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Crosscutting open source technology applied to Wave Energy Converters

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Abstract—**Wave energy technology developers have felt compelled to create patents out of concern that the big energy companies would copy their technology and then use their massive manufacturing, sales and marketing power to overwhelm these technology developers. They could not have been more wrong. The unfortunate reality is the opposite: wave energy programs at the major utilities or independent power producers are small to non-existent, constituting an average of far less than 0.1% of their total research and development resources.**

In the software industry, the success of open innovation strategies through open sourcing is widely known and acknowledged. The open source approach to create software innovations has become a vital alternative to in-house developments for many firms. In fact, in Open-source software projects, the major innovations come from the users, the open source community.

A new H2020 project called *surging energy absorption through increasing thrust and efficiency* (SEA-TITAN) aims to accelerate the advent of wave energy by opening the innovation process to the open source community by implementing an open business model, which facilitates the technology development, providing free use of patents by other competitors (wave energy technology developers), the ones who are in the project consortium or additional companies willing to join in the future.

Keywords—**Marine renewable energy, wave energy converter, power take off, open hardware model, business model.**

I. Introduction

THE concept of free sharing of technological information can be applied not only for software components but also for physical equipment or hardware. In the early years of automobile development, one enterprise owned the rights to a 2-cycle gasoline engine patent originally filed by George B. Selden. [1] By controlling this patent, they were able to monopolize the industry and force car manufacturers to adhere to their demands, or risk a lawsuit. In 1911, independent automaker Henry Ford won a challenge to the Selden patent. The result was that the Selden patent became virtually worthless and a new association (which would eventually become the Motor Vehicle Manufacturers Association) was formed [1]. The new association instituted a cross-licensing agreement among all US auto manufacturers: although each company would develop technology and file patents, these patents were shared openly and without the exchange of money between all the manufacturers [1]. By the time the US entered World War 2, 92 Ford patents and 515 patents from other companies were being shared between these manufacturers, without any exchange of money (or lawsuits).

Although many examples like the previous one can be found with any form of tangible products including machine tools, medical equipment or electronics [2] the concept of open source became known worldwide because of the open software, the first example of free and open-source software is believed to be the A-2 system, developed at the UNIVAC division of Remington Rand in 1953 [1] which was released to customers with its source code but the massive and widespread distribution of this kind of software started in the early 80s with the GNU project [3] which mixed with the Linux kernel in 1993 made the first complete free software operating system.

Just like Henry Ford did 108 years ago SEA-TITAN project is aiming to develop and share a crosscutting free-licensing power take-off among all wave energy technology developers worldwide within the limits of SEA-TITAN open platform, this is expected to be the starting point of a huge technology boost for the wave energy.

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II. TECHNOLOGY

It's hard to explain the innovation involved in the proposed business model without explaining some bits about the technology being developed along with it.

This section presents an analysis of the state of the art on wave energy that will help to better understand what specific key point is affected by the technological development undertaken in the SEATITAN project and the effects this has on the business models currently used by the different developers.

A. Wave energy technology

In the same way that a wind turbine transforms the kinetic energy of the wind in mechanical energy of rotation through the blades and this one in electrical energy through the electrical generator, a wave energy converter transforms the kinetic energy from the waves in mechanical energy through the wave energy converter (WEC) and this one in electricity through the power take-off (PTO).

In the wind energy sector, there is a predominant typology over the rest, the three-bladed horizontal axis turbine, not so for wave energy, where there is a wide spectrum of options for both converter and PTO without a clear predominant. Over 1000 wave energy conversion techniques have been patented in Japan, North America and Europe [4].

This generates a great feeling of uncertainty and little reliability when thinking about this type of solutions, creating a vicious circle where each individual developer believes he is in possession of the definitive technology that will achieve commercial success, promoting the unique patent concept.

