PROCEEDINGS OF SPIE

SPIEDigitalLibrary.org/conference-proceedings-of-spie

Wave energy: history, implementations, environmental impacts, and economics

Hangfei Li, Xiwen Sun, Hui Zhou

Hangfei Li, Xiwen Sun, Hui Zhou, "Wave energy: history, implementations, environmental impacts, and economics," Proc. SPIE 12326, 2nd International Conference on Materials Chemistry and Environmental Engineering (CONF-MCEE 2022), 123260N (5 August 2022); doi: 10.1117/12.2646119

Event: 2nd International Conference on Materials Chemistry and Environmental Engineering (CONF-MCEE 2022), 2022, ONLINE, United States

Wave Energy: History, Implementations, Environmental Impacts and Economics

Hangfei Li*[a], Xiwen Sun[b], Hui Zhou[c]
[a]School of Mechanical Engineering, Tianjin University, Tianjin, 300354, China
[b]Shanghai Weiyu High School, Shanghai, 200231, China
[c]Shanghai Foreign Language School Affiliated to SISU, Shanghai, 200083, China

ABSTRACT

The ocean, covering 70% of the earth's surface, is regarded as one of the largest reservoirs of renewable energy. Especially, the waves, with violent fluctuations, are widely distributed on the ocean, producing enormous energy yet to be fully exploited. Wave energy is known as clean, renewable energy in the global energy field with broad prospects. Its wide distribution, enormous content and high quality enable the wave energy to possess tremendous potential value in the global energy market. However, the wave energy faces the inevitable issues of relatively low efficiency and instability, and it still requires further scientific researches and more practical tests before fully exploiting the potential value. In this report, the development and current situation of wave energy are mainly discussed, including the history, implementations, environmental impacts, economics. Our group aims to gather comprehensive information about the wave energy, analyze the multiple impacts of the implementations and find out the promising field in the future development of wave energy.

Keywords: Wave energy, Development, Implementations, Multiple Impacts

1. INTRODUCTION

Wave energy refers to the potential and kinetic energy from the fluctuation on the ocean surface. This kind of energy can be utilized when certain devices capture the movement of the waves and convert it to other motion to produce electricity or other forms of energy. Although the first concept of utilizing wave energy was proposed in late 18th century, it is not until 1970s when further scientific researches in worldwide scale were conducted and wave energy technology grew rapidly. The history of wave energy has indicated that this development can heavily affected by the global situation of energy field. With a relatively short history of modern development, only a small number of wave energy technology has commercialized and occupied the international energy market, which means the wave energy still has a long path to go. However, with the demand for clean, renewable energy growing rapidly and further innovative experiments being conducted, the wave energy technology still has a bright future facing these favorable conditions.

2. HISTORY

2.1 First utilization of wave energy

The first concept about utilizing wave energy could date back to 1799, when a Frenchman Girard applied for a patent of wave energy technology [1]. In 1910, a Frenchman named Busso Belasek invented a power station driven by wave energy, which provided 1000-watt electricity for his buildings. The power station generated power through a pneumatic wave device which could compress or drain the air with the power from the fluctuation of waves and push a piston to do reciprocating motion, which was converted into the rotation of the turbine to produce electricity.

* Corresponding author. Email: dandelion1024k5@163.com
These authors contributed equally to this work and should be considered co-first authors.

2nd International Conference on Materials Chemistry and Environmental Engineering (CONF-MCEE 2022),
edited by Shuai Chen, Proc. of SPIE Vol. 12326, 123260N

2.2 First commercialization of the wave energy devices

In 1940s, the famous Japanese inventor, Yoshio Masuda, conducted substantial researches about the implementation of wave energy and soon invented a new type of oscillating water column device to generate power for navigation buoys [2]. This new device utilized the wave energy by absorbing and compressing the air to drive the generator to provide electricity. In 1965, this kind of buoys charged with wave energy was commercialized and put into quantity production. These products, whose rated power ranged from 60 watts to 500 watts, were popularized in the Japan market and exported to various countries. This is the first successful commercialization of the wave energy devices and it has become one of the minor commercialized wave energy facilities in current international market.

