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# A Review on Wave Energy Harvesting Technologies

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*Yenilenebilir Enerji*
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*Gelgit Enerjisi*
*Enerji Dönüşümü*

***Graphical/Tabular Abstract (Grafik Özet)***

*In this study a historical development of wave energy harvesters has been reviewed. Additionally, classification strategies of wave energy harvesters have been explained based on literature.*

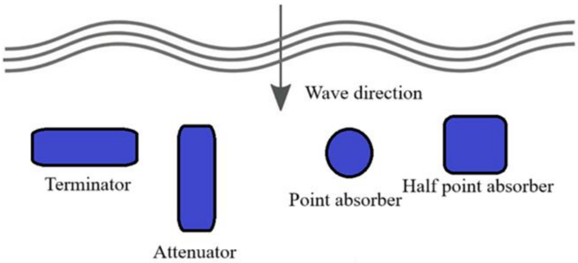


***Figure A****: Classification According to Wave Direction and Location /****Şekil A:*** *Dalga Yönü ve Lokasyonuna Göre Sınıflandırma*

***Highlights (Önemli noktalar)***

- *This study describes the historical development of wave energy harvesters. /Bu çalışmada dalga enerji hasatçılarının tahrihsel gelişimi açıklanmaktadır.*
- *Classifications of wave energy harvesters' strategies based on literature have been examined. /Dalga enerjisi hasadı stratejilerinin literatüre dayalı sınıflandırmaları incelenmiştir.*
- *Advantages and disadvantages of wave energy harvesters have been expressed. /Dalga enerji hasatçılarının avantajlı ve dezavantajlı yönleri açıklanmıştır*

***Aim (Amaç):*** *This study aims to present the historical development and classification of wave energy harvesters based on literature. /Bu çalışma dalga enerji hasatçılarının tahrihsel gelişimi ve sınıflandırmasının literatür temelinde sunmayı amaçlamaktadır.*

***Originality (Özgünlük):*** *In order to be able to explain the most important aspect of wave energy harvesters, an extensive literature search was carried out. /Dalga enerji hasatçılarının en önemli yönlerini açıklayabilmek için oldukça derin bir literatür taraması yapılmıştır.*

***Results (Bulgular):*** *Although the world, and Turkey in particular, has a great potential for wave energy and a long history of studies in this field, the amount of energy produced by wave energy harvesters is still far below what it should be. / Dünyada ve özellikle Türkiye'de dalga enerjisi açısından büyük bir potansiyel bulunmasına ve bu alanda uzun bir çalışma geçmişine sahip olunmasına rağmen, dalga enerjisi hasatçıları tarafından üretilebilecek enerji miktarı, olması gerekenin çok altındadır.*

***Conclusion (Sonuç):*** *This study provides a detailed classification and examines the historical development of wave energy devices from different perspectives. It also provides a thorough literature review to inform and guide future research efforts in the field of wave energy. / Bu çalışma ayrıntılı bir sınıflandırma sunar ve dalga enerjisi cihazlarının tarihsel gelişimini farklı perspektiflerden inceler. Ayrıca dalga enerjisi alanındaki gelecekteki araştırma çabalarını bilgilendirmek ve yönlendirmek için kapsamlı bir literatür incelemesi sağlar.*

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**Abstract**

With the rapid development of technology, the demand for electrical energy is increasing every year. Although electrical energy is a very clean form of energy in its direct use, the use of fossil fuels in the production process causes environmental problems. In this context, renewable energy sources are of critical importance in terms of clean and sustainable energy production. Wave energy stands out as a relatively under-researched topic in this field. Our country, which is surrounded by sea on three sides and has an inland sea, needs to invest more in wave energy and support more studies in this field. This study analyses the historical development of wave energy and aims to provide a perspective for future research.

# Dalga Enerjisi Hasat Teknolojileri Üzerine Bir İnceleme

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*Başvuru: 10/10/2024*
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**Öz**

Teknolojinin hızla gelişmesiyle birlikte elektrik enerjisine olan talep her geçen yıl artmaktadır. Elektrik enerjisi doğrudan kullanımında oldukça temiz bir enerji türü olmasına rağmen üretim sürecinde fosil yakıtların kullanılması çevre sorunlarına yol açmaktadır. Bu bağlamda yenilenebilir enerji kaynakları temiz ve sürdürülebilir enerji üretimi açısından kritik öneme sahiptir. Dalga enerjisi bu alanda nispeten az araştırılmış bir konu olarak öne çıkmaktadır. Üç tarafı denizlerle çevrili ve bir iç denize sahip olan ülkemizin dalga enerjisine daha fazla yatırım yapması ve bu alanda daha fazla çalışmayı desteklemesi gerekmektedir. Bu çalışma dalga enerjisinin tarihsel gelişimini analiz etmekte ve gelecekteki araştırmalar için bir perspektif sunmayı amaçlamaktadır.

## 1. INTRODUCTION (GİRİŞ)

The need for energy has led to the continuous evolutionary development of energy production methods to meet this need and paved the way for the diversification of energy production methods. Although the effective use of steam power led to a great leap in technology, the biggest breakthrough in civilization was undoubtedly the invention of electrical energy. Energy is defined as the capacity to do work. The energy required to move an object one meter with one Newton of energy is one Joule unit [1]. Energy has many forms such as kinetic, potential, thermal, electrical, chemical, nuclear and radiation. For a long time in its historical development, the first and most basic energy source of mankind has been fire. Before the industrial revolution, water and wind power were other important sources of energy used by mankind. However, these sources could not go beyond the principle of direct use of mechanical energy in the primitive periods of civilization. For example, the first windmill powered by wind power and used to grind grains was invented by the Persians in the 800s AD [2]. These windmills, which were widely used regionally in Arabia, China and India, started to be used in Europe between 1100 and 1200 AD. These windmills, which were primarily used for grinding grain and pumping water, were also used to drain flood plains in the Netherlands [3]. As an important innovation in antiquity, water-based energy was widely used by Roman and Greek societies in the 1st century BC. Horizontal axis water wheels, which were first used for agricultural irrigation, were also used in grain grinding processes over time. The mechanical energy obtained from the water wheels rotating on the horizontal axis was transferred to a vertical shaft