SEA-TITAN is here to break that circle, a group working together for the sake of the wave energy technology, developing a new product through collective intelligence [5], and the free use of patents thanks to the SEA-TITAN platform. External companies will be encouraged to join and collaborate with the project consortium members, giving or receiving feedback about the technology or just requesting access to the patents free of charge.

1) Wave Energy Converters

Despite the great number of different technologies for harvesting wave energy all of them can generally be categorized on the basis of three criteria (Fig. 1) [6-9]:

1.1) Location

According to the relative distance between the device and the coast:

Onshore: Located in shallow water, these converters are usually integrated in a breakwater, dam, fixed to a cliff, or rest on the seabed. The distinctive characteristics for these converters are easy maintenance and installation. The drawbacks are that coastline waves have less energy than deep-water waves along with a potential coastline reshape.

Nearshore: They are installed a few hundred of meters from the shore in moderate water depths. Their deployment and maintenance expenses are limited since they don´t need mooring systems as they usually rest on the seabed.

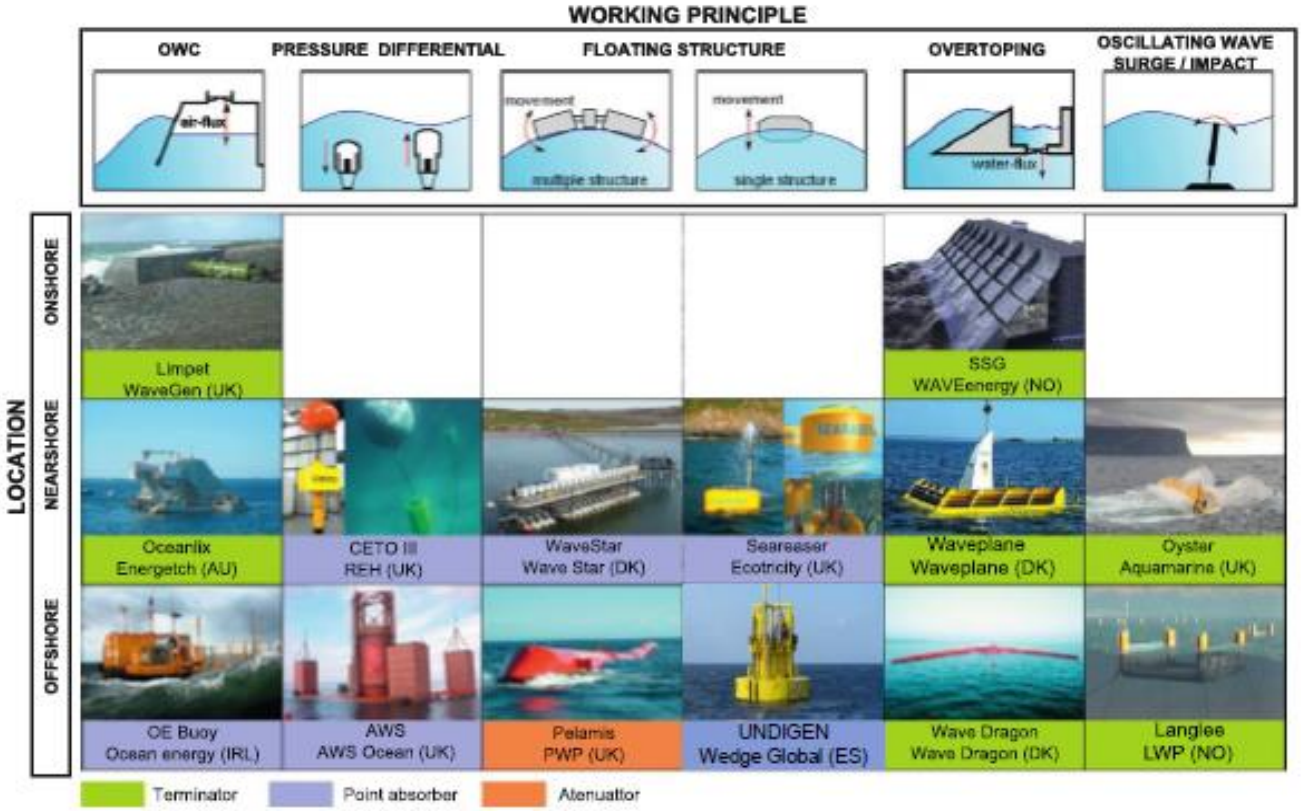

Fig. 1. Selection of existing WEC according to the classifications introduced in the text. Reprinted from [6] with modifications.