2.3 Further researches to wave energy in 1970s

In 1970s, as the oil crisis continued to influence the international energy field, numerous researchers began to focus on the study of renewable energy and then discovered the tremendous potential market of wave energy. Among these early researchers were Stephen Salter from Scotland, Kjell Budal from Norway, and Michael E. McCormick from America[3].In 1974, Stephen Salter of the University of Edinburgh published an article titled Wave Energy in the Nature magazine, arising much attention of international scientific research institutions to the development of wave energy[1].Many countries with huge amount of wave energy, including the UK, Japan and Norway, have considered the wave energy as a significant solution to energy crisis and invested much funding and manpower in wave power researches. During the 1970s, the "Hamming" wave power test ship from Japan succeeded in generating 190,000 kWh per year, and accomplished small-scale power transmission from offshore floating wave power plants to land. In 1976, Japanese Yoshio Masuda conducted more experiments about the combination of diverse types of wave energy devices [4]. The output efficiency, however, was not much improved, indicating that the large-scale utilization of wave energy still had a long way to go before the technology reached its maturity.

2.4 Development of wave power in the late 20th century

In the early 1980s, the fall in oil prices caused the decline of funding for wave energy [4]. For example, in 1982, the Department of Energy in UK cut down the sponsorship in wave energy technology [2]. However, certain researchers still conducted many experiments on the prototype and sustained other wave energy projects. In 1985, Norway conducted sea trials of two prototypes with power of 350 kW and 500 kW. In 1989, a prototype of oscillating water column converter, with power of 75 kW, was installed on Islay in Scotland [2]. Meanwhile, Japan and India have also installed wave energy devices of 60 kW and 125 kW respectively. In the 1990s, more politicians realized the potential market of wave energy and appealed for more funding and sponsorship to conduct further researches. Especially, European Union has launched an initiative to support the development of wave energy and soon established the European Wave Energy Thematic Network.

2.5 Current situation in 21st century

In the 21st century, the wave energy technology has gradually stepped in its maturity. Tremendous international interest in wave energy technology has grown since the 2000, as commercial investors and the government in different countries have put much more investment into the wave power. Scotland and Cornwall have both set up marine energy centers, offering facilities for researchers to conduct sea trials. In 2007, the oscillating float wave power station Aqua Buoy in Canada conducted the sea trial on the coast of Oregon, USA and this device proved to have high capture efficiency and application value in the device. Nowadays several devices have successfully industrialized and commercialized in the international market. At present, the most advanced wave energy equipment is the Pelamis generator in the United Kingdom, which has basically accomplished international commercial application.

3. PHYSICS PRINCIPLES

Wave energy is produced when the wind glides over the ocean surface and causes fluctuations to the waves. Actually, it comes from the kinetic energy of the wind, as a result of energy transformation. The wave energy includes kinetic energy produced by the movement of the water and potential energy resulting from the height difference relative to the sea level when the water is displaced.

Wave energy is transformed into electricity by the wave energy converter (WEC). Usually, it is utilized when the converter alters the fluctuation of waves into the rotation of a propelling turbine, which is connected to a generator to create electricity.

The wave model is shown in figure 1.The energy of a wave is related to the wavelength (λ) , height (H) and period (t).Theoretically, the energy is proportional to the square of the height, the period, and the width of the frontal surface. Approximately, the power per unit wavefront width, P(in kW per meter) can be estimated through the empirical formula, $P= 0.5H^2t$. H refers to the height (in meters) and t refers to the wave period (in seconds).

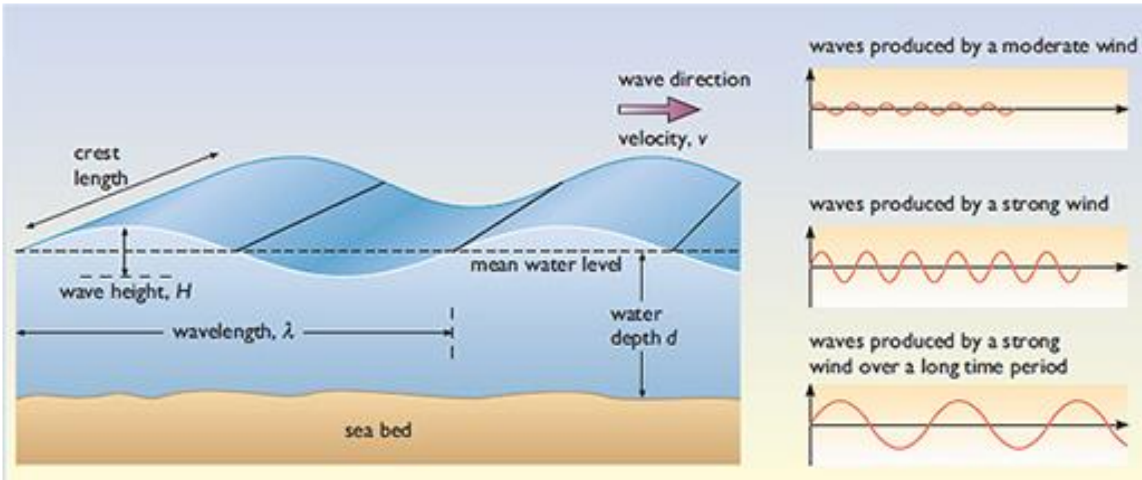

Figure 1: Wave model [5]

4. IMPLEMENTATIONS

Figure 2 shows the classification of wave energy converters by device dimensions and orientation:

Terminators: The principal axis is parallel to the incident wave. The length of the device is in the same order of magnitude (or greater) as the wavelength.