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and rotated the grinding stones, thus grinding grains such as wheat and corn into flour. This technology was adopted and widely used by many civilizations towards the end of the 1st century AD. In 1086 AD there were more than 5000 watermills in England, and this number exceeded 4000 by 1300 AD. While water mills were initially used to grind corn and grain, over time they were also used in a variety of industrial processes such as running bellows for iron production, paper making, timber cutting, olive oil production and powering textile mills [4]. Civilization made a significant leap with the use of steam power. The first recorded steam engine in history was the 'aeolipile' developed by Heron of Alexandria in the 1st century AD. This device, when heated, sprays water vapours out and allows it to rotate around an axis [5]. The first steam engine patent was obtained by Thomas Savery in 1698. The steam engine developed by Savery was designed to extract water from mines. The machine worked by evaporating water and condensing it in a secondary tank, creating a vacuum [6]. During the 1600-1800s, many different devices using steam power effectively were developed. However, the fact that these devices are difficult to control, have low reliability, short life span and the amount of energy they consume is very high has caused their usage areas to remain limited. In parallel with the development of steam power technology in these years, the research and conceptualization of electricity-related concepts also began. For example, in 1600, William Gilbert described the Earth's magnetic field in his work 'De Magnete' and explained the attraction of electrical substances to other substances [7]. In 1663, Otto von Guericke invented a device that can attract or repel substances with electric charge, which can be defined as an electrostatic generator today. However, he did not define the relationship of this device with electricity [8]. In 1785, Charles-Augustin de Coulomb published the law of electrostatic force (Coulomb's law), which explains that the electrostatic attraction or repulsion force between two-point charges is directly proportional to the product of the magnitudes of the charges and inversely proportional to the square of the distance between them [9]. This work is considered as the beginning of the theory of electromagnetism. However, these studies were mostly on the conceptualization of the nature of electricity and electromagnetism. During the industrialization process, the increasing application of steam engines led to a large increase in the demand for coal. Between 1800 and 1889, the global coal production volume increased from 11.6 million tons to 485 million tons [10]. By 1900, 95% of global energy was derived from coal.[11] The use of Newcomen and Watt steam engines made it possible for miners to dig deeper and thus extract more coal.[12] This shows the huge impact of steam engines on production, transport and employment [10]. The Second Industrial Revolution was characterized by the widespread use of electrical energy and the expansion of its fields of application. Following Faraday's discovery of electromagnetic induction, in 1866 Varley, Wheatstone and Siemens discovered the principle of reversibility of dynamos (usability as electric motors or generators). This coincided with the development of alternators for AC currents. In 1885, Stanley's development of the AC transformer led to the widespread use of AC currents and the development of distribution networks. The licensing of Nikola Tesla's AC and induction motor patents in 1888 was a significant advance in the field of electricity [11]. With the second industrial revolution, electrical energy replaced steam-powered systems and became the most dependent energy type of civilization. However, the discovery of electrical energy could not prevent the use of fossil fuels. The use of fossil fuels is increasing even today and causes very serious environmental problems such as global warming and climate change.[13] In the following section, the development of renewable energy will be briefly explained and then the development of wave energy, which is the main purpose of this study, will be examined in detail.

## 2.MATERIALS AND METHODS (MATERYAL VE METOD)

### 2.1. Renewable Energy Sources and Their Share In Production (Yenilenebilir Enerji Kaynaklari ve Üretimdeki Payi)

Since the oil crisis of the early 1970s, the need for alternatives to fossil fuel-based energy production has been universally recognized. This issue, which was initially raised only with concerns about energy costs, has become even more important in the last two decades due to factors such as increasing evidence that energy production and consumption lead to environmental degradation, industrial activities exacerbate this situation, population growth, economic growth and excessive consumption of the world's resources. According to the International Energy Agency, the distribution of $CO_2$ emissions caused by fossil fuel-based consumption between 1971 and 2021 is as given in Figure 1.

