **3,2** | **3,1** | 2,7 | 2,3 | 2,1 | 1,9 | 1,8 | 9 | **9** | **9** | **9** | **9** | 9 | 9 | 9 |
| **15.04.2016** | 1,6 | 1,6 | 1,6 | 1,8 | 2 | 1,9 | 1,7 | 1,6 | 9 | 8 | 8 | 8 | 7 | 8 | 8 | 8 |
| **16.04.2016** | 1,5 | 1,5 | 1,4 | 1,4 | 1,4 | 1,4 | 1,4 | 1,4 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 |
| **17.04.2016** | 1,4 | 1,3 | 1,3 | 1,2 | 1,1 | 1 | 1 | 1 | 8 | 8 | 8 | 7 | 7 | 7 | 7 | 7 |
| **18.04.2016** | 0,9 | 0,9 | 0,8 | 0,8 | 0,7 | 0,7 | 0,7 | 0,6 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 |
| **19.04.2016** | 0,6 | 0,7 | 1 | 1,3 | 1,5 | 1,9 | 2,1 | 2,1 | 7 | 8 | **9** | 9 | **9** | **11** | **11** | **11** |
| **20.04.2016** | 2,1 | 2 | 2 | 1,9 | 1,8 | 1,8 | 1,8 | 1,8 | **10** | **10** | **10** | **9** | **9** | **9** | **9** | **9** |
| **21.04.2016** | 1,8 | 1,9 | 1,9 | 1,9 | 1,8 | 1,7 | 1,6 | 1,5 | 9 | 9 | 9 | 9 | 9 | 8 | 8 | 8 |
| **22.04.2016** | 1,4 | 1,3 | 1,2 | 1,1 | 1 | 0,9 | 0,9 | 0,8 | 8 | 8 | 8 | 8 | 7 | 7 | 7 | 7 |
| **23.04.2016** | 0,8 | 0,8 | 0,9 | 0,9 | 1 | 1 | 1 | 1 | 7 | 7 | 7 | 8 | 8 | 8 | 8 | 9 |
| **24.04.2016** | 0,9 | 0,9 | 0,9 | 0,8 | 0,8 | 0,8 | 0,9 | 1 | **9** | 9 | 9 | 9 | 9 | 8 | 8 | 8 |
| **25.04.2016** | 1 | 1 | 1 | 0,9 | 0,9 | 0,9 | 0,9 | 0,9 | 8 | 8 | 8 | 9 | 9 | 9 | **10** | **11** |
| **26.04.2016** | 0,9 | 0,9 | 0,9 | 1 | 1 | 1,1 | 1,2 | 1,3 | **10** | **10** | **10** | **11** | **14** | **14** | **13** | **12** |
| **27.04.2016** | 1,3 | 1,3 | 1,2 | 1,2 | 1,2 | 1,2 | 1,2 | 1,2 | **12** | **12** | **12** | **12** | **13** | **13** | **13** | **12** |
| **28.04.2016** | 1,3 | 1,2 | 1,2 | 1,2 | 1,2 | 1,2 | 1,2 | 1,3 | **12** | **12** | **11** | **11** | **11** | **10** | **10** | **10** |
| **29.04.2016** | 1,3 | 1,3 | 1,2 | 1,1 | 1 | 1,1 | 1,3 | 1,7 | **10** | **9** | **9** | 9 | 9 | 9 | 8 | 8 |
| **30.04.2016** | 2 | 2 | 1,8 | 1,6 | 1,5 | 1,8 | 2 | 2 | 7 | 7 | 7 | 6 | 6 | 6 | 7 | 7 |
| **01.05.2016** | 1,8 | 1,5 | 1,3 | 1,1 | 1 | 1 | 1,1 | 1,2 | 8 | 8 | 7 | 8 | 9 | **9** | **11** | **11** |
| **02.05.2016** | 1,1 | 1,1 | 1 | 0,9 | 0,9 | 1,1 | 1,2 | 1,3 | **10** | **10** | **10** | **11** | **11** | **11** | **11** | **10** |
| **03.05.2016** | 1,4 | 1,4 | 1,4 | 1,4 | 1,4 | 1,5 | 1,6 | 1,6 | **10** | **10** | **11** | **11** | **11** | **13** | **13** | **13** |
| **04.05.2016** | 1,6 | 1,5 | 1,4 | 1,4 | 1,3 | 1,2 | 1,1 | 1,1 | **12** | **12** | **12** | **11** | **11** | **11** | **11** | **10** |
| **05.05.2016** | 1,1 | 1,1 | 1,3 | 1,4 | 1,5 | 1,5 | 1,5 | 1,5 | **10** | **13** | **15** | **14** | **14** | **13** | **13** | **12** |
| **06.05.2016** | 1,5 | 1,5 | 1,5 | 1,5 | 1,5 | 1,6 | 1,6 | 1,6 | **12** | **12** | **12** | **12** | **12** | **11** | **11** | **11** |
| **07.05.2016** | 1,6 | 1,5 | 1,5 | 1,6 | 2 | 2,4 | 2,5 | 2,3 | **11** | **11** | **11** | **11** | 7 | 7 | 8 | 8 |
| **08.05.2016** | 2,2 | 2,5 | **3** | **3,2** | **3,1** | 2,8 | 2,6 | 2,5 | 8 | 8 | 9 | **11** | **12** | **11** | **10** | **9** |
| **09.05.2016** | 2,5 | 2,3 | 2,3 | 2,3 | 2,2 | 2 | 1,8 | 1,7 | 9 | 9 | 9 | 9 | **11** | **10** | **9** | **9** |
| **10.05.2016** | 1,6 | 1,7 | 1,8 | 1,8 | 1,7 | 1,6 | 1,7 | 1,9 | 9 | **9** | **9** | 8 | 8 | 8 | 8 | 8 |
| **11.05.2016** | 2 | 1,8 | 1,7 | 1,7 | 1,6 | 1,5 | 1,4 | 1,3 | 8 | 8 | 8 | 8 | 8 | 9 | 9 | 9 |
| **12.05.2016** | 1,3 | 1,2 | 1,2 | 1,2 | 1,2 | 1,2 | 1,2 | 1,2 | 9 | 9 | 9 | 8 | 8 | 8 | 8 | 8 |
| **13.05.2016** | 1,2 | 1,2 | 1,2 | 1,1 | 1,1 | 1,1 | 1,1 | 1,1 | 8 | 8 | 8 | 8 | **10** | **9** | **9** | **9** |
| **14.05.2016** | 1,1 | 1,1 | 1 | 1 | 1 | 0,9 | 0,9 | 0,9 | 8 | 8 | 7 | 7 | 7 | 8 | 8 | 7 |
| **15.05.2016** | 0,9 | 0,9 | 0,9 | 0,8 | 0,9 | 1 | 1 | 1 | 7 | 7 | 7 | 7 | 7 | 5 | 5 | 5 |
| **16.05.2016** | 1 | 0,9 | 0,9 | 0,9 | 0,9 | 1 | 1,1 | 1,1 | 5 | 6 | 7 | 8 | **12** | **11** | **11** | **11** |
| **17.05.2016** | 1,2 | 1,3 | 1,3 | 1,3 | 1,3 | 1,3 | 1,4 | 1,5 | **10** | **10** | **10** | **10** | **10** | **11** | **12** | **11** |
| **18.05.2016** | 1,5 | 1,4 | 1,4 | 1,5 | 1,5 | 1,6 | 1,7 | 1,7 | **11** | **11** | **11** | **12** | **12** | **12** | **11** | **11** |
| **19.05.2016** | 1,7 | 1,6 | 1,5 | 1,5 | 1,5 | 1,5 | 1,5 | 1,5 | **11** | **11** | **11** | **11** | **11** | **11** | **11** | **11** |
| **20.05.2016** | 1,5 | 1,4 | 1,3 | 1,2 | 1,2 | 1,2 | 1,2 | 1,2 | **11** | **10** | **10** | **10** | **10** | **10** | **10** | **10** |
| **21.05.2016** | 1,2 | 1,2 | 1,2 | 1,2 | 1,2 | 1,3 | 1,4 | 1,6 | **10** | **10** | **10** | **10** | **10** | **10** | **11** | **11** |
| **22.05.2016** | 1,7 | 1,8 | 1,9 | 1,9 | 1,9 | 1,9 | 1,9 | 1,9 | **11** | **11** | **11** | **11** | **11** | **11** | **11** | **11** |
| **23.05.2016** | 1,8 | 1,7 | 1,6 | 1,5 | 1,4 | 1,3 | 1,2 | 1,1 | **11** | **10** | **10** | **10** | **10** | **10** | **10** | **10** |
| **24.05.2016** | 1 | 1 | 1,1 | 1,3 | 1,6 | 2 | 2,3 | 2,5 | **9** | **9** | **10** | **18** | **17** | **16** | **15** | **15** |

| | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 25.05.2016 | 2,6 | 2,7 | 2,8 | 2,8 | 2,8 | 2,8 | 2,7 | 2,7 | 15 | 14 | 14 | 14 | 13 | 13 | 13 | 13 |
| 26.05.2016 | 2,6 | 2,5 | 2,4 | 2,2 | 2,1 | 1,9 | 1,8 | 1,7 | 13 | 13 | 13 | 13 | 12 | 12 | 12 | 11 |
| 27.05.2016 | 1,6 | 1,6 | 1,5 | 1,6 | 1,6 | 1,7 | 1,6 | 1,6 | 11 | 10 | 10 | 9 | 9 | 8 | 8 | 8 |
| 28.05.2016 | 1,6 | 1,6 | 1,5 | 1,5 | 1,6 | 1,7 | 1,8 | 1,7 | 8 | 8 | 7 | 7 | 7 | 7 | 7 | 8 |
| 29.05.2016 | 1,7 | 1,7 | 1,7 | 1,6 | 1,5 | 1,4 | 1,4 | 1,3 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 |
| 30.05.2016 | 1,2 | 1,2 | 1,1 | 1 | 1 | 0,9 | 0,9 | 0,8 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 6 |
| 31.05.2016 | 0,8 | 0,7 | 0,7 | 0,7 | 0,8 | 0,9 | 1 | 1 | 6 | 7 | 9 | 10 | 10 | 10 | 9 | 9 |
| 01.06.2016 | 1 | 0,9 | 0,8 | 0,8 | 0,7 | 0,7 | 0,7 | 0,7 | 9 | 9 | 9 | 8 | 8 | 8 | 8 | 9 |
| 02.06.2016 | 0,8 | 0,9 | 1,1 | 1,2 | 1,3 | 1,3 | 1,2 | 1,2 | 16 | 15 | 14 | 13 | 12 | 12 | 12 | 11 |
| 03.06.2016 | 1,1 | 1,1 | 1 | 1 | 1 | 0,9 | 0,9 | 0,9 | 11 | 11 | 10 | 10 | 10 | 10 | 10 | 10 |
| 04.06.2016 | 0,9 | 0,8 | 0,8 | 0,8 | 0,7 | 0,7 | 0,6 | 0,6 | 10 | 9 | 9 | 9 | 9 | 9 | 9 | 8 |
| 05.06.2016 | 0,6 | 0,6 | 0,7 | 0,7 | 0,8 | 0,9 | 1,2 | 1,4 | 8 | 8 | 8 | 8 | 8 | 9 | 13 | 13 |
| 06.06.2016 | 1,7 | 1,9 | 2,1 | 2,1 | 2 | 1,9 | 1,8 | 1,6 | 13 | 14 | 13 | 13 | 12 | 12 | 12 | 11 |
| 07.06.2016 | 1,5 | 1,4 | 1,4 | 1,3 | 1,2 | 1,1 | 1,1 | 1 | 11 | 11 | 10 | 10 | 10 | 10 | 10 | 10 |
| 08.06.2016 | 1 | 0,9 | 0,8 | 0,8 | 0,7 | 0,8 | 0,8 | 0,8 | 9 | 9 | 9 | 9 | 9 | 9 | 8 | 8 |
| 09.06.2016 | 0,9 | 0,9 | 1 | 1 | 1,1 | 1,1 | 1,2 | 1,2 | 9 | 10 | 10 | 10 | 10 | 10 | 10 | 10 |
| 10.06.2016 | 1,2 | 1,3 | 1,4 | 1,3 | 1,3 | 1,3 | 1,3 | 1,3 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 |
| 11.06.2016 | 1,2 | 1,1 | 0,9 | 0,8 | 0,8 | 0,7 | 0,7 | 0,8 | 8 | 9 | 8 | 8 | 8 | 8 | 8 | 8 |
| 12.06.2016 | 0,9 | 1,1 | 1,2 | 1,2 | 1,2 | 1,3 | 1,3 | 1,3 | 8 | 10 | 10 | 10 | 10 | 10 | 10 | 10 |
| 13.06.2016 | 1,3 | 1,3 | 1,3 | 1,4 | 1,4 | 1,5 | 1,5 | 1,6 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 |
| 14.06.2016 | 1,6 | 1,6 | 1,5 | 1,5 | 1,5 | 1,5 | 1,6 | 1,7 | 10 | 10 | 10 | 11 | 11 | 11 | 10 | 10 |
| 15.06.2016 | 1,8 | 2 | 2,2 | 2,5 | 2,8 | 3 | 3,1 | 3,1 | 10 | 9 | 9 | 10 | 10 | 10 | 11 | 11 |
| 16.06.2016 | 3 | 2,9 | 2,8 | 2,6 | 2,5 | 2,3 | 2,2 | 2,1 | 11 | 11 | 11 | 11 | 11 | 11 | 10 | 10 |
| 17.06.2016 | 1,9 | 1,8 | 1,7 | 1,6 | 1,5 | 1,5 | 1,5 | 1,5 | 10 | 10 | 10 | 9 | 9 | 9 | 9 | 9 |
| 18.06.2016 | 1,5 | 1,4 | 1,3 | 1,3 | 1,3 | 1,4 | 1,6 | 1,6 | 9 | 9 | 8 | 8 | 8 | 8 | 6 | 6 |
| 19.06.2016 | 1,5 | 1,3 | 1,2 | 1 | 1 | 1 | 1,2 | 1,3 | 8 | 8 | 9 | 10 | 11 | 11 | 10 | 7 |
| 20.06.2016 | 1,2 | 1,2 | 1,1 | 1,1 | 1,1 | 1,2 | 1,4 | 1,5 | 7 | 9 | 9 | 10 | 10 | 10 | 10 | 10 |
| 21.06.2016 | 1,6 | 1,6 | 1,6 | 1,6 | 1,5 | 1,5 | 1,5 | 1,5 | 12 | 12 | 12 | 11 | 11 | 11 | 11 | 11 |
| 22.06.2016 | 1,5 | 1,4 | 1,4 | 1,4 | 1,3 | 1,3 | 1,4 | 1,4 | 11 | 11 | 11 | 11 | 11 | 11 | 11 | 11 |
| 23.06.2016 | 1,3 | 1,3 | 1,2 | 1,2 | 1,1 | 1,1 | 1,1 | 1,1 | 11 | 10 | 10 | 10 | 10 | 10 | 10 | 10 |
| 24.06.2016 | 1,2 | 1,3 | 1,3 | 1,4 | 1,5 | 1,7 | 1,8 | 1,9 | 10 | 10 | 9 | 9 | 9 | 9 | 7 | 7 |
| 25.06.2016 | 1,8 | 1,7 | 1,6 | 1,5 | 1,6 | 1,8 | 2 | 2,1 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 |
| 26.06.2016 | 2,2 | 2,1 | 1,9 | 1,7 | 1,7 | 1,8 | 1,9 | 1,9 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 |
| 27.06.2016 | 1,8 | 1,6 | 1,3 | 1,2 | 1,2 | 1,4 | 1,6 | 1,7 | 8 | 8 | 8 | 8 | 8 | 8 | 7 | 7 |
| 28.06.2016 | 1,8 | 1,8 | 1,7 | 1,7 | 1,9 | 2,1 | 2,1 | 2,1 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 |
| 29.06.2016 | 2 | 1,8 | 1,7 | 1,6 | 1,7 | 1,9 | 1,8 | 1,7 | 7 | 8 | 8 | 8 | 8 | 7 | 8 | 9 |
| 30.06.2016 | 1,5 | 1,4 | 1,3 | 1,3 | 1,3 | 1,4 | 1,4 | 1,4 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 |
| 01.07.2016 | 1,4 | 1,4 | 1,4 | 1,4 | 1,4 | 1,5 | 1,6 | 1,6 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 |
| 02.07.2016 | 1,7 | 1,7 | 1,7 | 1,7 | 1,7 | 1,8 | 1,9 | 2 | 10 | 10 | 10 | 10 | 10 | 10 | 9 | 8 |
| 03.07.2016 | 2 | 2 | 1,9 | 1,9 | 1,8 | 1,9 | 1,9 | 2 | 9 | 9 | 9 | 10 | 11 | 10 | 10 | 9 |
| 04.07.2016 | 1,9 | 1,9 | 1,8 | 1,7 | 1,6 | 1,6 | 1,6 | 1,6 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 |

| | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **05.07.2016** | 1,6 | 1,6 | 1,5 | 1,4 | 1,3 | 1,3 | 1,3 | 1,3 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 |
| **06.07.2016** | 1,3 | 1,2 | 1,2 | 1,1 | 1 | 0,9 | 0,9 | 0,9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 8 |
| **07.07.2016** | 0,9 | 0,9 | 0,9 | 0,9 | 0,9 | 1 | 1 | 1,1 | 8 | 8 | 8 | 8 | 9 | 9 | 9 | 9 |
| **08.07.2016** | 1,1 | 1,1 | 1 | 0,9 | 0,9 | 1 | 1,1 | 1,1 | 9 | 9 | 9 | 9 | 9 | 9 | 7 | 7 |
| **09.07.2016** | 1,1 | 1,1 | 1 | 1 | 1,1 | 1,3 | 1,7 | 1,9 | 8 | 9 | 9 | 10 | 10 | 15 | 17 | 16 |
| **10.07.2016** | 2,1 | 2,2 | 2,2 | 2,1 | 2 | 2 | 1,9 | 1,8 | 15 | 14 | 14 | 13 | 13 | 12 | 12 | 12 |
| **11.07.2016** | 1,7 | 1,7 | 1,6 | 1,6 | 1,6 | 1,7 | 1,7 | 1,7 | 12 | 11 | 11 | 11 | 11 | 10 | 10 | 10 |
| **12.07.2016** | 1,7 | 1,6 | 1,6 | 1,6 | 1,6 | 1,7 | 1,8 | 1,9 | 10 | 10 | 9 | 9 | 9 | 9 | 8 | 7 |
| **13.07.2016** | 1,9 | 1,8 | 1,6 | 1,5 | 1,5 | 1,6 | 1,7 | 1,7 | 8 | 8 | 8 | 8 | 8 | 6 | 7 | 7 |
| **14.07.2016** | 1,6 | 1,4 | 1,2 | 1,1 | 1 | 1 | 1,1 | 1,1 | 7 | 7 | 7 | 8 | 8 | 8 | 7 | 7 |
| **15.07.2016** | 1,1 | 1 | 1 | 0,9 | 0,8 | 0,8 | 0,8 | 0,8 | 8 | 8 | 8 | 8 | 9 | 9 | 9 | 9 |
| **16.07.2016** | 0,8 | 0,7 | 0,7 | 0,7 | 0,7 | 0,8 | 0,9 | 0,9 | 9 | 9 | 9 | 9 | 11 | 11 | 11 | 11 |
| **17.07.2016** | 0,9 | 0,9 | 0,9 | 0,9 | 0,9 | 0,9 | 0,9 | 0,9 | 11 | 11 | 11 | 11 | 10 | 10 | 10 | 10 |
| **18.07.2016** | 0,9 | 0,8 | 0,8 | 0,8 | 0,8 | 0,8 | 0,8 | 0,7 | 10 | 10 | 10 | 10 | 10 | 10 | 9 | 9 |
| **19.07.2016** | 0,7 | 0,7 | 0,7 | 0,7 | 0,6 | 0,7 | 0,7 | 0,7 | 9 | 9 | 9 | 9 | 9 | 10 | 10 | 10 |
| **20.07.2016** | 0,7 | 0,7 | 0,7 | 0,8 | 0,8 | 0,9 | 0,9 | 1 | 10 | 10 | 10 | 10 | 10 | 10 | 9 | 9 |
| **21.07.2016** | 1 | 1 | 1 | 0,9 | 1 | 1 | 0,9 | 0,9 | 9 | 9 | 9 | 10 | 10 | 10 | 9 | 9 |
| **22.07.2016** | 0,8 | 0,8 | 0,9 | 1 | 1,3 | 1,7 | 2 | 2,2 | 9 | 9 | 9 | 9 | 9 | 8 | 7 | 8 |
| **23.07.2016** | 2,2 | 1,9 | 1,7 | 1,5 | 1,4 | 1,6 | 1,7 | 1,7 | 8 | 8 | 8 | 8 | 8 | 8 | 7 | 7 |
| **24.07.2016** | 1,6 | 1,4 | 1,2 | 1,1 | 1,1 | 1,2 | 1,3 | 1,4 | 7 | 7 | 7 | 7 | 8 | 8 | 7 | 7 |
| **25.07.2016** | 1,4 | 1,4 | 1,3 | 1,2 | 1,2 | 1,2 | 1,3 | 1,4 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 8 |
| **26.07.2016** | 1,4 | 1,4 | 1,4 | 1,4 | 1,3 | 1,3 | 1,4 | 1,6 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 |
| **27.07.2016** | 1,8 | 1,8 | 1,7 | 1,7 | 1,7 | 1,9 | 2 | 2,1 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 |
| **28.07.2016** | 2 | 1,7 | 1,5 | 1,4 | 1,3 | 1,2 | 1,3 | 1,3 | 8 | 8 | 7 | 7 | 7 | 7 | 7 | 7 |
| **29.07.2016** | 1,4 | 1,4 | 1,3 | 1,3 | 1,3 | 1,4 | 1,5 | 1,6 | 7 | 7 | 7 | 7 | 7 | 7 | 8 | 8 |
| **30.07.2016** | 1,6 | 1,5 | 1,4 | 1,3 | 1,2 | 1,2 | 1,1 | 1,1 | 8 | 8 | 8 | 9 | 9 | 9 | 9 | 9 |
| **31.07.2016** | 1,1 | 1,1 | 1 | 0,9 | 0,9 | 0,9 | 1,1 | 1,2 | 8 | 8 | 8 | 8 | 8 | 8 | 7 | 6 |
| **01.08.2016** | 1,2 | 1,2 | 1,1 | 1,1 | 1,1 | 1,2 | 1,4 | 1,4 | 6 | 7 | 7 | 7 | 7 | 6 | 6 | 6 |
| **02.08.2016** | 1,4 | 1,3 | 1,2 | 1,1 | 1,1 | 1,3 | 1,5 | 1,6 | 7 | 7 | 6 | 6 | 6 | 6 | 6 | 7 |
| **03.08.2016** | 1,7 | 1,7 | 1,7 | 1,7 | 1,7 | 1,7 | 1,6 | 1,5 | 7 | 10 | 12 | 11 | 11 | 11 | 11 | 10 |
| **04.08.2016** | 1,4 | 1,4 | 1,3 | 1,3 | 1,3 | 1,3 | 1,3 | 1,3 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 9 |
| **05.08.2016** | 1,4 | 1,4 | 1,3 | 1,3 | 1,2 | 1,3 | 1,4 | 1,5 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 8 |
| **06.08.2016** | 1,4 | 1,3 | 1,2 | 1 | 1 | 1 | 1,1 | 1,2 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 |
| **07.08.2016** | 1,1 | 1,1 | 1,1 | 1 | 1,1 | 1,4 | 1,6 | 1,8 | 8 | 8 | 8 | 9 | 17 | 16 | 15 | 14 |
| **08.08.2016** | 1,8 | 1,8 | 1,7 | 1,6 | 1,5 | 1,5 | 1,6 | 1,8 | 13 | 12 | 12 | 12 | 11 | 11 | 11 | 10 |
| **09.08.2016** | 1,8 | 1,7 | 1,6 | 1,6 | 1,8 | 2 | 2,2 | 2,4 | 10 | 10 | 10 | 9 | 9 | 8 | 8 | 9 |
| **10.08.2016** | 2,2 | 2 | 1,8 | 1,6 | 1,5 | 1,5 | 1,6 | 1,7 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 8 |
| **11.08.2016** | 1,6 | 1,4 | 1,1 | 0,9 | 0,8 | 0,8 | 0,8 | 0,7 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 7 |
| **12.08.2016** | 0,7 | 0,6 | 0,6 | 0,5 | 0,4 | 0,4 | 0,5 | 0,5 | 7 | 7 | 8 | 8 | 8 | 8 | 6 | 5 |
| **13.08.2016** | 0,5 | 0,5 | 0,5 | 0,5 | 0,5 | 0,5 | 0,6 | 0,6 | 6 | 5 | 5 | 6 | 5 | 6 | 6 | 6 |
| **14.08.2016** | 0,6 | 0,7 | 0,7 | 0,7 | 0,7 | 0,7 | 0,6 | 0,6 | 10 | 10 | 9 | 9 | 9 | 9 | 8 | 8 |

| | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **15.08.2016** | 0,6 | 0,5 | 0,5 | 0,5 | 0,5 | 0,5 | 0,5 | 0,5 | 8 | 8 | 8 | 8 | 9 | 9 | 9 | 9 |
| **16.08.2016** | 0,5 | 0,5 | 0,5 | 0,6 | 0,7 | 0,9 | 1 | 1,1 | 9 | 8 | 9 | 12 | 12 | 12 | 11 | 11 |
| **17.08.2016** | 1,2 | 1,2 | 1,3 | 1,3 | 1,4 | 1,4 | 1,5 | 1,5 | 11 | 11 | 10 | 10 | 10 | 10 | 11 | 11 |
| **18.08.2016** | 1,6 | 1,5 | 1,4 | 1,3 | 1,2 | 1,2 | 1,1 | 1 | 12 | 12 | 12 | 12 | 11 | 11 | 11 | 11 |
| **19.08.2016** | 0,9 | 0,9 | 1 | 1,1 | 1,2 | 1,3 | 1,5 | 1,9 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 11 |
| **20.08.2016** | 2,1 | 2,2 | 2,1 | 2 | 1,9 | 1,9 | 1,9 | 1,9 | 13 | 12 | 12 | 11 | 11 | 11 | 11 | 11 |
| **21.08.2016** | 1,9 | 1,8 | 1,7 | 1,6 | 1,5 | 1,5 | 1,5 | 1,4 | 11 | 11 | 11 | 11 | 11 | 11 | 10 | 10 |
| **22.08.2016** | 1,3 | 1,2 | 1,1 | 1 | 1 | 1 | 1 | 1 | 10 | 10 | 10 | 9 | 9 | 10 | 11 | 11 |
| **23.08.2016** | 1,1 | 1 | 1 | 1 | 1 | 1,1 | 1,2 | 1,3 | 11 | 10 | 10 | 10 | 10 | 10 | 10 | 10 |
| **24.08.2016** | 1,2 | 1,2 | 1,2 | 1,2 | 1,2 | 1,2 | 1,2 | 1,2 | 10 | 10 | 9 | 9 | 9 | 9 | 9 | 9 |
| **25.08.2016** | 1,3 | 1,3 | 1,3 | 1,3 | 1,2 | 1,3 | 1,4 | 1,5 | 9 | 10 | 11 | 11 | 11 | 10 | 10 | 10 |
| **26.08.2016** | 1,5 | 1,4 | 1,3 | 1,2 | 1,1 | 1,1 | 1 | 1 | 10 | 8 | 9 | 9 | 9 | 9 | 9 | 9 |
| **27.08.2016** | 1 | 0,9 | 0,9 | 0,8 | 0,8 | 0,8 | 0,8 | 0,9 | 9 | 9 | 9 | 9 | 9 | 8 | 7 | 7 |
| **28.08.2016** | 0,9 | 0,9 | 1 | 1,2 | 1,4 | 1,6 | 1,7 | 1,7 | 9 | 9 | 9 | 10 | 10 | 10 | 10 | 10 |
| **29.08.2016** | 1,6 | 1,6 | 1,5 | 1,4 | 1,4 | 1,4 | 1,5 | 1,5 | 10 | 9 | 9 | 8 | 8 | 8 | 7 | 7 |
| **30.08.2016** | 1,4 | 1,2 | 1,1 | 0,9 | 0,8 | 0,8 | 0,9 | 1,1 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 |
| **31.08.2016** | 1,3 | 1,4 | 1,4 | 1,4 | 1,4 | 1,5 | 1,6 | 1,7 | 7 | 7 | 7 | 8 | 8 | 9 | 8 | 9 |
| **01.09.2016** | 1,8 | 1,8 | 1,8 | 1,8 | 1,7 | 1,6 | 1,5 | 1,5 | 15 | 14 | 14 | 13 | 13 | 12 | 12 | 12 |
| **02.09.2016** | 1,4 | 1,3 | 1,2 | 1,2 | 1,1 | 1 | 1 | 1 | 11 | 11 | 11 | 10 | 10 | 10 | 10 | 10 |
| **03.09.2016** | 1 | 1,1 | 1,2 | 1,3 | 1,5 | 1,6 | 1,7 | 1,7 | 12 | 14 | 13 | 13 | 13 | 13 | 13 | 14 |
| **04.09.2016** | 1,7 | 1,7 | 1,7 | 1,6 | 1,5 | 1,5 | 1,4 | 1,4 | 16 | 16 | 15 | 15 | 14 | 14 | 13 | 13 |
| **05.09.2016** | 1,3 | 1,3 | 1,3 | 1,3 | 1,4 | 1,4 | 1,3 | 1,3 | 12 | 12 | 11 | 11 | 10 | 10 | 10 | 9 |
| **06.09.2016** | 1,2 | 1,2 | 1,2 | 1,3 | 1,3 | 1,4 | 1,4 | 1,3 | 9 | 9 | 9 | 13 | 12 | 12 | 11 | 11 |
| **07.09.2016** | 1,3 | 1,3 | 1,2 | 1,2 | 1,1 | 1,1 | 1,2 | 1,3 | 11 | 11 | 10 | 10 | 10 | 10 | 10 | 10 |
| **08.09.2016** | 1,5 | 1,7 | 1,8 | 1,9 | 1,8 | 1,8 | 1,8 | 1,7 | 10 | 10 | 10 | 10 | 10 | 11 | 11 | 10 |
| **09.09.2016** | 1,6 | 1,5 | 1,4 | 1,4 | 1,3 | 1,3 | 1,3 | 1,2 | 10 | 10 | 10 | 10 | 9 | 9 | 9 | 9 |
| **10.09.2016** | 1,2 | 1,2 | 1,2 | 1,3 | 1,4 | 1,6 | 1,7 | 1,7 | 9 | 9 | 9 | 9 | 9 | 11 | 12 | 12 |
| **11.09.2016** | 1,7 | 1,7 | 1,6 | 1,6 | 1,6 | 1,5 | 1,5 | 1,4 | 11 | 11 | 11 | 11 | 11 | 11 | 11 | 11 |
| **12.09.2016** | 1,4 | 1,4 | 1,3 | 1,3 | 1,3 | 1,5 | 1,8 | 2,1 | 10 | 10 | 11 | 11 | 12 | 12 | 13 | 12 |
| **13.09.2016** | 2,3 | 2,3 | 2,3 | 2,3 | 2,3 | 2,2 | 2,1 | 2 | 12 | 12 | 12 | 12 | 12 | 11 | 11 | 11 |
| **14.09.2016** | 2 | 2 | 2 | 2 | 1,9 | 1,8 | 1,8 | 1,8 | 11 | 11 | 11 | 11 | 11 | 11 | 11 | 11 |
| **15.09.2016** | 1,8 | 1,8 | 1,8 | 1,7 | 1,6 | 1,5 | 1,5 | 1,4 | 11 | 10 | 10 | 10 | 10 | 10 | 9 | 9 |
| **16.09.2016** | 1,4 | 1,4 | 1,4 | 1,5 | 1,5 | 1,7 | 1,9 | 2 | 9 | 9 | 9 | 11 | 11 | 14 | 15 | 14 |
| **17.09.2016** | 2 | 1,9 | 1,9 | 1,8 | 1,8 | 1,8 | 1,8 | 1,8 | 14 | 13 | 13 | 13 | 13 | 13 | 12 | 12 |
| **18.09.2016** | 1,7 | 1,6 | 1,5 | 1,4 | 1,3 | 1,2 | 1,3 | 1,4 | 12 | 12 | 11 | 11 | 11 | 10 | 10 | 11 |
| **19.09.2016** | 1,4 | 1,3 | 1,3 | 1,3 | 1,3 | 1,3 | 1,3 | 1,4 | 14 | 14 | 14 | 13 | 13 | 12 | 12 | 12 |
| **20.09.2016** | 1,5 | 1,6 | 1,6 | 1,6 | 1,6 | 1,5 | 1,5 | 1,5 | 12 | 11 | 11 | 11 | 10 | 10 | 10 | 13 |
| **21.09.2016** | 1,6 | 1,6 | 1,6 | 1,7 | 1,7 | 1,7 | 1,6 | 1,6 | 17 | 16 | 16 | 15 | 15 | 14 | 14 | 14 |
| **22.09.2016** | 1,6 | 1,6 | 1,6 | 1,6 | 1,6 | 1,5 | 1,4 | 1,3 | 14 | 13 | 13 | 13 | 12 | 12 | 12 | 12 |
| **23.09.2016** | 1,3 | 1,3 | 1,2 | 1,2 | 1,2 | 1,1 | 1,1 | 1,1 | 12 | 12 | 11 | 11 | 11 | 11 | 11 | 11 |
| **24.09.2016** | 1,2 | 1,2 | 1,2 | 1,1 | 1 | 1 | 1,1 | 1,2 | 11 | 12 | 12 | 12 | 11 | 11 | 11 | 11 |

| | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **25.09.2016** | 1,4 | 1,5 | 1,5 | 1,5 | 1,6 | 1,9 | 2,1 | 2,2 | **11** | **11** | **10** | **10** | **10** | **10** | **13** | **12** |
| **26.09.2016** | 2,2 | 2,1 | 2 | 1,9 | 1,8 | 1,6 | 1,5 | 1,4 | **12** | **12** | **12** | **12** | **11** | **11** | **11** | **10** |
| **27.09.2016** | 1,4 | 1,5 | 1,6 | 1,7 | 1,7 | 1,8 | 1,9 | 1,9 | **10** | **10** | **10** | **10** | **10** | **10** | **10** | **10** |
| **28.09.2016** | 1,7 | 1,6 | 1,6 | 1,7 | 1,7 | 1,8 | 1,8 | 1,8 | **10** | **10** | **10** | **13** | **15** | **14** | **14** | **14** |
| **29.09.2016** | 1,7 | 1,6 | 1,6 | 1,5 | 1,4 | 1,4 | 1,4 | 1,4 | **13** | **13** | **13** | **13** | **13** | **13** | **12** | **12** |
| **30.09.2016** | 1,4 | 1,3 | 1,3 | 1,2 | 1,2 | 1,2 | 1,2 | 1,2 | **12** | **11** | **11** | **11** | **11** | **10** | **10** | **10** |
| **01.10.2016** | 1,3 | 1,3 | 1,3 | 1,3 | 1,3 | 1,3 | 1,3 | 1,3 | **10** | **10** | **10** | **10** | **10** | **10** | **10** | **10** |
| **02.10.2016** | 1,3 | 1,4 | 1,4 | 1,4 | 1,3 | 1,3 | 1,3 | 1,3 | **10** | **10** | **10** | **10** | **10** | **10** | **10** | **10** |
| **03.10.2016** | 1,2 | 1,1 | 1 | 1 | 1,1 | 1,4 | 1,8 | 2,1 | **10** | **10** | **10** | **10** | **13** | **15** | **14** | **15** |
| **04.10.2016** | 2,3 | 2,3 | 2,2 | 2,1 | 2 | 1,9 | 2 | 2 | **15** | **14** | **14** | **13** | **13** | **13** | **12** | **12** |
| **05.10.2016** | 2,1 | 2 | 2 | 1,9 | 1,9 | 1,8 | 1,8 | 1,7 | **12** | **12** | **13** | **13** | **13** | **13** | **13** | **13** |
| **06.10.2016** | 1,6 | 1,5 | 1,4 | 1,3 | 1,2 | 1,2 | 1,2 | 1,3 | **12** | **12** | **12** | **12** | **12** | **12** | **12** | **12** |
| **07.10.2016** | 1,3 | 1,3 | 1,3 | 1,3 | 1,3 | 1,4 | 1,5 | 1,6 | **12** | **12** | **11** | **11** | **11** | **11** | **11** | **13** |
| **08.10.2016** | 1,6 | 1,6 | 1,6 | 1,5 | 1,5 | 1,6 | 1,6 | 1,6 | **13** | **13** | **12** | **12** | **12** | **12** | **12** | **12** |
| **09.10.2016** | 1,5 | 1,5 | 1,4 | 1,3 | 1,3 | 1,2 | 1,1 | 1,1 | **11** | **11** | **11** | **11** | **11** | **10** | **10** | **10** |
| **10.10.2016** | 1,1 | 1,1 | 1,1 | 1,1 | 1 | 1 | 0,9 | 0,8 | **10** | **10** | **10** | **12** | **12** | **12** | **11** | **11** |
| **11.10.2016** | 0,8 | 0,7 | 0,7 | 0,7 | 0,9 | 1,2 | 1,6 | 1,9 | **11** | **11** | **11** | **12** | **14** | **15** | **14** | **13** |
| **12.10.2016** | 2 | 2 | 2 | 2,1 | 2,3 | 2,4 | 2,4 | 2,3 | **13** | **12** | **12** | **12** | **13** | **12** | **12** | **12** |
| **13.10.2016** | 2,1 | 2 | 1,9 | 1,7 | 1,6 | 1,5 | 1,5 | 1,6 | **12** | **11** | **11** | **11** | **11** | **10** | **10** | **9** |
| **14.10.2016** | 1,6 | 1,5 | 1,3 | 1,1 | 1 | 0,9 | 0,9 | 1 | **9** | 8 | 9 | 9 | 9 | **9** | **11** | **13** |
| **15.10.2016** | 1,1 | 1,2 | 1,3 | 1,5 | 1,7 | 1,8 | 1,9 | 2 | **14** | **13** | **13** | **12** | **11** | **11** | **11** | **11** |
| **16.10.2016** | 2 | 1,9 | 1,9 | 1,9 | 1,8 | 1,8 | 1,7 | 1,6 | **11** | **12** | **12** | **12** | **11** | **11** | **11** | **11** |
| **17.10.2016** | 1,5 | 1,4 | 1,3 | 1,3 | 1,3 | 1,4 | 1,5 | 1,5 | **11** | **10** | **10** | **10** | **10** | **10** | **10** | **9** |
| **18.10.2016** | 1,5 | 1,4 | 1,3 | 1,3 | 1,3 | 1,3 | 1,3 | 1,3 | **9** | **9** | 9 | 9 | **9** | **10** | **17** | **16** |
| **19.10.2016** | 1,3 | 1,3 | 1,3 | 1,3 | 1,3 | 1,3 | 1,3 | 1,3 | **16** | **15** | **15** | **15** | **15** | **15** | **14** | **14** |
| **20.10.2016** | 1,4 | 1,5 | 1,5 | 1,6 | 1,6 | 1,5 | 1,5 | 1,4 | **14** | **13** | **14** | **16** | **15** | **14** | **14** | **14** |
| **21.10.2016** | 1,3 | 1,2 | 1,2 | 1,2 | 1,3 | 1,4 | 1,5 | 1,6 | **13** | **13** | **12** | **12** | **13** | **16** | **16** | **15** |
| **22.10.2016** | 1,6 | 1,6 | 1,6 | 1,5 | 1,5 | 1,4 | 1,4 | 1,6 | **15** | **14** | **14** | **14** | **14** | **13** | **13** | **13** |
| **23.10.2016** | 1,8 | 1,9 | 2,2 | 2,5 | **3,1** | **4** | **4,3** | **4,2** | **10** | 7 | 7 | 8 | **16** | **15** | **15** | **15** |
| **24.10.2016** | **4** | **3,8** | **3,5** | **3,3** | **3,1** | 2,8 | 2,6 | 2,4 | **14** | **14** | **14** | **14** | **15** | **15** | **15** | **15** |
| **25.10.2016** | 2,2 | 2,1 | 2 | 1,9 | 1,8 | 1,7 | 1,6 | 1,5 | **15** | **14** | **14** | **14** | **13** | **13** | **13** | **12** |
| **26.10.2016** | 1,4 | 1,3 | 1,3 | 1,2 | 1,1 | 1,1 | 1 | 1 | **12** | **11** | **11** | **12** | **12** | **12** | **11** | **11** |
| **27.10.2016** | 1 | 0,9 | 0,9 | 0,9 | 0,9 | 0,9 | 1 | 1 | **11** | **12** | **12** | **13** | **12** | **13** | **13** | **13** |
| **28.10.2016** | 1,1 | 1,1 | 1 | 1 | 1 | 0,9 | 0,9 | 0,8 | **13** | **12** | **12** | **12** | **12** | **11** | **11** | **11** |
| **29.10.2016** | 0,8 | 0,8 | 0,7 | 0,7 | 0,7 | 0,7 | 0,8 | 0,9 | **11** | **11** | **11** | **11** | **11** | **11** | **11** | **13** |
| **30.10.2016** | 0,9 | 1 | 1 | 1 | 1 | 1,1 | 1,2 | 1,2 | **14** | **13** | **13** | **13** | **13** | **15** | **15** | **14** |
| **31.10.2016** | 1,3 | 1,3 | 1,4 | 1,4 | 1,4 | 1,4 | 1,3 | 1,3 | **14** | **13** | **13** | **13** | **14** | **13** | **13** | **13** |
| **01.11.2016** | 1,3 | 1,3 | 1,3 | 1,3 | 1,3 | 1,3 | 1,3 | 1,2 | **12** | **12** | **12** | **12** | **11** | **11** | **11** | **11** |
| **02.11.2016** | 1,1 | 1,1 | 1,1 | 1,1 | 1 | 1 | 0,9 | 0,9 | **11** | **10** | **10** | **10** | **10** | **10** | **10** | **10** |
| **03.11.2016** | 0,9 | 1 | 1 | 1,1 | 1,2 | 1,2 | 1,2 | 1,1 | **10** | **10** | **10** | 8 | 8 | 8 | 7 | 7 |
| **04.11.2016** | 1,1 | 1 | 1 | 1 | 0,9 | 0,9 | 0,8 | 0,8 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 |

| | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **05.11.2016** | 0,7 | 0,8 | 1 | 1,4 | 1,6 | 1,7 | 1,7 | 1,6 | 8 | 10 | 12 | 7 | 7 | 7 | 7 | 8 |
| **06.11.2016** | 1,6 | 1,6 | 1,6 | 1,6 | 1,6 | 1,7 | 1,7 | 1,7 | 8 | 9 | 10 | 10 | 10 | 10 | 10 | 10 |
| **07.11.2016** | 1,6 | 1,5 | 1,4 | 1,4 | 1,4 | 1,4 | 1,5 | 1,5 | 10 | 10 | 9 | 9 | 9 | 9 | 9 | 10 |
| **08.11.2016** | 1,4 | 1,3 | 1,2 | 1,2 | 1,1 | 1,1 | 1,1 | 1,3 | 10 | 11 | 12 | 13 | 13 | 13 | 13 | 12 |
| **09.11.2016** | 1,8 | 2,1 | 2,1 | 2 | 1,9 | 1,9 | 1,8 | 1,7 | 9 | 7 | 8 | 8 | 9 | 9 | 9 | 9 |
| **10.11.2016** | 1,6 | 1,5 | 1,4 | 1,4 | 1,4 | 1,5 | 1,5 | 1,6 | 9 | 9 | 9 | 9 | 9 | 10 | 11 | 12 |
| **11.11.2016** | 1,7 | 1,7 | 1,8 | 1,8 | 1,7 | 1,7 | 1,6 | 1,6 | 12 | 12 | 13 | 13 | 13 | 13 | 12 | 12 |
| **12.11.2016** | 1,5 | 1,5 | 1,4 | 1,3 | 1,2 | 1,2 | 1,3 | 1,5 | 12 | 12 | 12 | 11 | 11 | 11 | 11 | 11 |
| **13.11.2016** | 1,7 | 1,7 | 1,7 | 1,7 | 1,6 | 1,5 | 1,5 | 1,4 | 11 | 11 | 11 | 11 | 11 | 10 | 10 | 10 |
| **14.11.2016** | 1,4 | 1,3 | 1,3 | 1,2 | 1,1 | 1,1 | 1,1 | 1,1 | 10 | 11 | 11 | 11 | 11 | 11 | 10 | 10 |
| **15.11.2016** | 1 | 1 | 0,9 | 0,9 | 0,9 | 0,9 | 0,9 | 0,9 | 10 | 10 | 10 | 10 | 10 | 13 | 13 | 13 |
| **16.11.2016** | 0,9 | 1 | 0,9 | 0,9 | 0,9 | 0,9 | 0,9 | 0,9 | 12 | 12 | 12 | 12 | 11 | 11 | 11 | 11 |
| **17.11.2016** | 0,9 | 0,9 | 0,9 | 0,9 | 1 | 1,3 | 1,5 | 1,8 | 11 | 11 | 10 | 10 | 12 | 15 | 19 | 18 |
| **18.11.2016** | 1,9 | 2 | 2,1 | 2,3 | 2,5 | 2,8 | 3 | 3 | 17 | 16 | 15 | 15 | 15 | 14 | 14 | 14 |
| **19.11.2016** | 3 | 3 | 2,9 | 2,8 | 2,6 | 2,6 | 2,5 | 2,6 | 15 | 15 | 14 | 14 | 14 | 14 | 14 | 14 |
| **20.11.2016** | 2,6 | 2,7 | 2,8 | 2,8 | 2,8 | 2,7 | 2,7 | 3 | 13 | 13 | 13 | 12 | 12 | 12 | 12 | 12 |
| **21.11.2016** | 3,5 | 4,1 | 4,4 | 4,4 | 4,2 | 4 | 3,7 | 3,5 | 11 | 11 | 12 | 12 | 13 | 13 | 13 | 13 |
| **22.11.2016** | 3,2 | 2,9 | 2,6 | 2,4 | 2,2 | 2 | 1,9 | 1,9 | 12 | 12 | 12 | 12 | 11 | 11 | 11 | 11 |
| **23.11.2016** | 1,9 | 1,8 | - | - | 1,9 | 1,9 | 1,9 | 1,8 | 11 | 11 | - | - | 10 | 10 | 10 | 10 |
| **24.11.2016** | 1,7 | 1,5 | 1,3 | 1,2 | 1,2 | 1,4 | 2 | 2,4 | 10 | 10 | 9 | 9 | 9 | 9 | 7 | 8 |
| **25.11.2016** | 2,3 | 2,2 | 2 | 1,8 | 1,6 | 1,4 | 1,3 | 1,3 | 9 | 9 | 9 | 9 | 8 | 6 | 6 | 6 |
| **26.11.2016** | 1,4 | 1,3 | 1,2 | 1,2 | 1,1 | 0,9 | 0,8 | 0,8 | 6 | 6 | 6 | 6 | 6 | 8 | 13 | 13 |
| **27.11.2016** | 0,8 | 0,8 | 0,8 | 0,8 | 0,8 | 0,8 | 0,8 | 0,8 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 |
| **28.11.2016** | 0,8 | 0,9 | 0,9 | 1 | 1,2 | 1,3 | 1,3 | 1,4 | 12 | 12 | 14 | 14 | 13 | 13 | 13 | 13 |
| **29.11.2016** | 1,4 | 1,4 | 1,3 | 1,3 | 1,2 | 1,1 | 1,1 | 1,1 | 13 | 13 | 13 | 12 | 12 | 12 | 12 | 12 |
| **30.11.2016** | 1,1 | 1,1 | 1,1 | 1,2 | 1,3 | 1,4 | 1,4 | 1,5 | 12 | 11 | 11 | 11 | 11 | 12 | 13 | 12 |
| **01.12.2016** | 1,5 | 1,6 | 1,6 | 1,4 | 1,3 | 1,2 | 1,1 | 1 | 12 | 11 | 10 | 10 | 9 | 8 | 8 | 8 |
| **02.12.2016** | 1 | 1 | 0,9 | 0,9 | 0,9 | 0,8 | 0,8 | 0,8 | 10 | 8 | 10 | 12 | 12 | 12 | 11 | 11 |
| **03.12.2016** | 0,9 | 1 | 1,2 | 1,3 | 1,5 | 1,6 | 1,7 | 1,7 | 11 | 10 | 6 | 7 | 8 | 9 | 9 | 9 |
| **04.12.2016** | 1,7 | 1,8 | 2 | 2,3 | 2,5 | 2,4 | 2,2 | 2,1 | 9 | 9 | 11 | 12 | 12 | 12 | 12 | 11 |
| **05.12.2016** | 1,9 | 1,7 | 1,6 | 1,5 | 1,4 | 1,3 | 1,2 | 1,2 | 11 | 11 | 11 | 11 | 11 | 11 | 10 | 10 |
| **06.12.2016** | 1,1 | 1 | 1 | 0,9 | 0,9 | 0,9 | 0,9 | 1 | 10 | 10 | 10 | 9 | 9 | 9 | 9 | 12 |
| **07.12.2016** | 1,3 | 1,5 | 1,7 | 1,9 | 2 | 2,1 | 2,1 | 2,2 | 13 | 13 | 13 | 13 | 12 | 12 | 13 | 12 |
| **08.12.2016** | 2,1 | 2,1 | 2 | 2 | 2 | 1,9 | 1,9 | 1,9 | 12 | 12 | 12 | 12 | 12 | 12 | 13 | 13 |
| **09.12.2016** | 1,9 | 1,9 | 1,8 | 1,8 | 2 | 2,2 | 2,4 | 2,4 | 12 | 12 | 12 | 12 | 12 | 15 | 14 | 14 |
| **10.12.2016** | 2,5 | 2,5 | 2,5 | 2,4 | 2,3 | 2,1 | 2 | 2 | 14 | 14 | 13 | 13 | 13 | 12 | 12 | 12 |
| **11.12.2016** | 2 | 1,9 | 1,9 | 1,8 | 1,7 | 1,6 | 1,6 | 1,5 | 12 | 12 | 12 | 12 | 12 | 12 | 11 | 11 |
| **12.12.2016** | 1,5 | 1,4 | 1,3 | 1,3 | 1,2 | 1,1 | 1,2 | 1,3 | 11 | 11 | 11 | 11 | 11 | 11 | 13 | 13 |
| **13.12.2016** | 1,4 | 1,5 | 1,6 | 1,6 | 1,6 | 1,7 | 1,7 | 1,9 | 13 | 13 | 13 | 13 | 13 | 12 | 12 | 12 |
| **14.12.2016** | 2,2 | 2,4 | 2,5 | 2,6 | 2,8 | 3 | 3,1 | 3,1 | 9 | 10 | 13 | 14 | 13 | 13 | 13 | 13 |
| **15.12.2016** | 3 | 2,9 | 2,8 | 2,7 | 2,6 | 2,5 | 2,8 | 3,5 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 |

| | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **16.12.2016** | **4,2** | **4,7** | **4,8** | **4,8** | **4,8** | **4,7** | **4,5** | **4,3** | **15** | **17** | **17** | **16** | **16** | **16** | **16** | **15** |
| **17.12.2016** | **3,9** | **3,6** | **3,3** | 3 | 2,7 | 2,5 | 2,3 | 2,1 | **15** | **15** | **14** | **14** | **14** | **13** | **13** | **13** |
| **18.12.2016** | 1,9 | 1,7 | 1,6 | 1,6 | 1,6 | 1,6 | 1,5 | 1,5 | **13** | **13** | **12** | **12** | **12** | **12** | **12** | **12** |
| **19.12.2016** | 1,5 | 1,5 | 1,6 | 1,7 | 1,8 | 2 | 2,3 | 2,5 | **12** | **12** | **13** | **15** | **15** | **14** | **16** | **17** |
| **20.12.2016** | 2,6 | 2,7 | 2,7 | 2,7 | 2,7 | 2,7 | 2,7 | 2,6 | **16** | **16** | **15** | **15** | **15** | **15** | **15** | **15** |
| **21.12.2016** | 2,5 | 2,4 | 2,2 | 2,1 | 2,2 | 2,4 | 2,8 | **3** | **15** | **14** | **14** | **14** | **13** | **14** | **15** | **17** |
| **22.12.2016** | **3,1** | **3** | 2,9 | 2,8 | 2,8 | 2,7 | 2,7 | 2,7 | **16** | **16** | **15** | **15** | **15** | **14** | **14** | **14** |
| **23.12.2016** | 2,7 | 2,7 | 2,7 | 2,7 | 2,6 | 2,5 | 2,4 | 2,3 | **14** | **14** | **14** | **16** | **15** | **15** | **15** | **15** |
| **24.12.2016** | 2,2 | 2,1 | 2 | 2,1 | 2,2 | 2,5 | 2,6 | 2,6 | **14** | **14** | **14** | **14** | **14** | **14** | **15** | **15** |
| **25.12.2016** | 2,5 | 2,4 | 2,2 | 2,1 | 2 | 1,9 | 1,8 | 1,7 | **14** | **14** | **13** | **13** | **13** | **12** | **12** | **12** |
| **26.12.2016** | 1,6 | 1,6 | 1,7 | 1,9 | 2,2 | 2,4 | 2,4 | 2,3 | **12** | **12** | **12** | **13** | **16** | **16** | **15** | **14** |
| **27.12.2016** | 2,2 | 2,2 | 2,1 | 2,1 | 2 | 2 | 1,9 | 1,8 | **14** | **14** | **14** | **13** | **13** | **13** | **13** | **13** |
| **28.12.2016** | 1,7 | 1,6 | 1,5 | 1,4 | 1,4 | 1,3 | 1,2 | 1,2 | **13** | **12** | **12** | **12** | **12** | **12** | **12** | **14** |
| **29.12.2016** | 1,1 | 1,1 | 1,1 | 1,2 | 1,2 | 1,2 | 1,2 | 1,2 | **14** | **14** | **13** | **13** | **13** | **13** | **14** | **14** |
| **30.12.2016** | 1,2 | 1,2 | 1,3 | 1,3 | 1,3 | 1,3 | 1,2 | 1,2 | **13** | **13** | **13** | **13** | **13** | **13** | **13** | **13** |
| **31.12.2016** | 1,1 | 1,1 | 1 | 0,9 | 0,9 | 0,9 | 0,9 | 0,9 | **12** | **12** | **12** | **12** | **13** | **13** | **13** | **12** |
| **01.01.2017** | 0,9 | 1 | 1,1 | 1,2 | 1,3 | 1,4 | 1,5 | 1,6 | **12** | **12** | **13** | **16** | **15** | **14** | **14** | **14** |
| **02.01.2017** | 1,8 | 2,1 | 2,3 | 2,5 | 2,8 | **3,1** | **3,1** | **3,1** | **13** | **13** | **12** | **11** | **10** | **10** | **10** | **10** |
| **03.01.2017** | 2,9 | 2,6 | 2,4 | 2,2 | 2 | 1,9 | 1,7 | 1,6 | **10** | **10** | **10** | **10** | **10** | **10** | **10** | **10** |
| **04.01.2017** | 1,5 | 1,4 | 1,3 | 1,3 | 1,2 | 1,2 | 1,2 | 1,1 | **9** | **9** | 9 | **9** | **9** | **9** | **10** | 9 |
| **05.01.2017** | 1,1 | 1,1 | 1,2 | 1,2 | 1,2 | 1,2 | 1,3 | 1,3 | **12** | **12** | **10** | **9** | **12** | **11** | **11** | **11** |
| **06.01.2017** | 1,3 | 1,2 | 1,2 | 1,1 | 1,1 | 1,1 | 1,1 | 1,1 | **11** | **11** | **11** | **11** | **11** | **10** | **11** | **12** |
| **07.01.2017** | 1,1 | 1,2 | 1,2 | 1,2 | 1,2 | 1,1 | 1,1 | 1 | **12** | **12** | **12** | **12** | **12** | **12** | **12** | **12** |
| **08.01.2017** | 1 | 1 | 1 | 0,9 | 0,9 | 0,9 | 0,9 | 0,8 | **12** | **12** | **12** | **13** | **13** | **12** | **12** | **12** |
| **09.01.2017** | 0,8 | 0,8 | 0,8 | 0,8 | 0,8 | 0,9 | 0,9 | 1 | **11** | **11** | **11** | **11** | **13** | **14** | **14** | **13** |
| **10.01.2017** | 1,1 | 1,2 | 1,4 | 1,7 | 2 | 2,4 | 2,6 | 2,7 | **13** | **13** | **13** | **13** | **17** | **16** | **15** | **15** |
| **11.01.2017** | 2,7 | 2,5 | 2,4 | 2,2 | 2,1 | 1,9 | 1,8 | 1,7 | **14** | **14** | **13** | **13** | **13** | **12** | **12** | **12** |
| **12.01.2017** | 1,6 | 1,5 | 1,5 | 1,5 | 1,6 | 1,7 | 1,9 | 2 | **12** | **11** | **11** | **11** | **11** | **14** | **14** | **14** |
| **13.01.2017** | 2,2 | 2,4 | 2,6 | 2,7 | 2,8 | 2,9 | **3,1** | **3,1** | **13** | **13** | **13** | **13** | **13** | **15** | **15** | **15** |
| **14.01.2017** | 3 | 2,8 | 2,7 | 2,5 | 2,4 | 2,2 | 2,1 | 2 | **14** | **14** | **14** | **14** | **14** | **13** | **13** | **13** |
| **15.01.2017** | 1,9 | 1,7 | 1,6 | 1,5 | 1,4 | 1,3 | 1,4 | 1,4 | **13** | **13** | **12** | **12** | **12** | **12** | **11** | **11** |
| **16.01.2017** | 1,3 | 1,3 | 1,2 | 1,1 | 1,1 | 1 | 1 | 1 | **11** | **11** | **10** | **10** | **10** | **9** | **9** | **9** |
| **17.01.2017** | 0,9 | 0,9 | 0,8 | 0,8 | 0,7 | 0,7 | 0,8 | 0,9 | 9 | 8 | 7 | 8 | **12** | **16** | **15** | **15** |
| **18.01.2017** | 1 | 1,1 | 1,2 | 1,2 | 1,1 | 1 | 0,9 | 0,9 | **14** | **14** | **13** | **13** | **13** | **12** | **12** | **12** |
| **19.01.2017** | 0,8 | 0,8 | 0,8 | 0,8 | 0,7 | 0,7 | 0,8 | 0,9 | **12** | **12** | **12** | **11** | **11** | **11** | **13** | **18** |
| **20.01.2017** | 1,2 | 1,4 | 1,5 | 1,6 | 1,6 | 1,5 | 1,4 | 1,4 | **17** | **16** | **15** | **15** | **14** | **14** | **13** | **13** |
| **21.01.2017** | 1,3 | 1,4 | 1,5 | 1,6 | 1,7 | 1,7 | 1,7 | 1,7 | **12** | **12** | **12** | **14** | **14** | **13** | **13** | **13** |
| **22.01.2017** | 1,6 | 1,5 | 1,4 | 1,4 | 1,3 | 1,3 | 1,4 | 1,4 | **13** | **13** | **12** | **12** | **12** | **12** | **11** | **11** |
| **23.01.2017** | 1,4 | 1,4 | 1,4 | 1,3 | 1,3 | 1,3 | 1,3 | 1,4 | **11** | **11** | **12** | **12** | **12** | **12** | **12** | **13** |
| **24.01.2017** | 1,6 | 1,9 | 2 | 2,1 | 2,2 | 2,2 | 2,2 | 2,2 | **15** | **17** | **17** | **17** | **16** | **15** | **15** | **14** |
| **25.01.2017** | 2,1 | 2 | 1,9 | 1,8 | 1,7 | 1,7 | 1,7 | 1,8 | **14** | **14** | **13** | **13** | **13** | **13** | **12** | **12** |

| | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **26.01.2017** | 2 | 2,2 | 2,5 | **3** | **3,2** | 3 | 2,7 | 2,5 | **12** | **12** | **12** | **12** | **12** | **12** | **12** | **11** |
| **27.01.2017** | 2,5 | 2,6 | 3 | **3,4** | **3,9** | **4,2** | **4,1** | **3,9** | **11** | **11** | **11** | **11** | **11** | **13** | **13** | **16** |
| **28.01.2017** | **3,7** | **3,5** | **3,2** | **3** | 2,8 | 2,6 | 2,5 | 2,3 | **16** | **15** | **15** | **15** | **14** | **14** | **14** | **13** |
| **29.01.2017** | 2,2 | 2,3 | 2,4 | 2,5 | 2,4 | 2,3 | 2,1 | 2,1 | **13** | **13** | **10** | 9 | 8 | 9 | **9** | **10** |
| **30.01.2017** | 2,1 | 2,1 | 2,1 | 2,1 | 2,1 | 2,3 | 2,4 | 2,5 | **10** | **11** | **13** | **12** | **12** | **10** | **10** | **10** |
| **31.01.2017** | 2,7 | 2,9 | **3,1** | **3,3** | **3,3** | **3,2** | **3,1** | 3 | **9** | **11** | **13** | **13** | **15** | **14** | **14** | **14** |
| **01.02.2017** | 2,9 | 2,9 | 2,8 | 2,8 | - | - | - | - | **14** | **14** | **13** | **13** | - | - | - | - |

| | Waves (m) | | | | | | | | Wave period (s) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 00h | 03h | 06h | 09h | 12h | 15h | 18h | 21h | 00h | 03h | 06h | 09h | 12h | 15h | 18h | 21h |
| **Average** | 1,8 | 1,7 | 1,7 | 1,7 | 1,7 | 1,7 | 1,8 | 1,8 | 11,1 | 11,1 | 11,0 | 11,1 | 11,1 | 11,1 | 11,1 | 11,1 |
| **Average** | **1,73** | | | | | | | | **11,08** | | | | | | | |

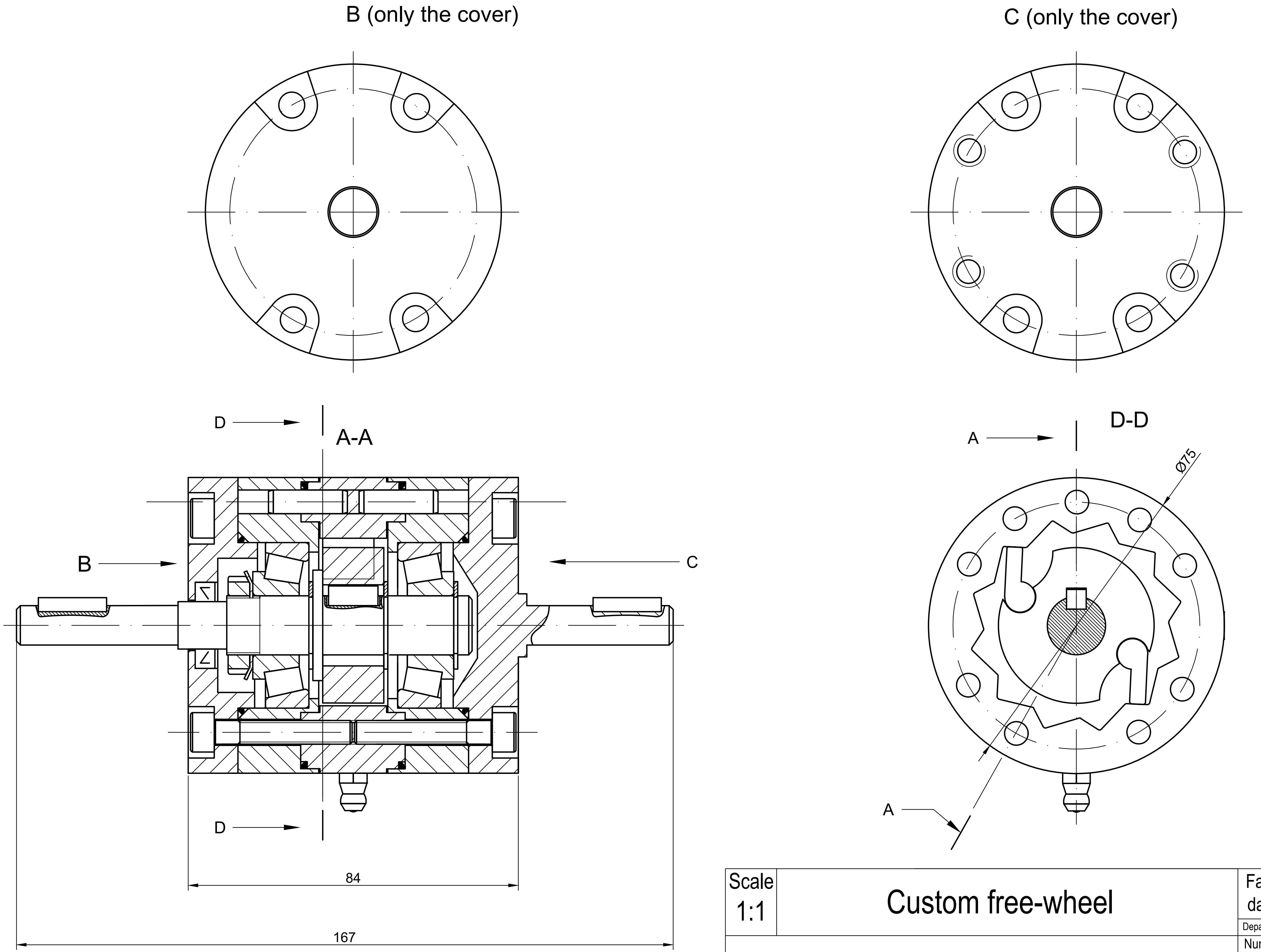
| | Waves (m) | | | | | | | | Wave period (s) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 00h | 03h | 06h | 09h | 12h | 15h | 18h | 21h | 00h | 03h | 06h | 09h | 12h | 15h | 18h | 21h |
| **Maximum** | 6,1 | 5,9 | 5,4 | 5,8 | 6,1 | 6,1 | 6,1 | 6,1 | 19,0 | 18,0 | 18,0 | 18,0 | 17,0 | 18,0 | 19,0 | 20,0 |
| **Maximum** | **6,10** | | | | | | | | **20,00** | | | | | | | |

| | Waves (m) | | | | | | | | Wave period (s) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 00h | 03h | 06h | 09h | 12h | 15h | 18h | 21h | 00h | 03h | 06h | 09h | 12h | 15h | 18h | 21h |
| **Minimum** | 0,5 | 0,5 | 0,5 | 0,5 | 0,4 | 0,4 | 0,5 | 0,5 | 5,0 | 5,0 | 5,0 | 6,0 | 5,0 | 5,0 | 5,0 | 5,0 |
| **Minimum** | **0,40** | | | | | | | | **5,00** | | | | | | | |