Attenuators: The principal axis is perpendicular to the incident wave, usually the same dimension as terminators.

Point Absorbers: The principal axis is perpendicular to the ocean surface, and can draw energy with a very small size compared to the former ones, known as antenna effect.

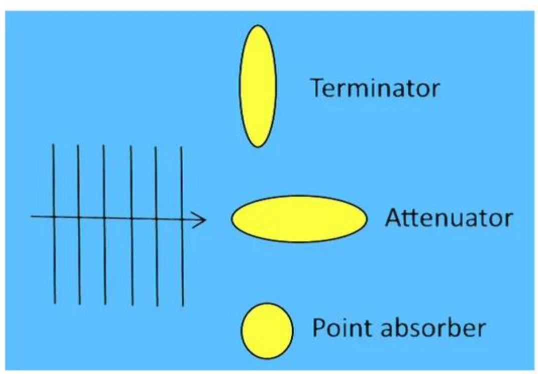

Figure 2: Classification according to device dimensions and orientation. [6]

4.1 Oscillation Water Column

Oscillation Water Column (OWC), classified as terminator, is the most common type of the wave energy devices used currently. This device is often built near the sea bottom, and fits well regardless of the location is near or far from the coast. The wall named breakwater serves the function of protecting the coast and enclosing the chamber. The wave pushes water into the chamber, and the troughs and crests produce high-velocity airflows with different directions through the wells turbine to generate electricity. The wells turbine, whose details will be thoroughly explained in the next part, is a specific device broadly used by OWC generators.

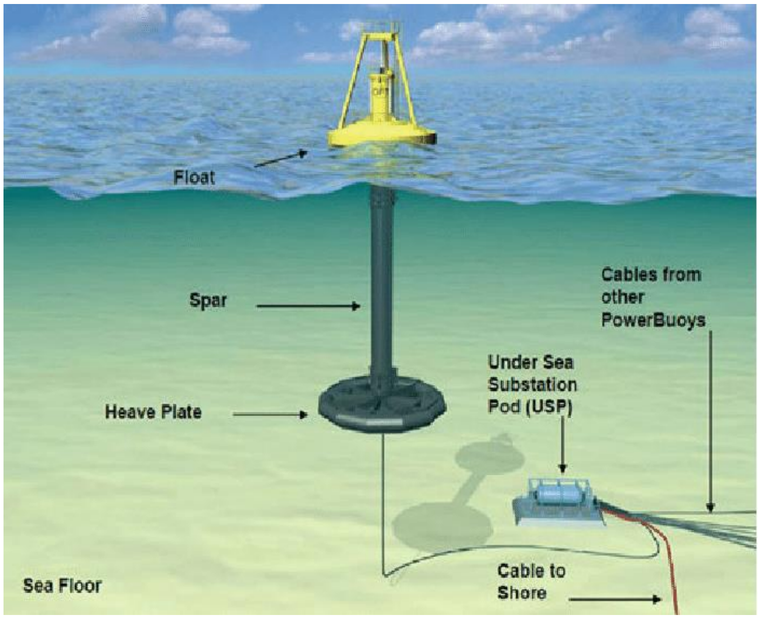

Figure 3: Point Absorber Buoy [1]

4.2 Point Absorber Buoy

As shown in Figure 3, most parts of the point absorber buoy are submerged by sea water, except for the float floating. Therefore, this kind of device is commonly constructed off-shore with deep sea water but near the surface. As a single point in the ocean, the float can easily extract kinetic energy through the oscillating cycle of the waves from all directions, and then deliver the vertical translational motion and generate electricity under the surface. Not disrupting each other, the point absorber buoys always appear as clusters, tethered or chained, with the purpose of fully utilizing the wave energy.

4.3 Attenuator

As shown in Figure 4, it is oriented parallel to the direction of wave travel. This wave energy device has components of four tubes, which will bend when a wave hits this device. The main tubes consist of a nose tube, end tube and two mid tubes. The topical example for this type is Pelamis. Additionally, with the movement of the waves, the hydraulic cylinder can pump high-pressure oil through motors.

