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Harnessing Ocean Power: Comparing Theoretical Wave Energy Outputs Across Global Regions

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Abstract

Wave energy is an abundant yet underutilised renewable energy source with the potential to meet nearly 10% of global electricity demand, equivalent to approximately 29,500 TWh annually. This paper explores the theoretical and technical potential of wave energy, evaluates various Wave Energy Converter (WEC) types, and compares wave energy with other renewable sources in terms of cost and efficiency. Results indicate that the most efficient WEC, the point absorber, achieves superior energy capture due to its compact design and multidirectional interaction. Despite its high energy density and predictability, wave energy's adoption is limited by high costs ($0.35–$0.85 per kWh) compared to solar ($0.06 per kWh) and wind ($0.081 per kWh). Analysis highlights Alaska as the region with the most potential, with an average wave power of approximately 58 kW/m along its coastline. Overcoming economic and technological barriers through innovation and policy support could enable wave energy to significantly contribute to sustainable energy goals by 2050.

Keywords: Wave energy – Renewable energy – Wave Energy Converters (WECs) – Energy efficiency

1. Introduction

1.1 Renewable Energy

The type of energy that can't be replenished from Earth in the near future is known as renewable energy. Renewable energy has emerged as a critical area of focus in addressing global energy demands, climate change, and sustainable development. The utilization of renewable energy sources, such as solar, wind, hydro, and biomass, offers significant potential to reduce greenhouse gas emissions, diversify energy supply, and enhance energy security. By 2040, the energy converted from fossil fuels will not be enough for global energy consumption [1]. There are many types of renewable energies, which are outlined and discussed in the following section.

1.2 Types of renewable energy

1.2.1 Solar energy

Solar power harnesses energy from the sun using photovoltaic (PV) cells or concentrated solar power (CSP) systems. Recent advancements in PV technology have improved efficiency and reduced costs, making solar energy increasingly competitive with conventional energy sources.

1.2.2 Wind energy

Wind turbines convert kinetic energy from wind into electricity. Research into turbine design and offshore wind farms has significantly boosted wind energy capacity in recent years.

1.2.3 Hydropower

Hydropower, the largest source of renewable electricity, uses flowing water to generate power. While it is reliable and scalable, concerns about ecological disruption remain by changing the natural flow of river.

1.2.4 Wave energy

The energy produced by the rising of ocean waves is known as wave energy. It uses Wave Energy Convertors (WECs) to achieve this. Wave energy has a high capital cost but it is not as well-known as the other renewable energies, so the investment is quite low. It is better and more efficient than solar and wind energy in terms of the energy produced.

1.3 Introduction to wave energy

Wave energy is a form of renewable energy harnessed from the movement of ocean waves. It is generated by the wind as it blows across the surface of the ocean, transferring its energy to the water. This energy, in the form of wave motion, can then be captured and converted into mechanical and electrical energy. It is considered one of the most prominent sources of energy, particularly because of its high density and predictable nature. It is far better than solar and wind energy as wave energy can be more efficient than solar and wind energy because it's more predictable and reliable. It also has a higher energy density and can generate power throughout the day, unlike solar and wind which can be more unreliable. Waves are generated by wind activity, which is driven by solar energy as the uneven heating of Earth's surface by the sun creates wind. Therefore, waves can also be considered an indirect form of solar energy.

1.4 Types of wave energy converters

Wave energy technology has developed significantly over the recent years. Now there are different types of wave energy converters based on different site conditions, environmental impact and cost effectiveness.

1.4.1 Oscillating Water Columns (OWC)

Oscillating Water Columns (OWCs) are devices that use the rise and fall of waves to create air pressure differences. As waves move, they force air in and out of a chamber, creating an airflow that drives a turbine connected to a generator. Most of these are or were located on the shoreline or near shore, and are sometimes named first generation devices. These devices are mostly place at the sea bottom and rocky cliffs. The devices placed at shoreline are easier to install.

1.4.2 Point absorber

Point absorbers are buoy-like devices that float on the ocean surface and convert vertical motion of waves into energy. When the waves move, the buoy moves vertically in response, creating relative motion between the buoy and the floating structure. This movement is then used to drive a power take-off system (PTO), which converts the mechanical energy into electrical power. Due to their small size, wave direction is not important for these devices.