# Appendix B

# Custom free-wheel

## Technical Drawing



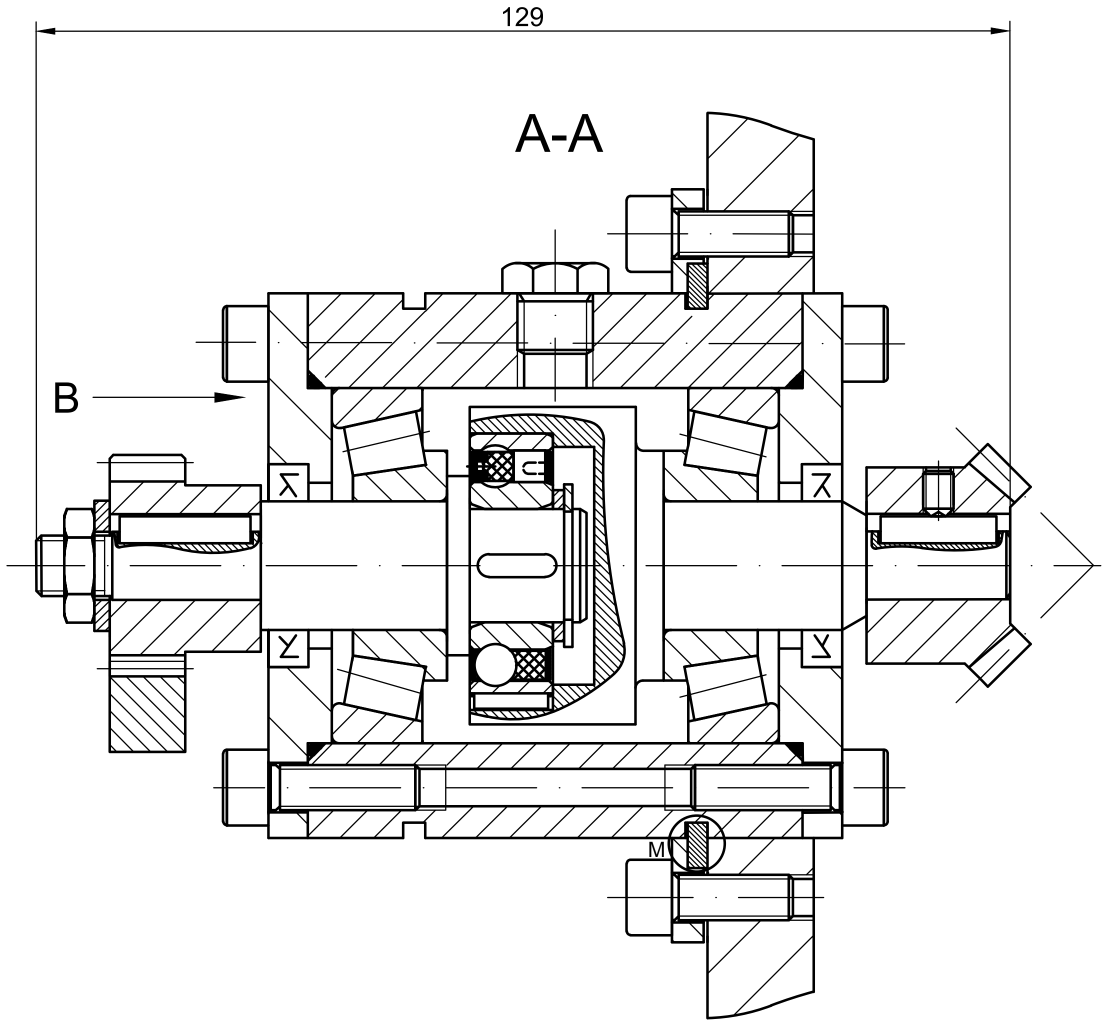

| Scale 1:1 | Custom free-wheel | Faculdade de Engenharia da Universidade do Porto<br>Departamento de Engenharia Mecânica - DEMec |
|---|---|---|
| | | Number MG_DT 1_2017 |
| Designed by: Miguel Godinho and Diogo Telo Rodrigues | | Revision / Date 23/06/2017 |

# Appendix C

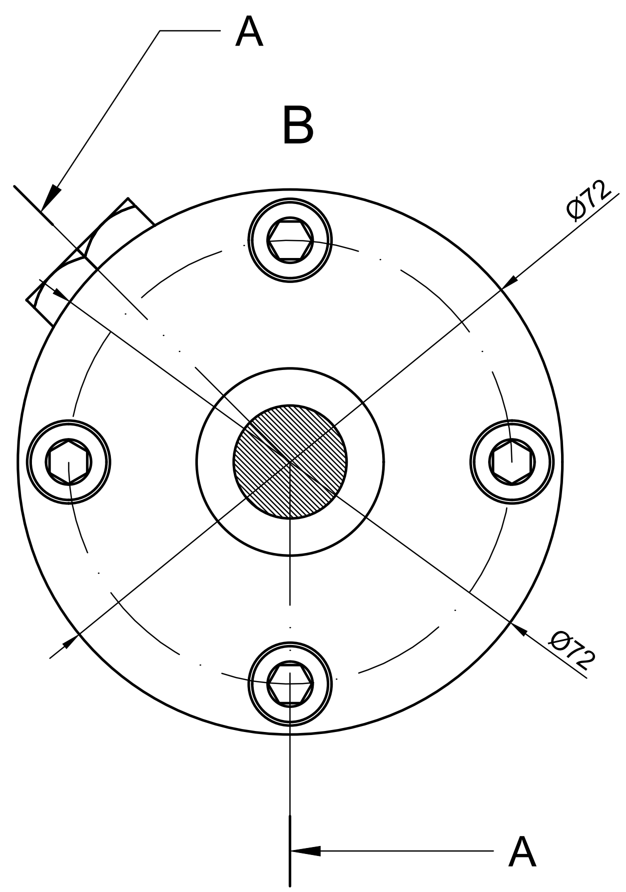
## “Wave cassette”

Technical Drawing

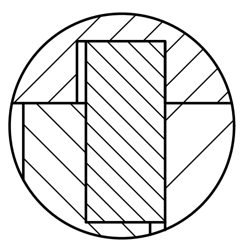
# A-A




# B




# M (4:1)

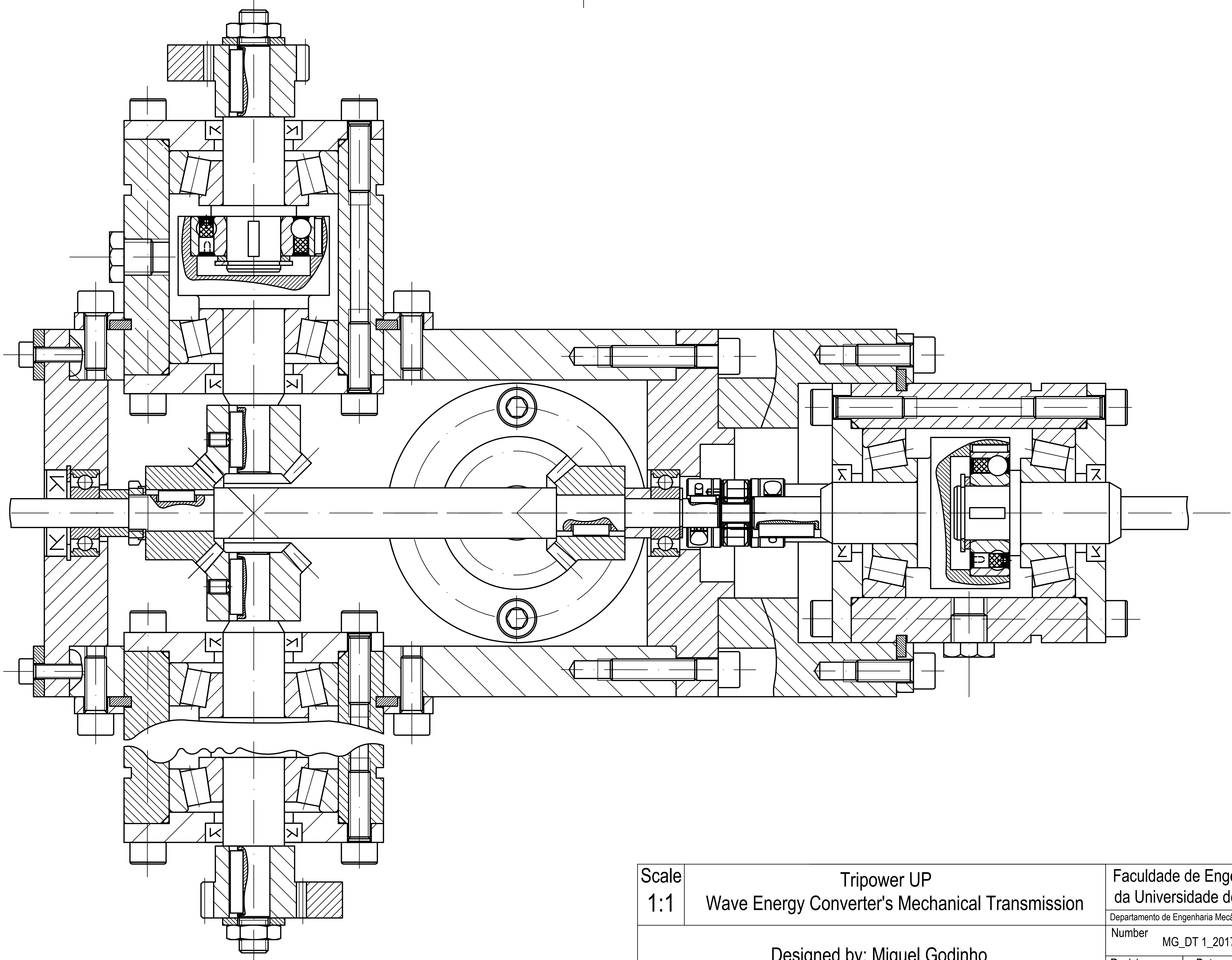


| Scale 1:1 | Tripower UP<br>Wave Cassette | Faculdade de Engenharia da Universidade do Porto<br>Departamento de Engenharia Mecânica - DEMec |
|---|---|---|
| | Designed by: Miguel Godinho | Number: MG_DT 1_2017<br>Revision:<br>Date: 23/06/2017 |

# Appendix D

# WEC's Mechanical Transmission

## Technical Drawing



| | | |
|---|---|---|
| Scale 1:1 | Tripower UP<br>Wave Energy Converter's Mechanical Transmission | Faculdade de Engenharia da Universidade do Porto<br>Departamento de Engenharia Mecânica - DEMec |
| | Designed by: Miguel Godinho | Number: MG_DT 1_2017<br>Revision<br>Date: 23/06/2017 |

# Appendix E

## Spider UP Patent Request

# MECANISMO MÚLTIPLO DE CONVERSÃO DE ENERGIA DAS ONDAS

Patent No.:
Int. Cl.
F03B

**Requerente:** Augusto Barata da Rocha

**Inventores:** Augusto Barata da Rocha; Diogo Telo de Castro Rodrigues; Miguel Eduardo dos Santos Godinho; Miguel Macieira

**RESUMO**

Um dispositivo de aproveitamento da energia das ondas converte o movimento vertical oscilante das ondas em energia elétrica.

Este dispositivo pode ser instalado em qualquer extensão de água (oceanos, rios, lagos, etc.) pois é um sistema flutuante. Mais especificamente, em cada extensão de água, pode ser instalado longe da costa (offshore), perto da costa ou na costa, independentemente da profundidade, por ser flutuante. Nas duas primeiras situações, o sistema é mantido na sua posição com recurso a um sistema de amarração constituído por uma âncora e uma corrente de amarração. Caso seja instalado na costa, pode ser fixo a uma estrutura montada num pontão ou outra estrutura semelhante.

A energia associada ao movimento das ondas é captada por um sistema de boias que através de um sistema pinhão-cremalheira converte este movimento vertical oscilante em movimento de rotação, que por sua vez, aciona um gerador elétrico.

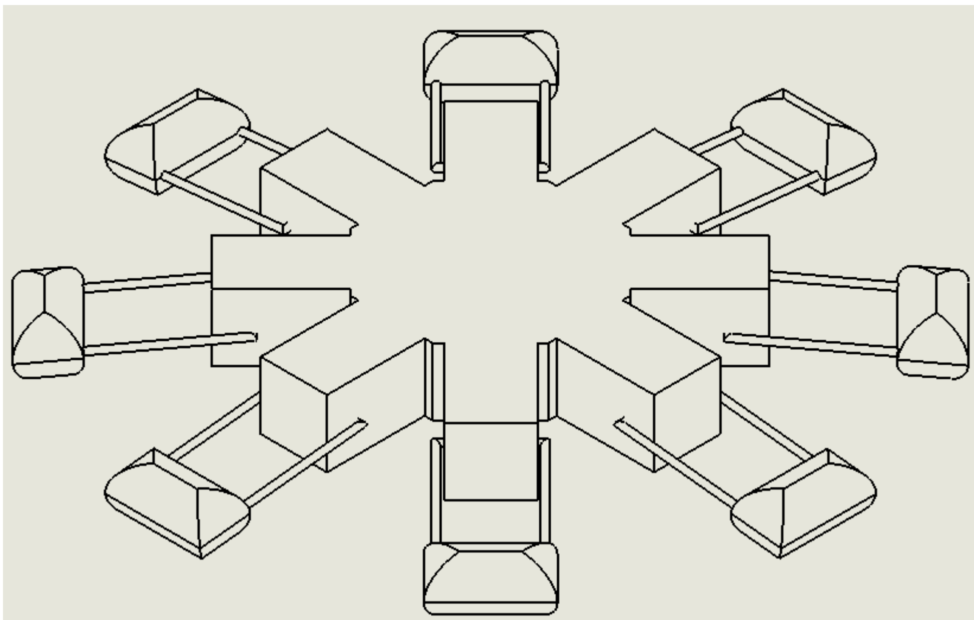
O sistema mecânico é constituído por vários braços, responsáveis pela transformação da energia potencial das ondas em energia cinética.