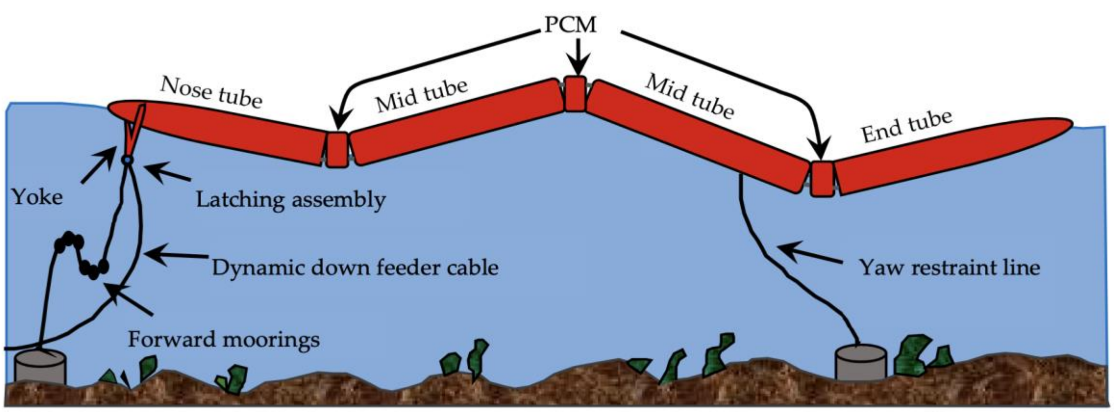

Figure 4: Attenuator wave energy harnessing device [7]

5. DETAILED DESCRIPTION OF ONE SYSTEM

Oceanlinx has put into operation a powerful wave power plant. The power plant's capacity was 1 MW. This station is located not far from Port MacDonnell, of course, off the coast. Despite the fact that the power plant is working and producing electricity, it is considered a test sample, in the image and likeness of which, in case of successful testing, other power plants will be built. Figure 5 shows the wave power station from Oceanlinx.

Figure 5: A Wave Power Station in South Australia [8]

The station was tested for 12 months. Now the station is connected to the general power grid of the region, after passing a series of tests, a little later in 2013. In the following year, the project was expanded by installing more wave converters called green WAVE. The plant's capacity has increased to 10 MW.

Of course, such a system is very complex, but everything is realizable. The station stands at the bottom of the sea, rising from the water by about 10-15 meters. The designers opted for a solution that requires little or no transformation of the seabed to create the foundation. This made it possible to reduce the impact of the construction on the environment.

The total cost of this station is not that great: $ 8 million. Part of the amount was provided by Oceanlinx, part (4.4 million US dollars) was provided by the agency (ARENA Australian Renewable Energy Agency).

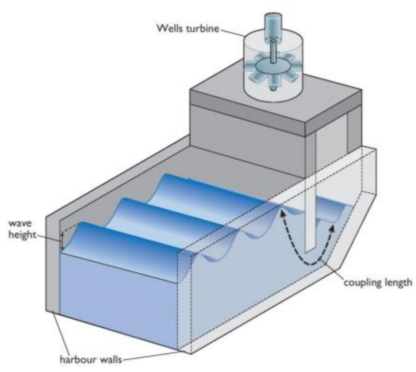

Figure 6: A resonant oscillating water column [9]

As shown in Figure 6, resonant OWC is used in the power station to generate electricity from wave energy. Most wave energy devices are resonant systems – they have a natural resonance period or time over which they repeat their motion. The resonance effect was originally a physical definition, and the pendulum oscillates at the natural frequency. When external disturbance happens, the corresponding oscillation law depends on whether the disturbance frequency is consistent with what it wants.

The resonant OWC's principle of operation (see in Figure 7) is based on a system of air ducts, through which, due to the action of waves, air enters the turbine, forcing its blades to rotate.

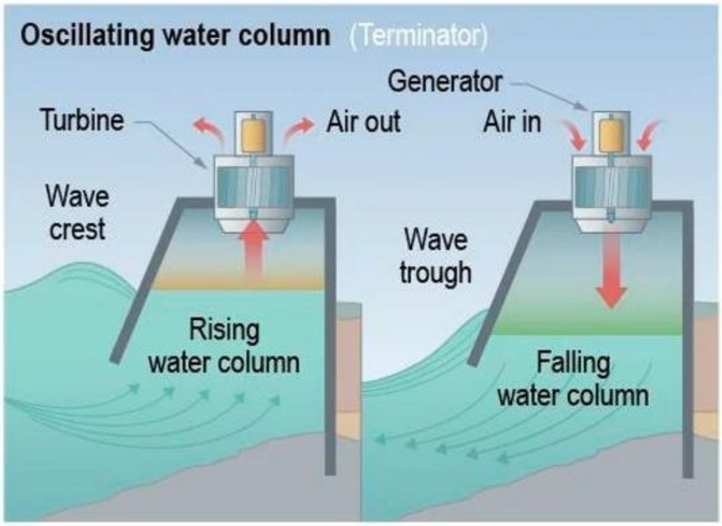

Figure 7: Oscillating water column working mode of operation [10]

As is mentioned in the third part, this OWC system is classified as terminators. In the system, the wave troughs and crests compress the air in and out the devices, and then the oscillation cycle of the wave makes the Wells Turbine work.