Offshore: They are placed in deep waters far from the shore. They are able to harvest energy from the most energetic places but installation and maintenance can be much more expensive.

1.2) Dimensions of the prime mover and orientation with respect to the wave (Fig. 2):

Attenuators: the length of the device is of the same order of magnitude (or larger) than the wavelength, these devices are oriented in such a way that they are parallel to the incident wave.

Terminators: Similar in dimensions to attenuators, but placed in perpendicular to the incident wave.

Point Absorbers: Axisymmetric devices capable of harvesting waves from any direction, known as antenna effect, their dimensions are usually an order of magnitude lower than the wavelength.

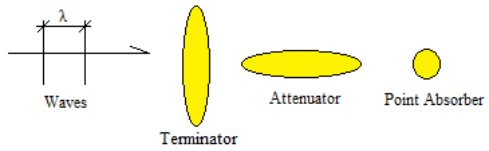

Fig. 2. Classification according to device dimensions and orientation. Reprinted from [7].

1.3) Working principle

Oscillating water column: For this technology, it is not the waves that move the turbines directly, but a mass of compressed air pushed by said waves. This is a structure generally located in a breakwater, but there are shore-based and floating models the upper part of which forms an air chamber (hence the compressed mass), and the lower part of which is submerged in water. In this way, the turbine takes advantage of the movement caused by the wave both, when it comes and when it goes. It has been suggested that one of the advantages of the oscillating water column concept is its simplicity and robustness [10]. A common example is Oceanlinx device deployed in 2005 designed to sit in shallow water with approximately 21 meters wide and 24 meters long.

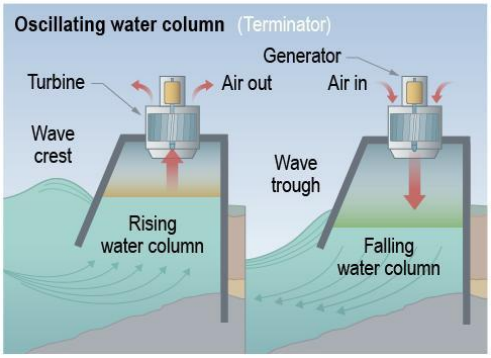

Fig. 3. Oscillating water column working mode of operation [11]

Floating structures: It is based on a floating body or bodies, which are moved by the waves vertically, horizontally, pitching or in any combination of the three. The relative movement between different parts of the device allows converting it into electricity. These kinds of devices are rarely named as *floating structures* but using the dimensions with respect to the wave: *attenuators* or *floating-point absorbers*. Multiples examples can be found for these kinds of technology, Pelamis was an attenuator floating structure deployed during 2007, the machine consists of a number of semi-submerged sections linked, these sections moved relatively when the waves pass along the length of the machine. W1 is a point absorber floating technology deployed during 2014, the machine has two main bodies linked without restrictions in heave motion that allows the relative movement between them (Fig. 4).

Pressure differential: This kind of technology can be explained as a combination of two technologies working together: oscillating water column and floating point-absorbers. This is because it uses the working principle for both: difference of pressure and vertical relative movement between parts, the sea bed fixed air-filled cylindrical chamber and the moveable upper cylinder. When a wave crest passes over the device, the water pressure above the device compresses the air within the cylinder, moving the upper cylinder down creating a relative movement in the same way as in punctual absorbers, this happens in the opposite way when a trough passes over. Potential advantages of these devices include: better survivability, they are not exposed to splash zone corrosion, nor the various hazards that could take effect when floating on surface, and reduced/negligible visual impact. Maintenance of the device is a possible issue however. These devices are typically located nearshore. A good example of evolution with pressure differential technology is Carnegie Clean Energy device: CETO, deployed in 2015 CETO 5 only served the purpose of deliver pressured water for reverse osmosis membranes in the desalination plant, but CETO 6 (still in development) will include electrical generation onboard as explained in this document.