1.4.3 Attenuators

These long, flexible structures capture energy from the horizontal movement of waves. The rise and fall of waves create a flexing motion which then is used to drive a hydraulic pump or a turbine to generate electricity. They typically consist of several connected segments that flex with wave motion, transferring mechanical energy to a generator.

1.5 Challenges of wave energy converters (WECs)

1.5.1 Regular maintenance practice

Regular maintenance practice leads to low reliability and high investment cost. In this case, the self-healing and resilient WEC systems are attractive solutions to encompass less frequent or no maintenance activities during the entire operating window (see page 366 from [1] for more on this).

1.5.2 Structural and Environmental Durability

WECs are exposed to harsh marine conditions, including high salinity, strong currents, and extreme weather events. Corrosion and biofouling reduce device lifespan and efficiency. Innovations in materials, such as corrosion-resistant alloys and coatings, are critical for enhancing durability.

1.5.3 High Costs and Scalability

The capital cost of deploying WECs, including design, installation, and maintenance, remains significantly higher than that of mature renewables like wind or solar. Standardization of designs and large-scale manufacturing could reduce costs, but this requires significant investment and international collaboration.

1.5.4 Limited Deployment Sites

WECs require locations with consistent wave activity, such as coastlines with high-energy waves, limiting their applicability to certain regions. Deployment areas often overlap with other marine activities, including fishing, shipping, and recreation, leading to potential conflicts.

1.5.5 Environmental impacts

The noise created by WECs underwater can interfere with a marine animal's navigation, behaviour and communication. These animals, unable to detect devices through sound signals, may inadvertently collide with them or become entangled in mooring cables. WECs can alter wave energy patterns, potentially impacting coastal erosion, sediment transport, and local currents. Changes in wave dynamics may affect coastal ecosystems, such as seagrass meadows and coral reefs, which rely on specific energy conditions.

1.5.6 Public Acceptance and Policy Support

Nearshore WECs may affect the visual appeal of coastlines and restrict recreational activities like boating and surfing, leading to public resistance. The absence of well-defined regulations and incentives for wave energy development slows down progress and investor confidence.

1.6 Global Potential of Ocean Wave Energy

The oceans cover over 70% of the Earth's surface, and wave energy represents an abundant and predictable renewable energy resource. The global theoretical wave energy potential is estimated at approximately 2 TW [2], equivalent to nearly double the current global electricity demand. However, they note that only a fraction of this energy is technically recoverable due to limitations in WEC efficiency, site accessibility, and environmental factors. As we know that fossil fuels will not be able to satisfy the global energy production near 2040, other renewable resources such as wave, wind and solar will be required to fulfil this energy demand.

Wave energy resources are not evenly distributed. High-potential regions include:

- **North Atlantic Ocean:** A key area for wave energy, with consistent and powerful wave climates.
- **Pacific Northwest (USA) and Southern Australia:** Known for their energetic wave patterns and proximity to coastal infrastructure.
- **Europe's Western Coastlines:** Countries like the UK, Portugal, and Ireland lead in wave energy research and deployment.

- **Southern Hemisphere Oceans**: Vast potential due to consistent wave activity driven by strong winds and uninterrupted ocean currents.

1.6.1 Technical Potential vs. Theoretical Potential

While the theoretical potential is vast, the technical potential the amount of energy that can realistically be captured is much lower due to technological, environmental, and economic constraints. Factors reducing the technical potential include:

- Efficiency limitations of (WECs).
- Challenges in deploying WECs in remote or hostile marine environments.
- Conflicts with existing marine activities, such as fishing, shipping, and tourism.

1.7 Comparison with other renewable resources

Wave energy holds immense potential but faces significant challenges compared to other renewable energy sources. While it offers predictability and higher energy density than solar and wind, its technological development is still in early stages, and it suffers from high costs and limited scalability. By contrast, solar and wind energy have matured and are more easily scalable, though they face intermittency issues and land use concerns. Wave energy, with its high theoretical potential and predictability, could play a significant role in the global energy transition if technological, economic, and environmental barriers are overcome.