Wells Turbine (see in Figure 8) is a type of low-pressure air turbine. In a compression chamber, the turbine turns in the same direction, no matter in which direction the flow from the rising or falling water column passes through it. The Wells turbine features symmetrical airfoil blades, which allow it to keep the direction of rotation and airflow perpendicular. In addition, in Wells turbines, symmetrical airfoil blades have a higher Angle of attack (i.e., a lower blade/airflow velocity ratio). Wells turbines have efficiencies between 40% and 70% in oscillatory flows.

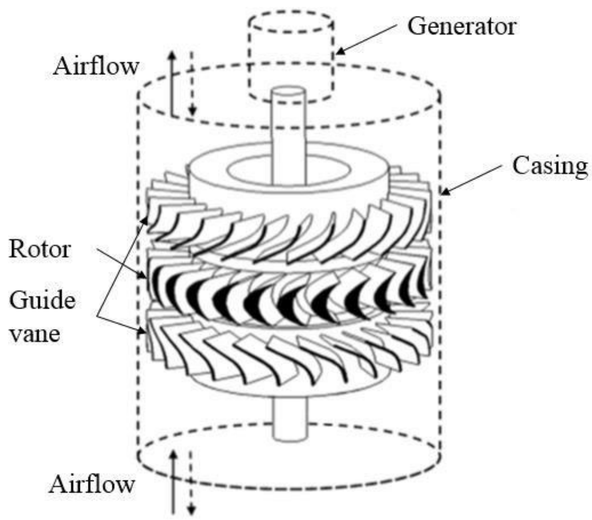

Figure 8: Wells Turbine [11]

The rolling Wells turbine then activates DFIG (doubly-fed induction generator), which is commonly used in wind energy and hydropower station to generate electricity. Figure 9 shows a DFIG-based OWC.

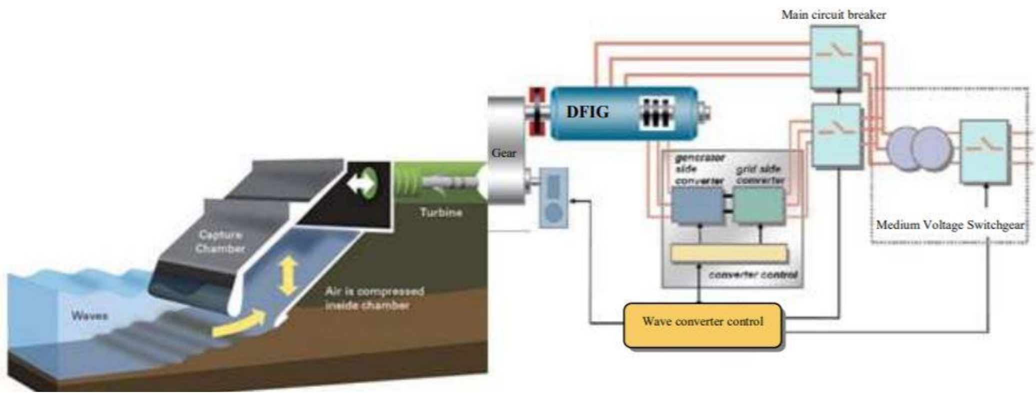

Figure 9: An illustrative example of DFIG-based OWC [12]

DFIG: The generator mainly consists of two parts: motor body with stator rotor and bearing system, and cooling system which can be divided into water-cooled, air-cooled and air-water-cooled structures.

The generator consists of a winding induction generator with stator windings directly connected to a fixed-frequency three-phase grid and a two-way back-to-back IGBT voltage source converter mounted on the rotor windings. “Doubly-fed” means that the stator and rotor can exchange power with the grid. The system accepts variable speed operation over a limited wide range. The converter compensates for the difference between the mechanical and electrical frequencies by injecting rotor current into the converter.

The converter consists of the rotor-side converter and grid-side converter. The rotor-side converter controls active and reactive power through the rotor current component, and the grid-side converter controls the DC bus voltage to make sure the converter operates at a uniform power factor.