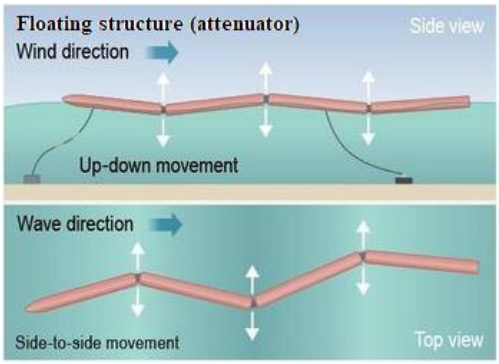

Fig. 4. Floating structure with multiples bodies, mode of operation. Reprinted from [11]

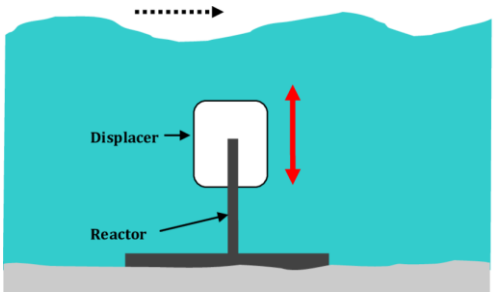

Fig. 5. Pressure differential, mode of operation [12]

Overtopping devices: These devices collet the water from the incident waves into a reservoir in order to move one or more reduced jump hydraulic turbines (usually Kaplan turbines), taking advantage of the potential energy of the waves to convert it, through synchronous generators, into electrical energy. Within this type of device, we can distinguish between converters with a fixed structure located on the coast (onshore), and those with a floating structure far away from it (nearshore-offshore). A common example of these kind of devices is the Wave Dragon [14], which is characterized by having a reflector that directs the incident waves towards a ramp to the reservoir above sea level.

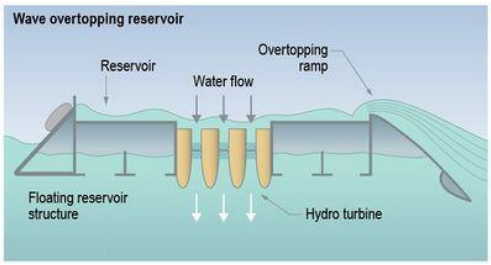

Fig. 6. Overtopping, mode of operation [11]

Oscillating wave surge: These devices typically have one end attached to a fixed structure or the bottom of the sea while the other end is free to move, a hinged deflector, this part is positioned perpendicular to the wave direction (terminator). The axis of the deflector (or paddle) oscillates like a pendulum mounted on a pivoting joint in response to the impact of the horizontal movement of the wave particle. They often come in the form of floats, fins, or membranes. This working principle is similar to the Japanese 'Pendulor' system [9]; however, these devices uses resonance of the water column rather than harbour resonance as its operating principle. An example for this kind of technology is the Aquamarine Power Oyster, a nearshore device, where the top of the deflector is above the water surface and is hinged from the sea bed.

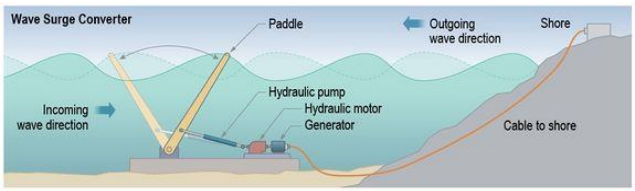

Fig. 7. Oscillating wave surge, mode of operation [11]

2) Power take-off systems

Currently there is a wide variety of power take-offs that can be applied to different wave energy converters, generally each power conversion chain is associated with a specific type of wave energy converter.