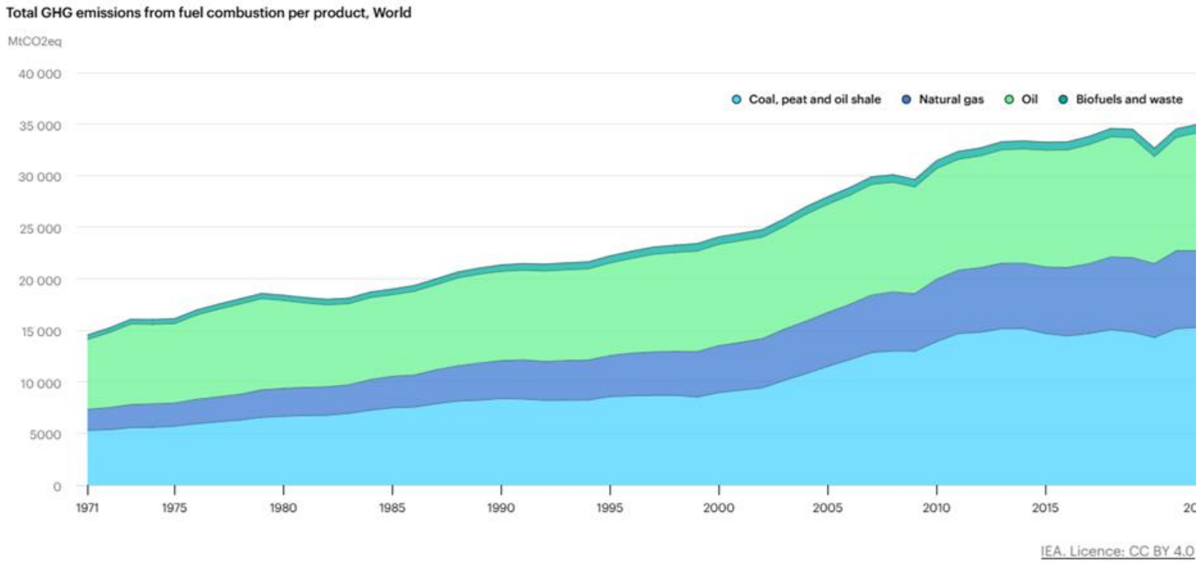


**Figure 1.** Total Greenhouse Gas Emissions from Fuel Consumption Worldwide [14] (Dünya Çapında Yakıt Tüketiminden Kaynaklanan Toplam Sera Gazı Emisyonları [14])

The most important option to overcome the negative effects of global climate change is undoubtedly to increase the use of renewable energy sources. For example, it has been reported that the increase in the use of wind and solar energy prevents a 4% increase in global fossil fueled energy production [15]. Regarding the orientation towards renewable energy sources, the change predicted by the International Energy Agency until 2028 is shown in Figure 2. Although the production segments of renewable energy sources vary according to years, it is seen that the largest share belongs to hydroelectric and solar energy. Concrete examples of renewable energy sources will reveal this situation more clearly. For example, the energy generation capacity of Three Gorges Dam, one of the largest hydroelectric dams in the world, is stated as 22.5GW [17]. However, Bhadla Solar Park, Rajasthan, India, is one of the largest solar parks in the world with a total capacity of 2.255 GW [18]. Gansu Wind Farm in Gansu Province of China is the world's largest onshore wind farm with an installed capacity of 10 GW [19]. However, wave energy has the lowest share among renewable energy sources, despite the fact that a large part of the world's surface is covered by seas and oceans. For example, the MeyGen Tidal Project in the Pentland Firth area of Scotland is one of the largest tidal energy projects in the world, but has an installed capacity of only 398 MW, and the Swansea Bay Tidal Lagoon Project in Wales utilizes the power of the tides to generate up to 320 MW of electricity. [20-22]. However, the global potential of wave energy generated by breaking waves along the coastline alone is estimated to be around 2-3 Terawatts (TW) [23].

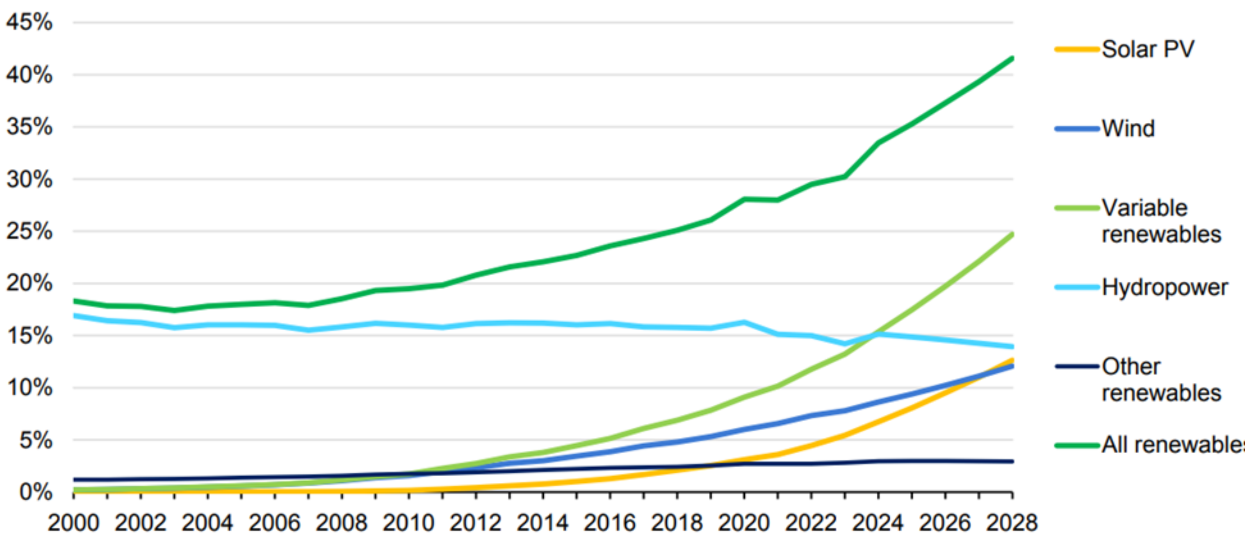


**Figure 2.** Change in renewable energy production between 2000 and 2028 [16] (2000 ile 2028 yılları arasında yenilenebilir enerji üretimindeki değişim [16])