It depends on the operation conditions of the transmission chain whether the power is fed into or extracted from the rotor. The power is fed in the super-synchronous state and extracted in the under-synchronous state.

The stator feeds into the grid in both cases.

As for advantages, first, the active power can be decoupled from the reactive power control through independent control on the rotor excitation current. Second, it is excited from the rotor circuit rather than grid. Finally, it can produce and transmit reactive power to the stator through the grid-side converter.

6. ENVIRONMENTAL IMPACT

Wave energy has less environmental impacts since there is no need to construct the access road. However, it still impacts on the environmental factors of wave, ecological system like marine animals, shipping and navigating, and so on [13].

6.1 Effects on the marine ecology

There are many parts about ecology: marine birds, marine mammals, benthic ecology, fish and shellfish [14]. The disturbance and noise during installation and operation of devices will affect marine species for their life. Also, there is a risk of collision with devices during forging, feeding and migrating. This wave devices probably will make water contaminated, which will have negative influence on marine species. Marine birds also face a risk of increasing mink predation. For marine mammals, the wave device will be a barrier to move due to avoidance reactions. The habitat of fish and shellfish will be excluded with the presence of devices.

6.2 Effects on the sea

First, when shipping and navigating on the sea, there is a risk of collision with installation vessels, equipment and operational devices due to their design making them difficult to detect by both eye and by radar. And there will be a reduction in the safety of navigation. Next, wave energy will have effect on benthic energy. The wave devices will increase suspended sediment from seabed disturbance during device installation and cable trenching. Additionally, there will be a risk of smothering from seabed disturbance. The substratum will loss by attaching devices to the seabed.

Wave energy has many advantages including but not limited to availability, which can be mainly divided into three parts: emission benefits, tourism stimulation and location. The wave energy converters are built in the sea. Therefore, there will be no reduction of efficient agricultural area and effect on agriculture. Also, wave energy will help islands maintain high-quality environment and sustainable development since the sheltered water behind the wave energy converters can be used for water sports like scuba diving and canoeing. Additionally, the wave energy grid is environmentally friendly and can be easily assimilated. Finally, it reduces greenhouse gases emissions.

7. SYSTEM ECONOMICS

The huge amount of wave energy shows the essential value of utilization. According to the "Ocean Energy Development" published by UNESCO, the magnitude of global wave energy resources is 10^6 MW [15]. Additionally, wave energy has unique advantages of high-grade energy, wide distribution and its power density, averaging 2-4 $\mathrm{kW/m^2}$, is much higher than other renewable energy, like wind energy and solar energy [16], indicating a huge economic market. Many projects have been put in practice to fully exploit the potential commercial value.

The Agucadoura Wave Farm was the world's first wave farm, which was near Povoa de Varzin, north of Porto, Portugal. The technology type of this farm is Pelamis, which is a floating articulated attenuator. In July 2008, the first phase started generating electricity, and the installed capacity of this farm was 2.25MW. At that time, there were only three Pelamis machines of 750kW. The cost is approximately 11.5 million dollars, and 2.25MW can power approximately 1600 homes per year [17]. The second phase of this project plans to exist to extend to 30 Pelamis machines, which have an installed capacity of 22.5MW. However, the second phase of this project has not been reached. As a result, this power plant is relatively small or medium size.

The South West England Wave Hub is a different example, which is located in the southwest of England. The technology type is electrical grid connection point into which different kinds of wave energy technologies can be connected. This plant has an installed capacity of 20MW. The total cost of it is 28 million Euro, which is equal to about 33 million dollars [18]. These two plants are on a different scale and have different productivity and cost. There will be more costly in large-scale wave power plants since they need more devices to generate electricity.

The greenWAVE, a commercial wave power plant, is located off the coast of South Australia at Port MacDonnell. The device uses oscillating water column and air turbine technologies to generate electricity. It has a capacity of 1MW, and its potential energy capacity can rise to 10MW. This wave energy demonstrator has a cost of 8 million dollars, with 4.4 million dollars of which supported by ARENA, Australian Renewable Energy Agency.

Another wave energy station called Bermuda Wave Buoy was deployed by Carnegie Wave Energy Limited and its Bermudan based partner Triton Renewable Energy Limited. This station used CETO to convert wave energy. The buoy was deployed in 25m of water on the eastern side of Bermudan and had cost the government 16 million dollars. Its initial capacity was 2 MW, but Carnegie and Triton proposed to produce 20MW of electricity by developing a commercial-scale wave farm.

For actual economics impacts, the wave energy provides more available energy since there is about 8000–80,000 TWh/year or 1–10 TW of wave energy in the oceans [19].