As shown in Fig. 8 there are three main alternatives to obtain electricity in the wave power conversion chain (PCC), to convert wave energy into relative linear motion, relative rotary motion or fluid capture. The greatest variety can be found associated with the rotary electrical generator path but these technologies imply a lot of intermediate steps: pistons, accumulators, air chambers or mechanical gear systems.

The number of intermediate steps in the PCC affect two main factors:

Efficiency: The greater the number of intermediate steps, the greater are the mechanical and transformation losses that we obtain as a result of the PCC, this causes a reduction in the annual energy production (AEP), which affects the levelized cost of the electricity (LCOE), increasing it.

Reliability: The offshore equipment undergoes an accelerated degradation in comparison with the same

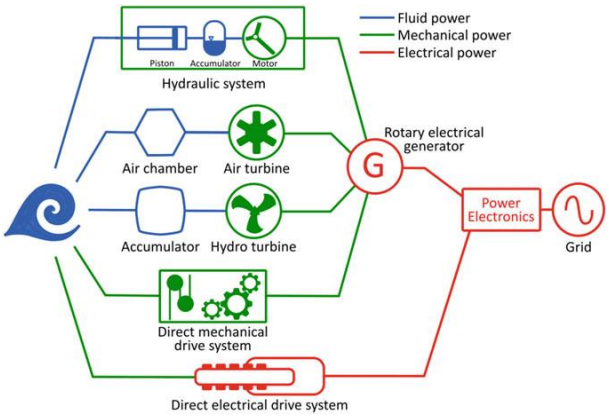

Fig. 8. Wave energy to electricity conversion paths [14]. This graphical classification is reprinted with cosmetic changes by a several number of references [6,14-16]

equipment implemented within a ground installation due to the high salinity of the maritime environment where it is implemented. This fact makes it desirable to minimize the amount of equipment to monitor and maintain while the equipment is in operation.

Direct drive electrical systems avoid all of the intermediate steps, which make the preferable technology for wave energy converters, over any other PTO solution.

B. SEA-TITAN technology

The project builds upon Wedge Global W200 power take-off [17] aiming to develop a new generation of direct drive linear generator, with two main characteristics:

Improved efficiency: A new PTO machine is proposed to overcome the previous W200 limitations based on two concepts: Multi-translator topology and azimuthal magnetic configuration to optimize adaptation to the WEC geometry. The resulting machine is named Azimuthal

Multi-translator Switched Reluctance Machine (AMSRM). In addition, a long-term solution based on superconducting technology will be analyzed, although is not the core activity of the project. The solution proposed in SEA-TITAN requires no failure-prone gearing or expensive material such as rare earth magnets. It is based on the very well-known concept of magnetic reluctance, which is especially appropriate for the application of a linear electric machine with a long translator, as it is the case of interest for wave energy generation.

Crosscutting technology: As explained above, the technical objective of SEA-TITAN is the development of a new power take-off technology. PTO technology usually associates its power conversion chain path (rotary, linear or fluid collection) to a specific type of wave energy converter, this is partly true, an example would be the oscillating water column or the overtopping technology

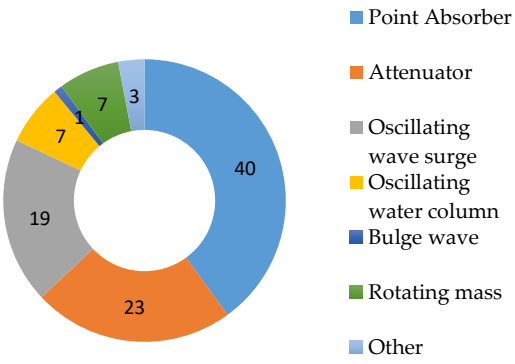

Fig. 7. Fig. 9. R&D effort for wave energy technologies. Nuno Filipe internal analysis.

that implies the required power conversion chain to be fluid capture (compressed air or water respectively), but other wave power conversion chain paths can be applied in a wider spectrum of devices, in particular the technical object of SEA-TITAN, the direct drive linear generators can be applied to different types of devices: floating structures, pressure differential and wave surge. Currently, the project focuses on floating devices, specifically point absorbers, which are the most commonly investigated and deployed kind of devices as shown in figure 9.