Cada braço atua de modo independente, transmitindo a energia cinética para uma roda dentada comum que, por sua vez, aciona um gerador elétrico.

Este equipamento foi desenhado para que possa ser trazido rapidamente para terra. Assim, pode ser facilmente desacoplado do sistema de amarração para que possa ser rebocado para operações de manutenção, proteção do equipamento em situações de tempestade, etc.

Devido à sua constituição modular, num estágio de exploração comercial, o dispositivo de conversão da energia das ondas pode ser combinado em rede com outros dispositivos semelhantes.

**Figura para Publicação**



**DESCRIÇÂO**

**Área técnica da invenção**

No mundo atual, altamente competitivo e submetido à globalização dos mercados, a energia é um vetor importante e estratégico de desenvolvimento.

O consumo de energia primária atual é já de cerca de 12 GTep/ano (Tep – Tonelada equivalente de petróleo) sendo que os combustíveis fósseis representam 70% deste total; o carvão e o petróleo representam 26% cada, o gás natural 18% e as fontes de energia não fósseis 30%. As fontes de energia não fósseis dividem-se quase em partes iguais, entre as energias renováveis e a energia nuclear.

A disponibilidade e independência energética são fatores considerados fundamentais no desenvolvimento económico dos vários países. As alterações climáticas e a escassez destes recursos impõem novos modelos energéticos assentes em energias limpas e renováveis.

Se por um lado é essencial mudar o padrão de consumo energético, também a mudança da matriz de consumo de energia primária está entre os maiores desafios que o mundo terá de enfrentar se quiser reduzir as emissões de gases que causam o efeito estufa e colaboram para o aquecimento global e minimizar outros problemas resultantes da utilização dos combustíveis fosseis.

O aumento quase exponencial da população mundial, e dos seus padrões de consumo, implicará uma crescente procura de energias renováveis, que poderá ser extraída dos oceanos.

Estima-se que, até 2030, as energias renováveis offshore deverão registar um aumento de 22%.

Entre as energias renováveis offshore destaca-se a energia das ondas que advém do movimento contínuo das águas do mar devido à ação do campo gravítico terrestre e do vento na superfície do mar.

De acordo com diversos estudos realizados no passado, constatou-se que as ondas, particularmente as oceânicas, apresentam uma grande densidade energética, não só devido à sua amplitude, mas também devido ao valor de densidade da água.

Este recurso é algo intermitente, pelo que é importante maximizar o seu aproveitamento.

Em estudos efetuados anteriormente, constatou-se que as ondas, particularmente as oceânicas, apresentam uma grande densidade energética, não só devido à sua amplitude, mas também devido ao valor da densidade da água. Assim, existe um enorme potencial energético a aproveitar.

Em termos de sistemas de aproveitamento da energia das ondas, existem poucos dispositivos num estágio de exploração comercial. A maioria dos sistemas desenvolvidos estão num estado avançado de I&D (Investigação e Desenvolvimento), protótipo ou num estágio pré-comercial.

Considerando que ainda não existem soluções já estabelecidas para os sistemas de aproveitamento de energia das ondas, facto que se pode constatar observando-se a variedade da tipologia de soluções que se tentaram implementar, existe ainda bastante por desenvolver nesta área de investigação.

## Estado da Técnica

### Revisão bibliográfica

Existem diversos sistemas desenvolvidos e patenteados ao longo dos anos que convertem a energia das ondas em energia elétrica.

#### Energia das ondas

Em termos de sistemas de aproveitamento da energia das ondas, existem poucos dispositivos num estágio de exploração comercial. A maioria dos sistemas desenvolvidos estão num estado avançado de I&D (Investigação e Desenvolvimento), protótipo ou num estágio pré-comercial.

Alguns dos sistemas mais avançados e representativos são descritos em seguida.

O sistema PowerBuoy, instalado na costa do Oceano Pacífico dos Estados Unidos, é baseado numa boia, ancorada ao fundo do mar que aciona um sistema hidráulico.

O sistema Pelamis Wave Energy Converter, testado na Aguçadoura, Portugal, consiste em vários cilindros articulados que, através da passagem das ondas, acionam um conjunto de cilindros hidráulicos. A conceção das articulações, sujeitas a grandes esforços, revelou-se problemática, uma vez que dificultou a vedação dos seus componentes internos do ambiente marítimo e, consequentemente, surgiram infiltrações nos tanques.

O sistema Wave Dragon, utilizado na Dinamarca, utiliza turbinas hidroelétricas para a produção de energia elétrica. Este sistema faz convergir a onda numa rampa que seguidamente atua uma turbina. O rendimento do sistema é baixo e a dimensão do sistema pode interferir com a navegação. Tem também vários elementos móveis facilmente danificáveis em caso de tempestade.

O Sistema Oyster Wave Energy Converter, instalado nas costas escocesas, é um conversor de energia das ondas oscilante, que aciona bombas hidráulicas que fazem mover uma turbina. A solução hidráulica introduz perdas importantes no sistema e gera problemas desgaste nos vedantes.

O Sistema WaveRoller aproveita as correntes submarinas de vaivém junto à costa e à rebentação, acionando elementos planos que, por sua vez, transmitem movimento a cilindros hidráulicos. A proximidade da costa e do fundo do mar potencia problemas nas articulações e vedações hidráulicas, devido às areias e detritos.

**Patentes**

A patente US2016333858 (A1), System And Method for Generating Electricity Using Grid of Wind and Water Energy Capture Devices, descreve um sistema que apenas capta energia das ondas e do vento. A combinação da energia gerada é feita eletricamente.

A patente US2015266549 (A1), Oscillating Piston-Type Wave Power Generation Method and System, descreve uma invenção que apenas capta a energia das ondas. Neste dispositivo, a boia move-se de acordo com a passagem das ondas para fazer movimentar um pistão que pressuriza um fluído hidráulico que induz rotação a um motor hidráulico, que, por sua vez, está acoplado a um gerador elétrico.

Na patente US9115688 (B1), Wind Resistance Wave Generator, é descrito um sistema que contem apenas uma turbina, que é movimentada pela ação conjunta da passagem das correntes, vento e ondas.

A patente WO2015086033 (A1), Hybrid Electricity Generators Using Wind Energy and Wave Energy, regista um dispositivo de captação de energia eólica, das correntes e das ondas. A energia das ondas é aproveitada de uma das 3 formas concebidas:

a. Por um sistema de molas de torção e com um mecanismo de roda livre que, com o movimento de oscilação de uma boia, colocam a mola sobre tensão, o que provoca a rotação de um veio. Com a instalação de um mecanismo de roda livre, o movimento alternado de tração e compressão das molas gera um movimento de rotação de um veio sempre no mesmo sentido;

b. Pela pressurização de um fluido hidráulico.

c. Por um mecanismo de roldanas. Com esta solução, é aproveitado o facto de o sistema ter de ser ancorado, para fazer passar o cabo de ancoragem por uma roldana colocada numa boia. Assim, o movimento de oscilação provocado pela passagem das ondas obriga a boia a movimentar-se da mesma forma, o que faz movimentar a roldana. Com um mecanismo de roda livre, o movimento de rotação alternado da roldana pode ser convertido num movimento de rotação com um só sentido.

A patente GB2515577 (A), Hybrid Electricity Generators Using Wind Energy and Wave Energy, descreve um sistema que apenas capta a energia das correntes e do vento.

A patente WO2014196921 (A1), A Water Based Modular Power Plant, descreve um sistema em que a energia é captada para produzir hidrogénio sendo que apenas indiretamente produz energia elétrica.

A patente US2014246792 (A1), Power Transfer and Generation Using Pressurize Fluids, descreve uma turbina (eólica ou de correntes) utilizada para bombear um fluido sob pressão, utilizado para movimentar um gerador elétrico.

A patente WO2014056049 (A1), Device Using Multiple Renewable Energy Sources, descreve um sistema em que a energia das correntes não é captada e o aproveitamento da energia do vento e das ondas é feita individualmente.

Na patente US2014091576 (A1), Offshore Combined Power Generation System, a energia eólica e das correntes é combinada eletricamente.

Na patente US2013028729, Power Generation Systems and Methods, o princípio de funcionamento é baseado em hidráulica. Além disso, é um sistema desenhado para apenas captar energia das correntes e do vento.

Na patente WO2012076851 (A1), Wave Energy Converter, apenas a energia das ondas é captada, através de um gerador linear.

Na patente US2011215650 (A1), Offshore Energy Harvesting, Storage and Power Generation System, a forma como a energia das ondas é captada é distinta, porque a água é conduzida para um reservatório para posteriormente passar por uma turbina segundo um princípio de funcionamento semelhante ao das turbinas numa barragem.

Na patente WO2011039536 (A1), Floating Power Plant Comprising Water Turbine and Wind Turbine, a turbina de correntes é movimentada pelas marés. Além disso, não capta a energia das ondas.

Na patente WO2010080043 (A2), Energy System, o mecanismo de captação da energia das ondas utiliza flutuadores para pressurizar um fluido.

Na patente WO2009005383 (A1), Joint System for Conversion of Eolic, Solar, Sea Waves And maritime Currents Energies, 15.é descrito um dispositivo, que, apesar de captar energia das ondas, do vento e das correntes, não utiliza uma solução de um gerador único, optando por dedicar um gerador para aproveitar individualmente cada uma destas fontes de energia.

Na patente US2008101865 (A1), Hydrodynamic Drive Train For Energy Converters That Use Ocean Currents, apenas a energia das correntes é captada.

A patente WO2006010783 (A1), Wind, Wave And Current Power Stations With Different Foundations Solutions And Methods How To Manufacture, Transport, Install And Operate These Power Stations, refere-se essencialmente às fundações dos dispositivos de captação de energia do vento, correntes e ondas, apresentando soluções para aproveitar as 3 fontes de energia num mesmo local;

Na patente US20030145587 (A1), Wind And Wave Energy Plant, só é captada a energia das ondas e do vento. Além disso, o movimento de oscilação de uma boia é utilizado para fazer movimentar um pistão, fazendo a bombagem de água do mar até um reservatório. A partir desse reservatório, a água faz movimentar uma turbina. Este princípio de funcionamento é o mesmo que faz movimentar as turbinas instaladas em barragens hidroelétricas.

Na patente US20130118176 (A1), Regenerative Offshore Energy Plant, o dispositivo capta apenas a energia do vento e das ondas. Para aproveitar a energia das ondas é aproveitado o movimento orbital das partículas de água de uma onda para fazer movimentar um rotor.

**Sumário da invenção**

A presente invenção permite converter a energia das ondas em energia elétrica.

Este processo é feito através de uma cadeia cinemática, com rodas cónicas e rodas livres, que permitirá que a oscilação vertical das boias provoque a rotação de uma roda central. Esta roda central por sua vez pode ou não ligar diretamente ao gerador, permitindo produzir energia. Na Fig.1 apenas está representado o sistema mecânico, sendo que a estrutura exterior poderá apresentar várias configurações. Este sistema mecânico é instalado no mar ou rio e funciona para qualquer tipo de profundidade e de ondulação presente nos mesmo.

O dispositivo apresenta "n" boias, sendo "n" maior ou igual a um que implicará "n" rodas cónicas a atacar a roda cónica central.

Uma descrição mais detalhada da cinemática estará presente na secção "Descrição detalhada da invenção".

O gerador poderá estar acoplado na parte superior ou inferior do veio central ou até mesmo diretamente na roda central, não estando, por isso, representado. O gerador irá variar de acordo com a dimensão do sistema implementado.

É de salientar que a roda cónica interior estará presente numa estrutura flutuante diferente das boias exteriores, denominada de boia grande interior ao longo deste documento.

Este mecanismo poderá ser implementado em separado ou poderá ser replicado ao longo de uma área, em rede.

## Breve descrição dos desenhos

Na Fig.1, apresenta-se o mecanismo do sistema que poderá ter "n" boias, sendo "n" maior ou igual a um, em que, neste caso, a oscilação das "n" boias exteriores através da cadeia cinemática, permite a rotação do veio central.

Na Fig. 2, podemos ver, em perspetiva, apenas um dos braços e a sua cadeia cinemática. Estes braços apresentam, à sua esquerda, uma boia, nº 1, e é a partir daí que se desenvolve toda a cadeia cinemática até à roda cónica final, passando pelo sistema de roda livre, pelas três engrenagens cónicas e pelo veio, números 2, 3, 4, 6 e 5, respetivamente.

Nas Figs. 3 e 4, podemos ver a vista lateral de apenas um dos braços e o seu engrenamento na roda cónica 7. É na roda cónica 7 que todos os braços se acoplam.

## Descrição da concretização preferida

Este sistema mecânico tem como vantagens uma rotação da roda central constante. Isto é possível visto que à medida que as ondas passam pelo dispositivo, as várias boias exteriores vão sendo solicitadas, em momentos distintos, mas consecutivos.

Apresenta também a vantagem de só ter de haver movimento relativo entre a boia grande interior, que contém o mecanismo central, e as boias exteriores para gerar rotação na roda interna e posterior energia, pelo gerador.

Outra das vantagens é o facto de, caso estejam duas boias exteriores a oscilar simultaneamente, as potências mecânicas produzidas pelas mesmas iram ser somadas produzindo assim mais energia.

Por último, este permite o aproveitamento do potencial energético da onda não só na subida como também na descida da onda.

Relativamente ao mecanismo em si, há a realçar que os mecanismos de 3 a 9 estarão suportados por uma boia grande interior, ancorada ou não, ou numa estrutura fixa ao solo. Esta estrutura grande interior tem de ser diferente das boias exteriores com o intuito de haver movimento relativo entre as duas estruturas, na imagem ligadas por 2.