### 2.2. Short History of Wave Energy Studies (Dalga Enerjisi Çalışmalarının Kısa Tarihi)

The first known proposals for utilising wave energy date back to the late 18th century. In 1799, French engineer Pierre-Simon Girard patented a pendulum device powered by the energy of waves. This device consisted of a lever mechanism attached to ships moored in a harbour, which moved up and down with wave motion. This movement was used to operate machinery on land. Girard's son Son de Marsiquese patented an early wave energy converter design in 1810. This design involved a buoy travelling up and down with the waves, converting mechanical energy into a mechanism to drive a pump or piston [24]. In the 1880s, J.M. Courtney of New York was granted a patent for a sound buoy design, another wave energy device based on buoys. This device consisted of a vertical cylindrical column that trapped a pocket of air at the top. As the waves interacted with the device, the air was expelled through a hole and retracted, activating a power receiver system and thus generating a warning sound. This device was used as a system to indicate the position of ships [25][23]. In 1895, Spanish engineer Isidoro Cabanyes received a patent for a device he called 'wave power machine'. The basic working principle of this device was based on pumps driven by rising and falling buoys that carried water to a high reservoir. The water in the reservoir, when released, drives a tribune to generate electrical energy. This process was based on the principle of converting the kinetic energy of the water into potential energy and passing it back through the tribune to generate electrical energy [26][24]. Thus, the way was paved for the production of electricity from wave power. In 1909, the first documented application for the conversion of wave energy into electrical energy was realized in California. During this period of intensive studies on electrical energy, California became the center of wave energy research. Several companies started to commercialize wave energy and develop wave engines. One of these companies, California Wave Power Company, converted the energy of waves into electrical energy and used it to operate small devices on the pier [27][25]. In 1910, French engineer Busso Balasek built an electric power plant that compresses and evacuates air by means of wave motion and thus provides energy by the reciprocating movement of a piston and produced 1000 Watts of energy from this plant [28][26]. Balasek drilled a vertical well at the top of a cliff by the sea, and the vertical piston he placed in this well moved with the rise and fall of the waves to drive a primitive turbine. This design is recognized as the first known oscillating water column (WEC) design [29]. An important milestone in the history of wave energy began in the 1940s when Yoshio Masuda, a naval officer and engineer in the Japanese navy, came up with the idea of harnessing wave power for self-powered navigation buoys. Masuda developed a system in which air rising and falling with wave action inside a chamber integrated into the buoy moved a tribune. In 1947, Masuda built and tested small-scale models about 1 meter high in order to validate the SSK idea. Initial results were promising. In 1965, he started to build and test offshore a large prototype 20-meter-high navigation buoy based on the wave-powered SSK design off the coast of Japan [30][27]. In the 1970s, he played an important role in the development of the Kaimei, which is now recognized as the first commercial wave energy device. This device was characterized as the first successful attempt to generate electricity using wave energy on a large scale. Kaimei was designed as a floating barge with SSK chambers. In the history of wave energy, this design was the first application recognized as a milestone. This work paved the way for larger wave energy research programs investigating oscillating water columns [31][28]. From the first British patent on wave energy in 1855 to 1973, 340 patents were granted [32][29]. Ocean and wave energy technology patents exhibit a growth pattern that can be evaluated in four main phases from 1900 to the present. These four main phases are as follows [33],[31]:

- First Period (1900-1940): During this period, patent applications for ocean and wave energy technology were very limited. This was a period when technology was in its infancy and innovative ideas were developed by only a few individuals or small groups.

- Research and Development Period (1940-1970): During and after the Second World War, interest in diversifying energy sources increased. During this period, more research was conducted on ocean and wave energy technologies and an increase in patent applications was observed. Studies in this period were mostly conceptual and experimental.

- Commercial Application and Development Period (1970-2000): During this period, interest in renewable energy sources increased significantly, especially with the impact of energy crises. There was a significant increase in patent applications for OET technologies and some commercial applications were realized. This was a period of wider acceptance and investment in technology.

- Modern Era (2000-present): As global awareness of renewable energy sources and efforts to combat climate change increased, interest in ocean and wave energy technologies grew rapidly. During this period, patent applications increased significantly, and technology development accelerated. More sophisticated and efficient wave energy devices were developed and some of them started to be used commercially. The oil crises of 1973 and 1979 led to a revival of interest in ocean and wave energy technologies. The United Kingdom, Norway, Japan and many other countries provided significant financial support for wave and tidal energy research and development by establishing government-funded programs. This period triggered a surge in patent applications for ocean and wave energy technologies, which peaked in the early 1980s. However, this interest and investment declined towards 1995 as oil prices stabilized again. However, despite these opportunities, ocean and wave energy technologies have historically faced barriers to widespread deployment as alternatives to fossil fuel-based systems due to their lack of infrastructural integration with main energy systems, commercial viability, etc. [33][32]. Developed by Alan Wells at Queen's University in the 1970s, the turbine had symmetrical blades designed to direct airflow in both directions over the same turbine rotor. This innovative design enabled power to be generated from both incoming and outgoing air currents in an oscillating water column. As a result of efforts to analyze and improve the aerodynamics and performance of the turbine for wave energy applications, Wells turbines have been adapted by many researchers for SSC devices [34][33]. In 1974, Stephen Salter of Edinburgh University designed a wave energy converter (Salter Duck). In Salter's paper [35][34] it was shown that wave energy could be converted into electrical energy with 80% efficiency. These findings attracted the attention of many researchers and universities in the field of wave energy and contributed significantly to the financial support of studies. Much of the research in the second half of the 1970s focused on the theoretical hydrodynamics of energy conversion. During this period, J. Falnes, K. Budal, D. V. Evans, J. N. Newman, C. C. Mei, J. Falnes, K. Budal, D. V. Evans, J. N. Newman and C. C. Mei independently analyzed the theoretical maximum efficiency of any wave energy converter and the conditions that must be met to achieve this efficiency. [31], [36], [35]. In the early 1980s, interest in sea wave energy started to decline with the decline in oil prices. Although prototype designs were developed during this period, the lack of sufficient information on wave power efficiency and the resistance of the systems to extreme weather conditions, as well as the projected high costs of machinery and power transmission lines, were the main reasons for the decline. For these reasons, the British government-funded wave energy program was closed in 1982. A 500-kW wave energy turbine built in Norway was severely damaged by unfavorable climatic conditions and decommissioned in 1988. Until the 1990s, wave energy research in Europe continued largely at an experimental and academic level [37- 39]. Sea wave energy research started to gain importance again in 1991 when the European Commission included wave energy in its R&D program on renewable energies. During this period, interest and investments in wave energy technologies increased, R&D activities accelerated and efforts to diversify renewable energy sources intensified [32]. Although interest in wave energy has increased since the 1970s, fluctuations in research funding have slowed down research in this field from time to time. However, in the last decade of the 20th century, research in this field regained momentum. Although less investment has been made compared to wind and solar energy, wave energy research and development continues rapidly, and efficiency is constantly increasing thanks to new designs and devices. Although wave energy is still considered to be in the development stage, it is rapidly progressing towards becoming a commercially viable technology [34]. Since 2015, it is estimated that more than 1000 wave energy converter systems have been patented each year worldwide and thousands of existing patents have been registered. A large number of devices are in development stages and many full-scale plants are either already in operation or in the testing phase. As a result of this ever-expanding technological development, new classification techniques are constantly being established [40][41].