This technology focus in SEA-TITAN is well align with the wave energy converter (WEC) developers that are partners in the project: Corpower, Hydrocap and Centipod. All of the companies offer point absorber or multi-point absorber solutions for collecting wave energy. Although Wedge Global can be seen as a WEC developer its role for SEA-TITAN is power take-off developer and coordinator for the open platform.

III. BUSINESS MODEL

C. Open Hardware

The technology developers involved in SEA-TITAN, listed before, are competitors in a more traditional business model approach, where each company focus on the study of its own wave energy converter and associated power take-off, conducting the necessary studies to demonstrate that it is better than the technology of its rivals, patenting it and converting it into an active value for the company.

SEA-TITAN will break this unproductive trend for a sector as weak, dispersed and lacking of standards as the wave energy sector. A disruptive breakthrough is going to be generated in business models based on *open hardware* where methods and work environments from open source software (OSS) [22] are translated into hardware environments by opening the innovation process to the open source community, SEA-TITAN can profit on the technology side through comments, ideas, and further developments. Through this, firms can improve quality and applicability of their technology [18]. Moreover, the open source concept allows the developers to base their developments and contributions on an already existent basis of technology, as Isaac Newton himself acknowledged, "*If I have seen far, it is by standing on the shoulders of giants*", [19] explains how to divide joint profit among innovators when one innovator's technology builds on another's.

Complementary products and services such as monitoring, training, maintenance, consultancy, and certifications will play a major role to achieve competitive advantage [20].

D. Open platform

Two key concepts have already been introduced in this paper which are an indivisible part of the technology core of the SEA-TITAN platform: quality and standardization.

Wedge Global in conjunction with certifying entities will provide a *seal of quality* for every power take-off manufactured through the use of the open access patents offered on the SEA-TITAN platform, this will ensure the optimum performance of the PTO for the final users, granting a degree of reliability and standardization that does not exist in the sector in these days.

SEA-TITAN will generate a nexus platform between the different key parts of the wave energy sector: WEC technology developers, industrial manufacturers and energy utilities.

WEC technology developers will have free and guaranteed access to all information contained in the open platform, including improvements and variations that have been developed as a result of different interactions with the development community or requirements perceived by the end users of the devices, along with this information there will also be a pool of companies certified in the manufacturing processes of the machines under a new standard of quality criteria supervised by Wedge Global.

Since this platform provides a free and unlimited access to patents, there may be cases of development by third parties with new solutions based on SEA-TITAN but that have not followed all the protocols and standards developed on the platform, these new iterations would