Será explicado o funcionamento apenas de um dos braços sendo que este se repete para os "n" braços.

A boia, nº 1, está conectada por dois veios, nº 2, a dois sistemas de roda livre que por sua vez estão conectados a uma roda cónica cada, nº 4.

Vamos dividir em conjunto 1 e 2 e agrupar cada roda cónica, nº 4, e o respetivo sistema de roda livre, nº 3.

Há que relembrar que o sistema de roda livre permite transmitir a rotação apenas para um lado. Logo, quando a boia anda para cima, devido à onda, o conjunto 1 realiza trabalho, pois o sistema da roda livre engrena e permite a transmissão de movimento entre as rodas nº 4 e nº 5. Durante esta transmissão de movimento, o conjunto 2 peliça, não havendo rotação da roda cónica deste conjunto. Quando a boia exterior desce devido ao movimento da cava da onda, acontece o contrário: o conjunto 2 realiza trabalho enquanto o conjunto 1 peliça, permitindo a roda nº 5 rodar sempre no mesmo sentido.

A roda cónica, nº 5, transmitirá a sua rotação para o veio nº6 que posteriormente criará o engrenamento da roda livre no final deste veio e a rotação da roda cónica nº 7.

A rotação da roda nº 7 levará à rotação da roda central nº 8 que criará o movimento de rotação do veio. Neste veio, ou mesmo diretamente na roda nº7, será conectado um gerador que produzirá energia elétrica.

Observe-se que no fim do veio nº6 encontramos uma roda livre nº3: isto deve-se ao facto de caso um dos braços esteja a rodar a uma velocidade mais elevada, os outros não diminuam a sua velocidade.

**Reivindicações**

1. Um dispositivo de aproveitamento da energia das ondas, que converte o movimento vertical oscilante das ondas num movimento de rotação de uma roda central, que por sua vez, aciona um gerador elétrico, utilizando um veio, a roda central ou qualquer sistema dinâmico que permite a obtenção de energia;

2. De acordo com a reivindicação 1, relativamente ao mecanismo em si, é de realçar que os mecanismos de 3 até 9 estarão suportados por uma boia grande interior, ancorada, ou não, numa estrutura fixa ao solo. Esta estrutura grande interior tem de ser diferente das boias exteriores com o intuito de haver movimento relativo entre as duas estruturas, na imagem ligadas por 2.

3. Será explicado o funcionamento de apenas de um dos braços sendo que este se repete para os "n" braços:
A boia, nº 1, está conectada por dois veios, nº 2, a dois sistemas de roda livre,nº3 que por sua vez estão conectados a uma roda cónica cada, nº 4.
Vamos dividir em conjunto 1 e 2 e agrupar cada roda cónica, nº 4, e o respetivo sistema de roda livre, nº 3. Há que relembrar que o sistema de roda livre permite transmitir a rotação apenas para um lado. Logo quando a boia ascende, devido à onda, o conjunto 1 realiza trabalho, pois o sistema da roda livre engrena e permite a passagem de movimento entre a roda nº 4 e nº 5. Durante esta passagem de movimento o conjunto 2 peliça, não havendo rotação da roda cónica deste conjunto. Quando a boia exterior descende devido ao movimento da cava da onda, acontece o contrário: o conjunto 2 realiza trabalho, enquanto o conjunto 1 peliça, permitindo que a roda nº 5 rode sempre no mesmo sentido.

A roda cónica, nº 5, transmitirá a sua rotação para o veio nº 6 que posteriormente criará o engrenamento da roda livre no final deste veio e a rotação da roda cónica nº 7.
A rotação da roda nº 7 levará a rotação da grande roda nº 8 que criará o movimento de rotação do veio. Neste veio, ou mesmo diretamente na roda nº 7 será conectado um gerador que produzirá energia elétrica. Podemos ver que no fim do veio nº 6 encontramos uma roda livre nº 3: isto deve-se ao facto de, caso um dos braços esteja a rodar a uma velocidade mais elevada, os outros não o "travem".

4. De acordo com a reivindicação 2, o gerador elétrico poderá ser ligado a qualquer ponto do veio nº 9, bem como diretamente a roda cónica central, nº 8, ou a qualquer sistema que permita a obtenção de energia elétrica.

5. De acordo com a reivindicação 2, existirão duas estruturas, que poderão ter três configurações: ambas flutuantes, obtendo-se o movimento relativo através da diferença de inércia; uma estrutura móvel e outra fixa, sendo que a fixa poderá ser a interior ou a exterior e a outra será a móvel.

6. De acordo com a reivindicação 1, 2 e 3, as duas estruturas conterão componentes específicos. A primeira estrutura terá a boia exterior nº1. A segunda estrutura conterá todos os outros componentes nº3,4,5,6,7,8,9. O movimento entre as duas será feita por um braço, nº 2, em que a configuração apresentada não é a definitiva.

7. De acordo com as reivindicações 1 e3, o dispositivo de conversão da energia das ondas pode trabalhar em qualquer maré e para qualquer tamanho de onda, desde que seja assim dimensionado.

8. De acordo com todas as 1 e 3, os sistemas que compõem o dispositivo de conversão da energia das ondas são blindados e, portanto, podem funcionar de forma isolada do ambiente marítimo.

9. De acordo com as reivindicações 1 e 3, o sistema mecânico de conversão da energia das ondas pode ser rebocado para terra, separando-o do sistema de amarração.

10. De acordo com as reivindicações anteriores, o dispositivo de aproveitamento da energia das ondas pode ser baseado em acoplamentos mecânicos, hidráulicos ou elétricos;

11. De acordo com a reivindicações 1 e 3, o dispositivo de aproveitamento da energia das ondas pode ser implementado em rede, formado por diversos dispositivos de aproveitamento da energia das ondas semelhantes.

Porto, 25 de janeiro de 2017

Desenhos

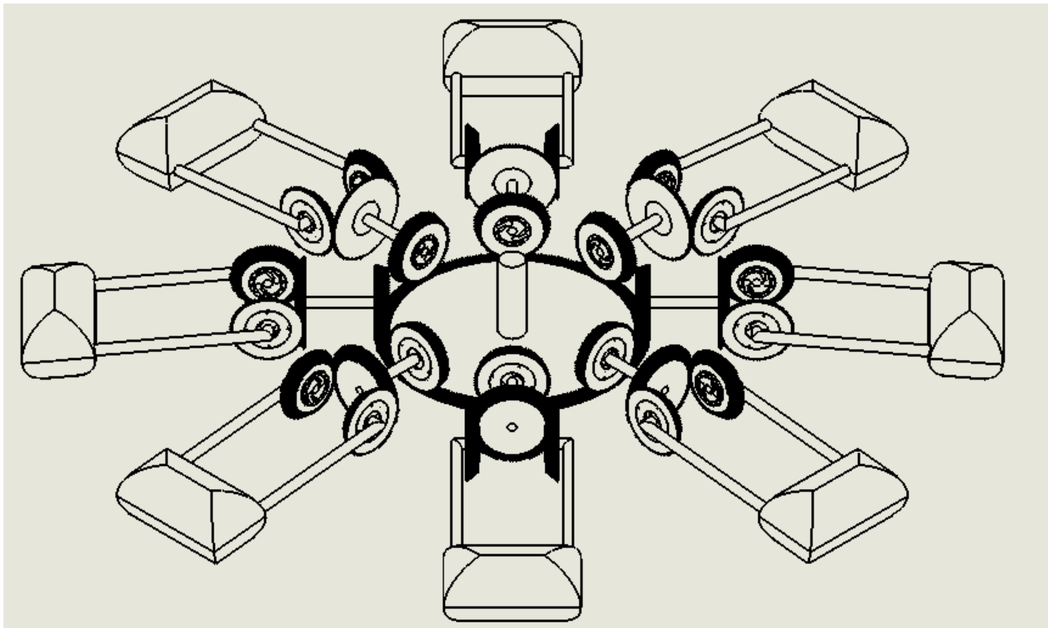


Fig.1- Desenho geral do sistema Spider UP

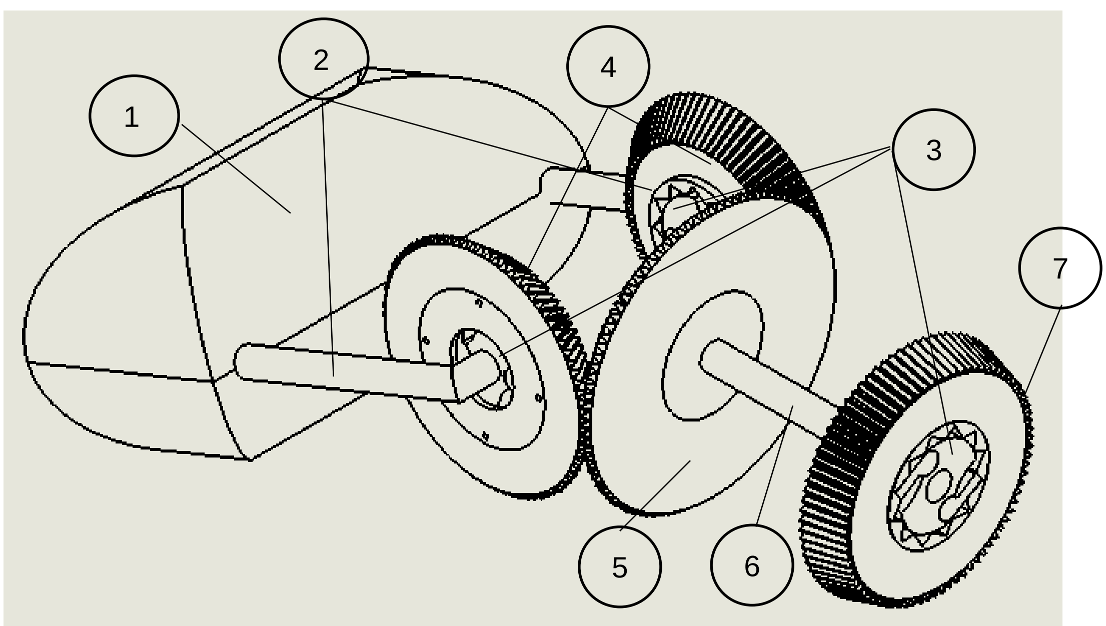



Fig.2 – Subsistema de um conjunto braço-boia

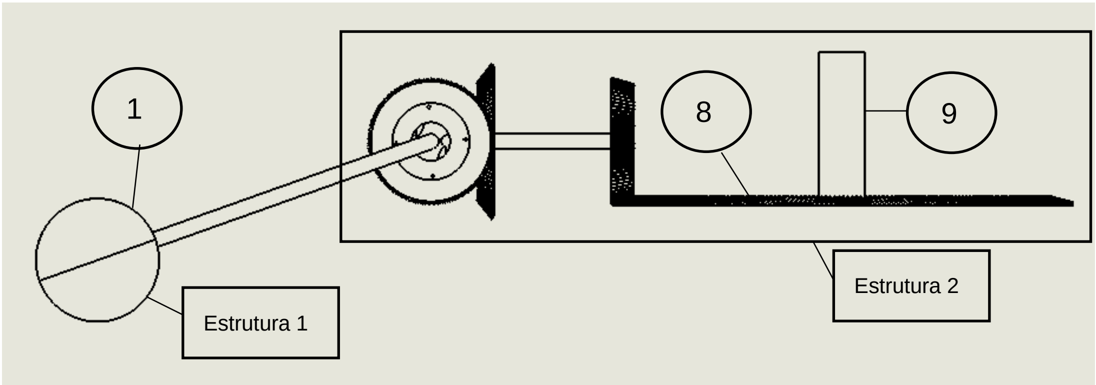



Fig.3 – Ligação do subsistema braço-boia à estrutura central (vista lateral)

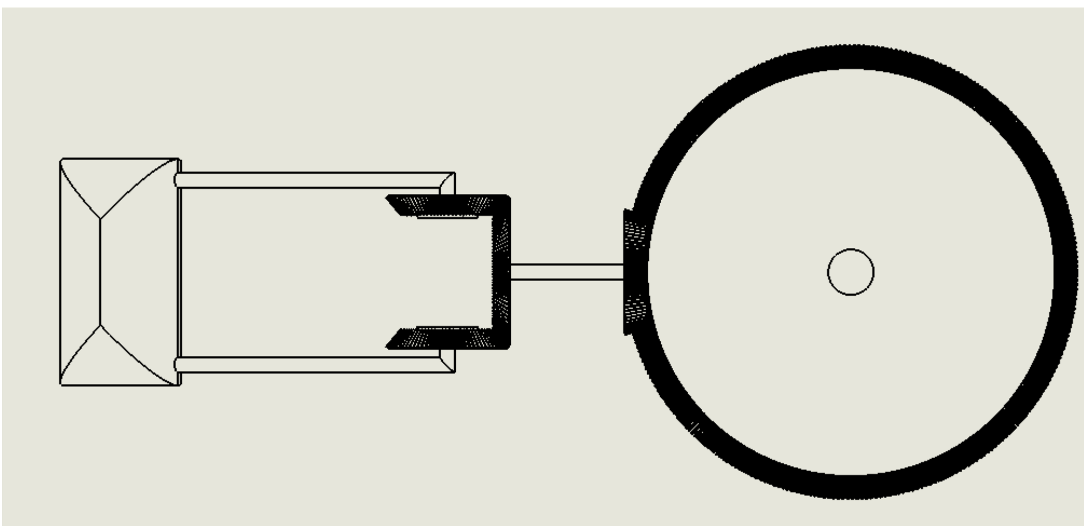


Fig.4 – Ligação do subsistema braço-boia à estrutura central (vista de cima)