2. Methodology

This study analysed theoretical wave energy outputs from different regions using publicly available datasets and compared the efficiency of various WEC technologies. The website "Marine Energy Atlas" [8] was also used to survey different generations of wave energy in different regions of the world. In this paper 10-15 random points were chosen from different coasts of the world and the average was taken to find the coast with the most wave energy generation. The cost of different types of wave energies to generate 1 kWh was also compared and the data was collected from different sources on the internet and from research papers, all of which are listed in the references section.

3. Results

TYPE	US cost (per kWh)
Wave energy	$0.35 – $0.85

Biomass	$0.8 – $0.15
Nuclear	$0.075
Solar thermal/concentrated	$0.06
Wind, offshore	$0.081
Hydropower	$0.061
Geothermal power	$0.049 - $0.08

Table 1: Cost comparison of different renewable energy types.

Wave energy has immense potential as a renewable energy source, with a theoretical global capacity of approximately 29,500 TWh annually, meeting nearly 10% of global electricity demand. However, current output remains below 100 MW, limited to pilot projects. Among Wave Energy Converters (WECs), point absorbers are the most efficient (see Figure 2), capturing multidirectional energy, while oscillating water columns (OWCs) and attenuators show promise for specific conditions. Despite its high energy density, wave energy faces significant challenges, including high costs, limited scalability, and environmental concerns such as corrosion, biofouling, and ecological disruptions. Its costs range between $0.35–$0.85 per kWh, making it more expensive than solar and wind energy though it is more efficient compared to them. High-potential regions include the North Atlantic Ocean, Pacific Northwest, and Europe's western coastlines, with Alaska emerging as the most productive area. Increased investment, innovation, and policy support are essential for wave energy to overcome its barriers and become a significant contributor to sustainable energy by 2050.

4. Discussion

4.1 Different renewable energies and their cost comparison

There are different types of renewable energies which vary from each other. The most dominating renewable energies include solar and wind energy as they are widely known and are cheap as well. However, the most efficient renewable energy is wave energy as it generates the most power in comparison to other energies. The major problem in the generation of wave energy is its cost. The cost requirement for development, deployment and maintenance is quite high which also requires high investment requirements compared to other renewable technologies. According to Table 1 wave energy is the most expensive and geothermal power is the cheapest in comparison to all the different renewable energies.

Table 2 highlights the significant disparity between wave energy's theoretical potential and its current contribution to global electricity production. Despite a global wave energy potential of 42.7 TW, only 2.7

TW is available in high-energy locations, and just 0.5 TW is estimated to be developable under current technological and economic constraints. This is in stark contrast to solar PV, which boasts a worldwide potential of 6500 TW and a much larger developable potential of 340 TW. Furthermore, wave energy's current contribution to electricity generation is negligible (0.000002 TW), underscoring the nascent stage of this technology compared to more mature renewables like hydroelectric power, which delivers 0.32 TW. These figures demonstrate the significant challenges facing wave energy in terms of scalability and efficiency, despite its high energy density and predictability. Bridging this gap will require substantial advancements in WEC technologies, as well as supportive policy frameworks to address economic and infrastructural barriers.

Energy technology	Power worldwide (TW)	Power in high-energy locations (TW)	Power in likely developable locations (TW)	Current power delivered as electricity (TW)
Wind	1700	120	40–85	0.02
Wave	42.7	2.7	0.5	0.000002
Geothermal	45	2	0.07-0.14	0.0065
Hydroelectric	1.9	1.9	1.6	0.32
Tidal	3.7	0.8	0.02	0.00006
Solar PV	6500	1300	340	0.0013
CSP	4600	920	240	46

Table 2: Energy production comparison of different renewable energy types.

4.2 Distribution of wave energy at different coasts

According to the website "Marine Energy Atlas" [8] there are three key coasts along the United States coastline regarding wave energy generation and the power generated varies from coast to coast. According to Fig 1 there is a large difference in wave energy generation at different coasts. We can see that the Alaskan coast generates the most energy per year and the Atlantic coast generates the least energy per year. If we take a look at table 3, we can see the coordinates and the power generated at different places along the Alaskan coast averaged annually and we see that the power generation does not vary significantly with location.