### 2.3. Classification of Wave Energy Converters

(Dalga Enerjisi Dönüştürücülerinin Sınıflandırılması)

Wave energy converters (WECs) can be classified under many different categories. The study on the classification of wave energy converters by Falnes and Budar in 1975 is one of the first studies in this field. In this study, wave energy converters were classified according to wave propagation direction, size and placement. This classification [41][42]:

- Terminators: Devices operating perpendicular to the wave direction, such as overlapping structures or oscillating wave surge converters. For example, Stephen Salter's Edinburgh Duck is classified as a terminator.

- Attenuators: Structures such as Pelamis that align parallel to the wave direction and attenuate the wave along their length.

- Point Absorbers: Smaller devices such as floating buoys that absorb energy from all directions.

- Semi-Point Absorbers: Devices that work in a similar way to point absorbers but are significantly larger in size.

This classification, shown schematically in Figure 3, has enabled a better understanding and development of wave energy technologies and explained how different devices convert wave energy.

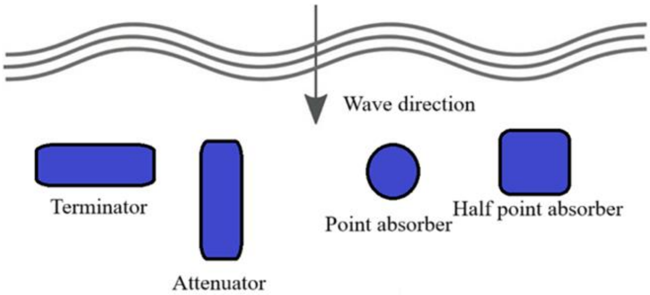


**Figure 3.** Classification According to Wave Direction and Location (Dalga Yönü ve Lokasyonuna Göre Sınıflandırma)

In 1988, Hegerman and Heller carried out a more detailed classification process. This classification has addressed in detail how wave energy converters work in different environments and is considered to be the first comprehensive classification in this field. In the study conducted by Hegerman and Heller, wave energy converters are basically classified under three different categories: according to wave capture methods, according to their structural characteristics and according to the power transmission systems used for energy conversion. Falnes and Lovseth defined oscillating water columns as a separate class and simplified this categorical distinction and divided it into six categories [42][43]. The first study on the current accepted classifications can be given as an example of the work done by Falcao in 2010 [31][44]. This classification is based on the operating principles of wave energy converters and can be summarized with a diagram as shown in Figure 4. The difficulty of classifying wave energy converters is due to the fact that the applications have different design features according to many conditions. In addition to basic design parameters such as the effort to obtain maximum efficiency from wave energy, many main variables such as resistance to corrosion and harsh weather conditions, maintenance, repair and operating costs, transmission of the generated energy have made it difficult to classify wave energy converters as a result of the diversification of applications.

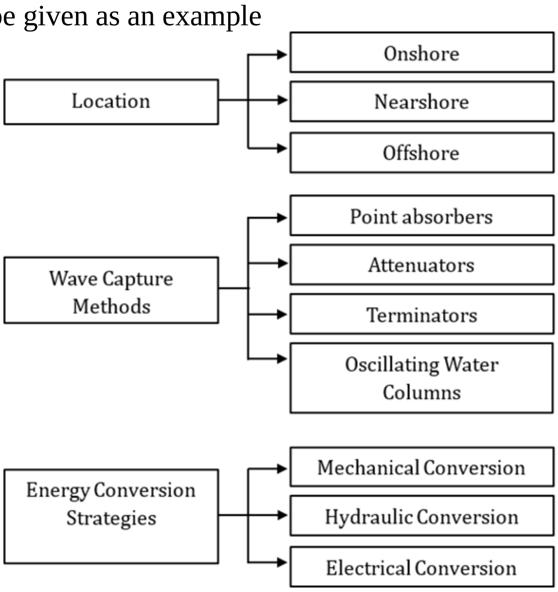


**Figure 4.** Block representation of the classification made by Falco (Falco tarafından yapılan sınıflandırmanın blok gösterimi)

The generally accepted study for classification was published in the report presented by the International Renewable Energy Agency (IRENA) in 2014 and wave energy converters were classified as shown in Figure 5 [43], [45].