According to Table 1, the cost of wave energy is less than solar/wind and coal plants when it is used as primary source. When it is used as secondary source, it is in medium, between fuel cells and solar/wind. As shown in table 2, wave energy has costs comparable with the other energy sources. Whichever the situation is, the wave energy owns less cost among three energy sources. As a result, wave energy is extremely competitive.

Table 1: Capital cost comparison with renewable energy sources [19]

Energy Source	**Cost as Primary Source(100MW)**	**Cost as Secondary Source(1MW)**
Coal Plants	1500-3500	-
Wind/Solar	4000	8000
Wave	2300	6200

Table 2: Operating cost with power sources [19]

Energy Source	Cost as Primary Source(100MW)	Cost as Secondary Source(1MW)
Solar	10-15	25-50
Wind	5-6	10
Wave	4-5	7-10

Table 3: Levelized electricity costs (in Europe Cent, kWh) for electricity generation by the renewable and non-renewable technology [19]

Source	Technology	Current Costs	Expected Future Costs beyond 2020
Solar	Thermal electricity	12-18	4-10
Wind	Onshore	3-5	2-3
	Offshore	6-10	2-5
Marine	Tidal stream	8-15	8-15
	Wave	8-20	5-7
Biomass	Electricity	5-15	4-10

As shown in table 3, wave energy's cost is in high level comparing with others in the current cost group. In the future cost group, wave energy's cost is in medium since it has a wide range. However, in the marine energy group, the expected future cost will be much lower than the tidal stream. In conclusion, the expense on wave energy is in the medium cost group comparing with other energy sources.

Table 4: Operational figures of Wave Energy [20]

	2010-2012	2020	2030	2050
Capital cost of farms [EUR/kW]	4840-9680	2723-4235	2118-2723	1513-2118
Operation & Maintenance cost [EUR/kW/yr.]	48-97	30-73	18-30	12-24
Availability [%]	70-80	90	90-95	95-98
Total electricity production cost [EUR/MWh]	242-605	121-242	85-121	61-97
Market share [%]	0	<<1	1-2	>10
Emissions (direct operation)	0			
Emissions (indirect operation)	25-50gram/kWh			

Table 4 illustrates operational figures of wave energy from 2010-2050. In this form, the cost will be reduced with time passing by, whatever the farm capital cost, maintenance or operation cost and electricity production cost. Also, the availability of this energy will increase from 80% to 95% approximately. The market share of global electricity output percentage of wave energy will increase as well, from 0 to over 10%. This is an extremely huge change. Additionally, wave energy has a superior advantage is that it will not have emissions from direct operation. However, there will be some indirect emissions for about 25-50 gram/kWh. In conclusion, the reason for the medium cost in previous forms is that the development of wave energy is not as mature as the other energy sources since it only develops for nearly 40-50 years. If wave energy field can develop for another 40-50 years, this field will have significant improvements like reducing cost, solving environmental problems and so on.

Table 5: Summary of drivers and barriers related to wave energy [19]

Driver	Onshore	Offshore
Guaranteeing Economically Viable Prices	S.P.D.	S.P.D.
Guaranteeing Security of Supply	S.P.D.	S.P.D.
Climate Protection	S.P.D.	S.P.D.
Enforced Direct Market Support	S.P.D.	S.P.D.
Research and Development (R&D) Spending	P.D.	P.D.
Very High Potentials Worldwide	P.D./S.I.	S.P.D.
Sea Use Competition	S.I.D.	I.D./S.I.
Aiming at Conflict Neutral Technologies	P.D.	P.D.
Increasing Demand for Local Added Value	P.D.	P.D.
Restricted Production Capacities	S.I.D.	S.I.D.
Development in Perception and Network Building	P.D.	P.D.

Additionally, the wave energy will provide more jobs for people. Table 5 summarizes the drivers and barriers related to wave energy. The S.P.D is the strong pushing driver and P.D is the pushing driver, which it will provide more job to people. In the onshore group, among 11 different drivers, wave energy strongly pushes or pushes 9 drivers. The percentage of this data is 81%, which means about 81% of fields need more workers. Additionally, in the offshore group, wave energy strongly pushes or pushes 9 drivers. The percentage of this is 81%. As a result, wave energy technology stimulates employment and economic development. Based on projections for installed capacity, the number of jobs wave energy provides will increase to 264,323 by 2050 [19].