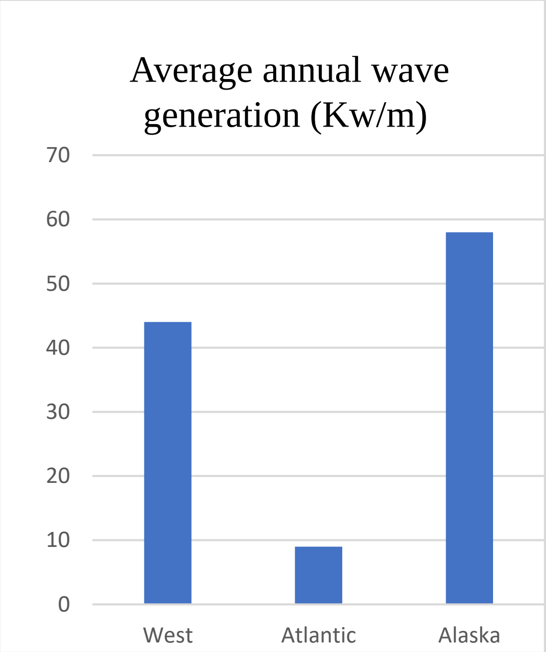

Figure 1: Wave energy generated at different United States coasts.

Coordinates	Average annual wave generation (Kw/m)
50.871902, -176.531430	58.03422656
50.872963, -176.655790	58.04041406
50.867783, -176.437990	58.07852734
50.866420, -176.565700	58.09294531
50.868225, -176.690340	58.09505078
50.867374, -176.340650	58.09527344
50.870674, -176.241470	58.09746094
50.872864, -176.852020	58.10078125
50.871048, -176.886660	58.13928125
50.861640, -176.472000	58.14065234

Table 3: Wave power generated in different areas along the Alaskan coast.

4.3 Extraction of wave energy

Wave energy devices extract energy through interaction with ocean waves, dissipating their energy in accordance with the law of conservation of energy. To achieve this, the devices create waves that cancel out incoming waves, thus permitting energy transfer. An effective device would have to be both absorber and generator; asymmetrical shapes, such as the Salter Duck, absorb more energy by creating directional waves, which is not so with symmetrical shapes, as they only absorb half. The width of the device, particularly in two-dimensional configurations, is vital for achieving maximum energy absorption. The process of energy extraction starts from primary conversion where wave energy is absorbed and converted into kinetic or potential energy by the use of structures that float, the flexible parts, or chambers. In the case of secondary conversion, the mechanical energy obtained from the capture process is then converted through hydraulic rams, pneumatic components, turbines, and controllable valves into rotational energy. Finally, in tertiary conversion, if electricity is the goal, a generator converts this energy into electrical power, with short-term energy storage incorporated to stabilize power output and handle wave variability. Efficient designs and proper energy storage are important for optimizing wave energy capture and utilization.

4.4 Different types of WECs

Wave Energy Converters operate by capturing the mechanical energy of ocean waves through various mechanisms and converting it into electrical energy. The efficiency and viability of WECs depend on factors such as device design, PTO optimization, environmental considerations, and durability in marine settings.

4.4.1 Point Absorbers

Point absorbers are floating devices that capture wave energy from all sides. They normally consist of a buoy that oscillates with wave motion.

Main Characteristics:

1. The relative motion between the buoy and a fixed reference (for example, seabed or another floating structure) is converted into electricity using a power take-off (PTO) system.
2. They can be installed singly or in arrays to enhance energy harvesting.

Advantages:

1. Compact design and flexibility in installation sites.
2. High energy capture potential due to multidirectional wave interaction.

4.4.2 Oscillating Surge

OWSCs harness the horizontal motion of waves close to the seabed. A flap or paddle oscillates with the wave motion and converts mechanical energy into electricity using a PTO system.

Main Characteristics:

1. Typically mounted in shallow waters with the strongest forces of wave surges.
2. Movement of the paddle is transmitted through a hydraulic system that drives the generator.

Advantages:

1. Efficiency is high, especially in shallow waters.
2. Possible integration with protection systems in coasts.

4.4.3 Attenuators

The attenuators are long, segmented structures floating on the surface, aligned parallel to wave direction. They capture energy from relative motion of the segments.