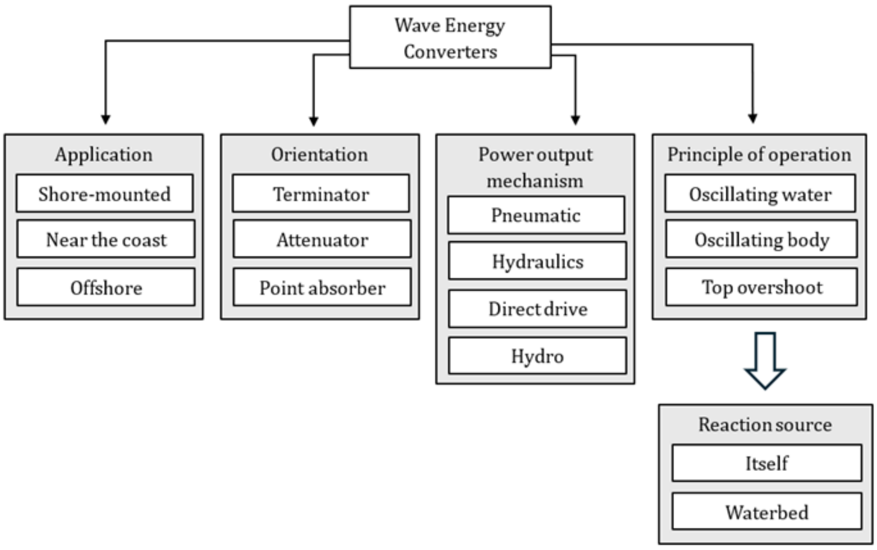


**Figure 5.** Block Diagram representation of the classification made by IRENA (IRENA tarafından yapılan sınıflandırmanın Blok Diyagram gösterimi)

The classification made by IRENA and the utilization rates of installed wave energy systems according to this classification in the same period are shown in Figure 6 [43][45].

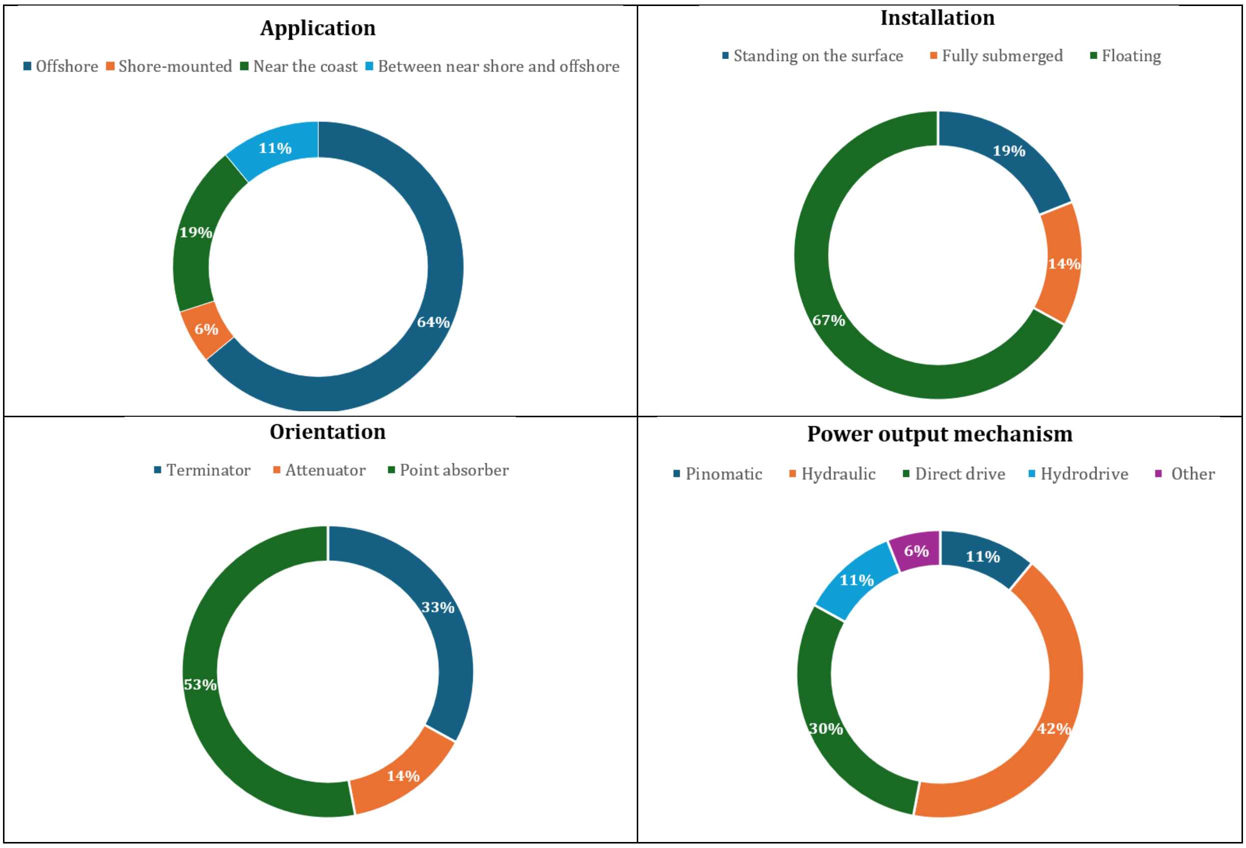


**Figure 6.** Utilizations rates of wave energy converters (Dalga enerjisi dönüştürücülerinin kullanım oranları)

**- Point absorbers:** The devices in this scope are mostly buoy type energy harvesters that generate electrical energy from the rising and falling motion provided by the wave. Systems in this scope are energy harvesters with relatively low power capacity. There are different configurations according to the power transmission systems for the devices in this scope. These can be direct-drive systems, hydraulic power transmission systems, air-pressurised (pneumatic) power transmission systems and hydro systems that directly rotate water turbines. In direct drive systems, a shaft is often used to transfer the rising and falling motion to a linear generator. In hydraulic and pneumatic powered systems, the float motion is used to pump working fluid or air through the system. Point absorbers can be highly efficient in energy capture due to their smaller size compared to the wavelength. [44 – 46].

**- Attenuators:** Devices in this scope are structures positioned parallel to the direction of the incident wave. The flexure or movement caused by the wave hitting the structures intersecting with the propagation direction is used for energy conversion. As the wave passes over the attenuator, it bends and bends, creating mechanical movement. For this reason, they mostly have an articulated structure that can be bent and twisted. As in point attenuators, they generate energy with the help of direct drive or hydraulic power transmission principles [44], [46],[48].