Wave energy will be a priority in the future because of its leading technology to produce a huge amount of electricity in the energy market. Not only because it is environmentally friendly, but it is also easy to predict. In 2015, countries change their goal of producing wave energy from 10% to 40%, which will be achieved by 2020-2030. This modification will not only provide the country with enough green energy but will also reduce energy crises like pollution. Wave energy start its journey several years ago while others are utilized it for a long time. Wave energy still hides some potential advantages that wait for people to study.

8. CONCLUSIONS

In this review, wave energy is discussed in different aspects, mainly from the development history to the future prospects, which includes development in chronological order, introduction of implementations and systems and multiplied impacts on the environment and economics. The wave energy is clean and renewable resource of energy, with huge potential to be released and enormous energy market yet to be filled. Despite of a relatively short history of rapid development, its technical implementation is promising. Nowadays, the early researches on the wave energy since 1970s has established firm practical foundation for further experiments. As for the future prospects, the scientists and researchers should seek for appropriate directions for wave energy by analyzing the current technical situation and multiplied impacts on the society. Besides, more innovative implementations, such as microgrid and integration into large power grid, should be invented to improve the efficiency of wave energy and continue to minimize the negative impacts on the environment.

REFERENCES

[1] Falcão AFDO (2010) Wav energy utilization: A review of the technologies. Renewable & Sustainable Energy Reviews, 14: 899-918.

[2] Peake, S. (2012) Renewable Energy: Power for a Sustainable Future, Oxford University Press, Oxford.
[3] Falnes J. (2007) A review of wave-energy extraction[J]. Marine Structures, 20(4): 185-201.
[4] Yanjun Liu, Tongtong He. (2007) Development history and key technologies of wave energy utilization [J]. JOURNAL OF OCEAN TECHNOLOGY, 36(4)
[5] Boyle, G., (2012) Can renewable energy sources power the world?
[6] https://www.open.edu/openlearn/ocw/mod/oucontent/view.php?id=73764&section=2
[7] Maria-Arenas, A., Garrido, A.J., Rusu, E., Garrido, I. (2020.04.02) Control Strategies Applied to Wave Energy Converters: State of the Art, Energies 2020, 13(7), 1665
[8] Farrok, O., Ahmed, K., Tahlil, A.D., Farah, M.M., Kiran, M.R., Islam, Md. R. (2020.03.11) Power Generation from the Oceanic Wave for Sustainable Advancement in Renewable Energy Technologies
[9] PVSM (2013.11.07) “В Южной Австралии заработала волновая электростанция мощностью 1 МВт”, https://www.pvsm.ru/budushhee-zdes/47775
[10] Peake, S. (2012) Renewable Energy: Power for a Sustainable Future, Fourth Edition, 2018, Oxford University Press, EISBN 978-0-19-253777-5, pp. 627
[11] Maria-Arenas, A., Garrido, A.J., Rusu, E., Garrido, I. (2020.04.02) Control Strategies Applied to Wave Energy Converters: State of the Art, Energies 2020, 13(7), 1665
[12] Takao, M., Fukuma, S., Okuhara, S., Kinoue, Y. (2019.3) Performance comparison of turbines for bi-directional flow
[13] Lagoun, M., Benalia, A., Benbouzid, M. (2014.07.13) A Predictive power control of Doubly Fed Induction Generator for Wave Energy Converter in Irregular Waves
[14] Behrang Chenari, Almerindo Ferreira, Shiva Saadatian（2014）, WAVE ENERGY SYSTEMS: AN OVERVIEW OF DIFFERENT WAVE ENERGY CONVERTERS AND RECOMMENDATION FOR FUTURE IMPROVEMENTS.,6-7
[15] Per Holmberg, Magnus Andersson, Björn Bolund, Kerstin Strandanger(2011), Wave Power: Surveillance study of the development., 28-29
[16] Wick G L, Schmitt W R, Clark R. （1981）Harvesting Ocean Energy[M]. Paris: The Unesco Press.
[17] Zhongfeng Sun. （2007）Research on Oscillating Float Wave Power Generation Device [D]. Shanghai：Shanghai University.
[18] 2008, Aquatic Renewable Energy Technologies (Aqua-RET), Okeanós Pelamis Wave Farm, http://www.aquaret.com/images/stories/aquaret/pdf/cswavepelamis.pdf
[19] 2008, Aquatic Renewable Energy Technologies (Aqua-RET), The Wave Hub Project (Cornwall/UK), http://www.aquaret.com/images/stories/aquaret/pdf/cswavewavehub.pdf
[20] Sevda Akar(2016), Environmental and Economic Impacts of Wave Energy., 288-293
[21] Ruud Kempener (IRENA), Frank Neumann (IMIEU), 2014, Wave Energy: Technology Brief, https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2014/Wave-Energy_V4_web.pdf