Main Characteristics:

1. The segments move with the wave, and mechanical energy is converted into electricity through hydraulic systems.
2. Captures the wave energy over large surface areas.

Advantages:

1. Attenuators are scalable and adaptable to most circumstances of waves.
2. Very low in visual impact compared to any other type of WECs.

4.4.4 Direct WEC comparisons

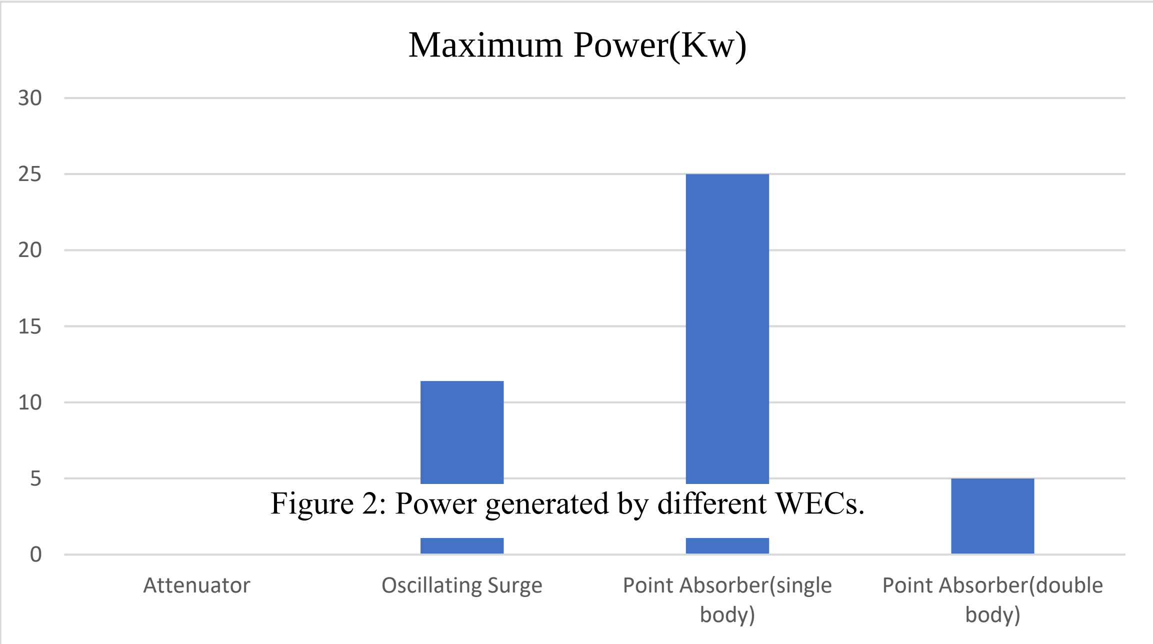

Figure 2: Power generated by different WECs.

Figure 3: Condition of WEC projects in different countries.