**- Terminators:** Terminator type wave energy harvesters are positioned perpendicular to the direction of wave propagation to convert wave energy into electrical energy and terminate the wave motion by hitting a hard object in the vertical direction or by directing the wave to the reservoir by means of a ramp. These devices have two different configurations. The first of these is called overshot systems and the other is called oscillating systems. The overcome wave energy harvesting devices consist of floating or fixed structures that allow the incoming wave to overcome a ramp or embankment and fill into a reservoir to convert wave energy into electrical energy. The potential energy of the stored water is then converted into electrical energy through turbines or similar mechanical devices. Oscillating wave energy harvesters are structures designed to oscillate with the motion of waves to convert wave energy into electrical energy. They are usually mounted on the seabed and oscillate back and forth with wave fluctuations. This oscillating motion converts kinetic energy into electrical energy by operating hydraulic pistons or mechanical linkages connected to turbines or generators. Systems operating on the terminator principle can capture a significant portion of the wave's energy [44] [50].

### 2.4. Working Principles of Wave Energy Converters (Dalga Enerjisi Dönüştürücülerinin Çalışma Prensipleri)

This section describes the methods used to harvest the mechanical energy from the wave, independent of the energy conversion method.

**- Oscillating Water Column systems**: Oscillating water column (WEC) wave energy harvesters are a type of system used to convert wave energy into electrical energy. These devices consist of column-shaped chambers with a lower side open to wave action and an air tribune on the upper side. Waves move in and out of the SSS chamber, causing the water column to rise and fall. The rise of the water column compresses the air in the chamber. The lowering of the water column reduces the air pressure and allows air to enter the chamber. The air passes through the air tribune, causing the turbine to rotate. The rotation of the turbine drives a generator that produces electricity. These systems can efficiently capture energy over a wide range of wave frequencies. They can be designed as offshore floating and shore-fixed [31], [51].

**- Wave Interactive Body or Oscillating Devices:** These devices are generally considered to be in the class of point absorbers described above. It converts the relative motion between a floating component and a fixed base or multiple floating components into electrical energy. They take advantage of all oscillatory motions caused by waves, including rise (up and down), surge (forward and backward) and tilt (slope). By utilizing the motion energy of a buoy or hull affected by wave motion, it is converted into electrical energy by intermediate hydraulic systems or by direct drive to generators. These systems are generally designed to convert the available energy that can be obtained from complex wave movements into energy that can be utilized at the highest level. According to the classification by IRENA, it is divided into subclasses as fixed to the seabed and self-oscillating. In addition, it can be categorized as single-hull ascending buoy systems, two-hull ascending systems, underwater ascending systems, tilting devices, seabed hinged systems and multi-hull systems. They are used in offshore and near shore applications [31], [43], [44].

**- Overtopping wave energy harvesting devices**: As discussed above in the terminator section, these devices consist of floating or fixed structures that allow the incoming wave to overcome a ramp or embankment and fill a reservoir to convert wave energy into electrical energy. The potential energy of the stored water is then converted into electrical energy through turbines or similar mechanical devices [44].

- **Pressure Difference Transducers**: Underwater pressure difference devices are systems that are located under the sea surface and convert the pressure changes created by the waves into energy. Such devices generate energy by using dynamic pressure differences caused by wave movements under water. Underwater pressure differential devices collect energy using changes in water pressure near the seabed, usually during wave passage. The water pressure increases when the wave crest passes through the area where the device is located and decreases as the wave bottom passes. The moving components inside the device react to the changing pressures during wave passage, causing them to move up and down or oscillate. These pressure changes cause the piston inside the device to move up and down. This movement is converted into mechanical energy and electrical energy is obtained through a generator. These devices are placed close to the seabed. Since the devices in this class are completely under the sea, they are included in the wave-interactive hull class, but the wave interaction is not directly caused by the wave, but indirectly due to the pressure difference created by the wave causing the upward movement [44].

- **Pressure Delayed Osmosis method**: These systems are systems that generate energy by utilizing the salinity differences of sea water. These devices obtain energy by utilizing the osmotic pressure difference that occurs in areas such as estuaries or salt lakes where fresh water and saltwater meet. The semi-permeable membrane allows fresh water to pass through to the salt water, while blocking the salt molecules. This process causes the water in the area with a high salt concentration to increase, which leads to an increase in pressure. The increased pressure moves the water and drives a piston in hydraulic systems or directly drives a turbine, converting mechanical energy into electrical energy. Mechanical energy is converted into electrical energy through a generator [47], [52].

- **Thermal Wave Energy Converters**: Thermal wave energy converters are innovative systems that aim to generate electricity by utilizing thermal energy in seawater. Thermal wave energy converters utilize the heat capacity of seawater and the energy differences resulting from the formation of different temperature layers of water by wave action. These devices generally generate energy using the temperature differences of seawater and thermal fluctuations caused by waves.

Ocean Thermal Energy Conversion Systems generate energy by utilizing the temperature differences at different depths of seawater. It generally utilizes the temperature difference between warm surface water and cold deep water. Two types of cyclic systems are used. These are closed loop and open loop systems. Closed Loop OTEC; Hot surface water vaporizes a liquid (usually ammonia) at a low boiling point. The vapour generates electricity by turning a turbine. Cold deep water completes the cycle by turning the vapour back into liquid. Open Loop OTEC: Hot surface water is vaporized directly in a vacuum and this vapour spins a turbine to generate electricity. The vapour is then condensed and re-liquefied with cold deep water. It is used in a hybrid system where these two cycle systems are used together.

- **Wave Assisted Thermal Energy Systems**: These systems generate energy from the temperature differences at the surface and bottom of the water caused by wave action. Waves store thermal energy by increasing the temperature differences at the surface and bottom of the water. This energy is collected through heat exchangers and converted into electrical energy in a thermal cycle.