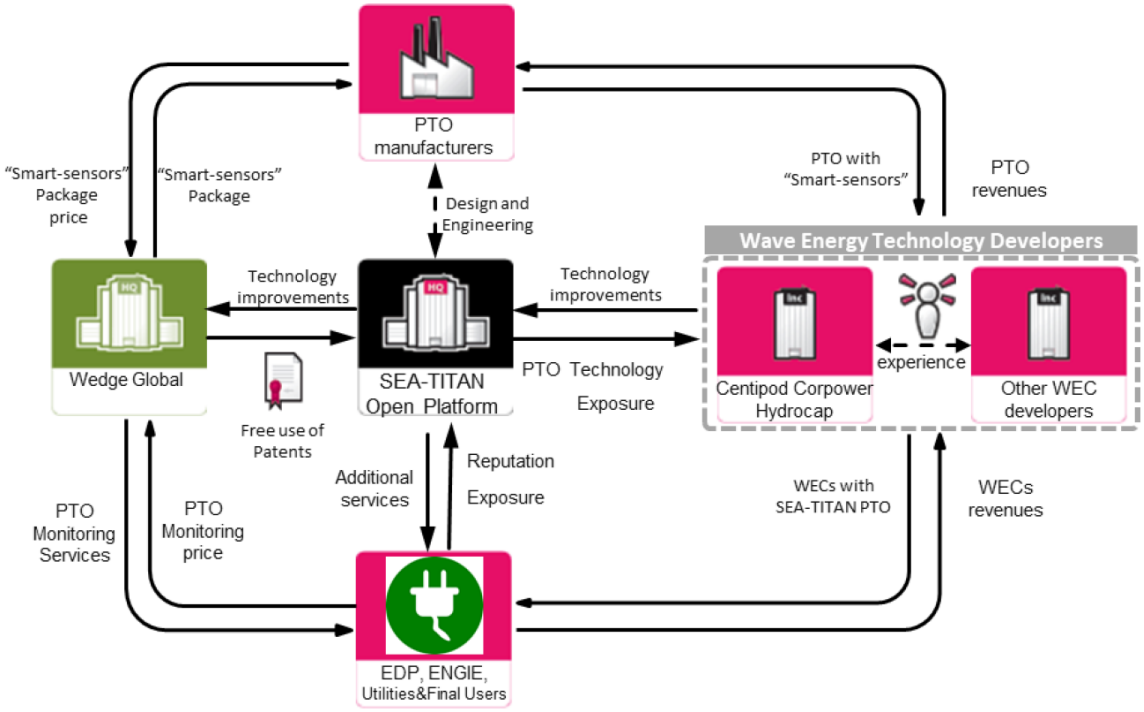

Fig. 10. SEA-TITAN Open Platform concept. Key stakeholders interaction to accelerate wave energy deployment. Block source: Board of Innovation.

lack of two main characteristics that the sector needs to evolve in the following years, reliability in the form of standardization and a quality seal.

The supervision by Wedge Global does not stop at the certification in the construction processes ensuring the quality chain, but goes beyond, all PTO's that have been built under the seal of SEA-TITAN will have a direct supervision in operation that gives a higher degree of reliability to the process, always ensuring optimal operation of the machine for any location or device where it has been installed. In spite of offering the use of patents free of charge, offering the quality seal and the operation monitoring as a service generates an economic flow allowing the sustainability of the platform.

E. Innovation

According to D. Burkus [21] innovation is the application of ideas that are both novel and useful, wave energy sector is still unmatured but it is rapidly evolving, almost every day we can find a novel idea about new ways to harnessing the wave energy, conversion chains, hybrid systems or controllability functions that could drastically change the reality of the sector, but not all of them can be considered as innovation because of that *useful* term of the equation. Being useful or relevant implies that said novelty can be applied efficiently to the product, solving a problem present in an earlier stage of development. Applying this innovation concept to SEA-TITAN we can consider the concept of open hardware for wave energy as a *novelty* because of: 1) the free use of patents by any wave energy technology developer and 2) the quality standards and crosscutting technology being technically developed within the project.

Open business model for PTO equipment can be implemented in a practical way solving at the same time the main *problems* identified in the wave energy sector, adding value in two ways: 1) reducing costs and increasing reliability through the use of standardized, certified and mass-produced equipment at industrial level and 2) increasing energy production through lifetime monitoring to optimize performance.

IV. SUMMARY

The implementation of this business model in the current sector is a disruptive change of the classic model where each developer makes use of his own idea without becoming concerned about minimum standards of standardization or quality

Creating an open hardware platform which enables the free use of patents will allow technology developers to manufacture and implement a reliable and optimized PTO system in their WEC that will be subsequently monitored to ensure optimal performance, this implies a large increase in the global reliability of the system, a reduction in costs because of the serial production and an increase in efficiency due to the performance monitoring by the specialized team of the platform.

This business model and the new platform will make possible to advance the state of the art in the wave energy sector addressing once and for all the three main barriers the sector faces on a daily basis: high costs, low reliability and low production.

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