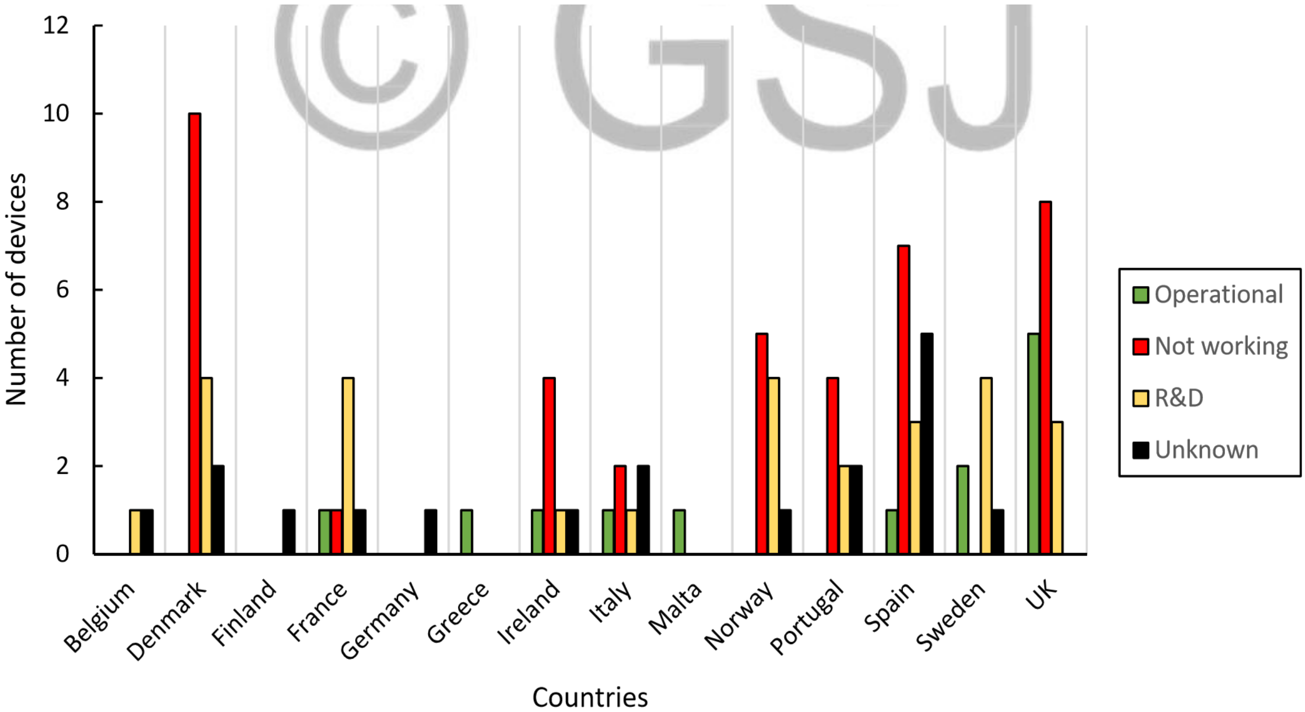

Fig 2 compares the power generation in different WEC types. Inspection of the figure suggests that point absorber generates the most power and this is due to their compact design and flexibility in installation sites. They also have high energy capture potential due to their multidirectional wave interaction. The power generation of attenuators is so small in comparison that it is barely visible in the figure. They are efficient when the wavelength of the water waves is large and the water is deep. Despite their low power output, they are adaptable and also provide much less visual impact so could become more easily accepted by the public as a large-scale renewable energy source.

Fig 3 shows us the current state of WECs in different countries in Europe. By looking at the figure closely we understand that Denmark has the most WECs that are not operational. This may be because Denmark has not developed a national strategy for wave energy. Despite this, they have plenty of experience with wind power, and Denmark has invested heavily in its wind infrastructure. The United Kingdom currently has the most operational WECs in Europe. Furthermore, the UK's wave energy resources are estimated to be 35% of Europe's and 1% of the World's [9]. This is due to their excellent natural wave resources as well as advanced techniques boosted by investment and favourable policies.

4.5 Global Wave Energy Output: a Summary of Wave Energy

Wave energy is a very promising yet largely underutilized renewable energy source that can contribute significantly to the global energy mix. The theoretical global potential of wave energy is estimated at around 29,500 TWh annually, which could meet nearly 10% of the world's electricity demand if harnessed efficiently. High-resource areas comprise the Atlantic coasts, the Pacific regions, and the southern oceans, thus holding the most promise for the capture of wave energy. But the actual world output of wave energy is currently very small indeed, with installed capacity less than 100 MW, essentially limited to pilots and experimental test sites. The large-scale development of wave energy technology faces some significant barriers. Technological barriers are the inefficiency and limited durability of current WECs, as well as their adaptability to varying wave conditions. The high costs of installation, operation, and maintenance also add to the limitations of scalability. Environmental concerns, such as impacts on marine ecosystems and regulatory complexities, add to the difficulties of wide-scale adoption. However, the future of wave energy is vast. Increased investment in research and development is expected to drive advancements in WEC design, improve efficiency and reliability, and lower costs. With supportive government policies, international collaboration, and continued innovation, wave energy could become a more substantial part of the global renewable energy portfolio by 2050, helping to meet the growing demand for sustainable and clean energy solutions.

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