- **Wave Heat Pumping Systems**: Wave motion creates thermal gradients in the water. These gradients are converted into electrical energy by collecting energy through heat pumps. This technology is still in the development stage, and research on seawater thermal energy continues.

- **Ocean Thermal Gradient Energy**: Energy is generated using the variation of seawater temperature along the depth (thermal gradient). The temperature difference between the sea surface and the seabed causes heat flow. Hot water at the surface vaporizes a liquid with a low boiling point, while cold deep water condenses the vapour and this cycle generates energy. Such systems are still under development and are being tested in deep-sea research projects. Ocean and sea waters have relatively constant temperature differences throughout the year, enabling continuous energy production. The availability of large ocean areas can potentially provide high amounts of energy production. Therefore, these systems can play an important role in renewable energy production by utilizing the thermal energy of the seas. These systems have great potential, especially in tropical regions and where seawater temperature differences are significant [48].

### 2.5. Energy Conversion Methods in Wave Energy Harvesters (Dalga Enerjisi Dönüştürücülerinde Enerji Dönüşüm Metotları)

There are a limited number of energy conversion methods for converting wave energy into electrical energy. In this section, these methods will be explained.

- **Reverse Electrodialysis**: Electrochemical cells are used to convert chemical reactions into electrical energy. In salinity difference energy production, electrochemical cells are used to generate electricity from the ion flow between fresh water and saline water. Fresh water and saline water move between electrodes through a semi-permeable membrane. Water of different salinity levels moves ions through the membrane. These travelling ions create an electric current by moving between the electrodes. REDstack's Afsluitdijk project in the Netherlands is an example of such systems [49], [53].

- **Electromagnetic induction**: These systems are the most widely used energy conversion method in wave energy harvesters. Basically, the mechanical energy from the wave is transferred to a generator and an electric current is generated in the conductor under the changing magnetic flux by the movement of permanent magnets or a coil bundle. These systems can be analyzed under two categories depending on the structure of the generator used. These are systems with linear generators and rotary generators. In linear generator structures, the mechanical movement provided by the wave works on the principle of moving the coil or permanent magnet blocks forward and backward along a linear line. Rotary generator systems, as the name suggests, the wave motion is converted into rotational motion with a complete or certain angle change [44]. [54].

- **Piezoelectric energy conversion**: Piezoelectric materials are materials that are polarized as negative on one side and positive on the other side as a result of the stress in their crystal structure under mechanical pressure applied to them. Electrical energy can be generated by using this potential difference between the surfaces of the material. However, the energy efficiency of these systems is quite low. In addition, piezoelectric materials have a fragile structure. Another important disadvantage is that they have a water-soluble structure. Therefore, the structures where these systems are used must be isolated from water [50].

- **Triboelectric energy conversion**: Triboelectric conversion is an energy conversion method based on the charge exchange that occurs on the surfaces of materials due to friction. In such systems, electrical energy is generated by storing the static electric charges generated by friction in a capacitor. However, although the energy efficiency is quite low in this method, friction-induced wear and heating problems constitute other important disadvantages of these systems [51].

## 3.CONCLUSIONS (SONUÇLAR)

The increasing need for energy and the environmental problems caused by the methods used to meet this need have led to an increasing interest in clean and renewable resources. In this context, seas and oceans can be considered as resources with great energy potential. However, it is seen that the lowest share among renewable energy sources belongs to wave energy systems. The reasons for this can be briefly summarized as follows:

- **High Initial Investment Cost:** Wave energy technology is still under development and therefore the initial investment cost is relatively high.

- **Variability:** The amount of wave energy can vary depending on the weather and season, which can make it difficult to integrate it into the grid.

- **Environmental Impact:** Wave power plants can damage marine life and coastlines.

- **Technical Challenges:** Wave energy devices need to be designed and built to withstand the harsh conditions of the marine environment.

- **Visual and Noise Pollution:** Wave power plants can create visual and noise pollution.

- **Limited Compatibility:** Wave power plants are limited to coastal areas with strong waves.

However, with the developing technology, the cost per watt of wave energy systems is decreasing year by year. In this context, it is predicted that the share of wave energy harvesters and new harvesting methods among renewable energy sources will increase significantly in the near future [52]. Especially considering the marine resources of our country, the necessity of investing much more in this resource is clearly seen. The aim of this study is to provide a general classification of wave energy systems, and a brief description of the technologies used in this field and to emphasize the importance of wave energy systems in the light of scientific data.

## DECLARATION OF ETHICAL STANDARDS
(ETİK STANDARTLARIN BEYANI)

The author of this article declares that the materials and methods they use in their work do not require ethical committee approval and/or legal-specific permission.

Bu makalenin yazarı çalışmalarında kullandıkları materyal ve yöntemlerin etik kurul izni ve/veya yasal-özel bir izin gerektirmediğini beyan ederler.

## AUTHORS' CONTRIBUTIONS (YAZARLARIN KATKILARI)

***Alaaddin YILMAZER*:** He conducted a literature review on history of wave energy harvesters and performed the writing process.

Dalga enerjisi hasatçılarının tarihçesi hakkında literatür taraması yapmış ve yazım sürecini gerçekleştirmiştir.

***Ali Ekber ÖZDEMİR*:** He conducted a literature review on classification methodologies of wave energy harvesters and performed the writing process.

Dalga enerjisi toplayıcılarının sınıflandırma metodolojileri konusunda literatür taraması yapmış ve yazım sürecini gerçekleştirmiştir.

## CONFLICT OF INTEREST (ÇIKAR ÇATIŞMASI)

There is no conflict of interest in this study.

Bu çalışmada herhangi bir çıkar çatışması yoktur.

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