

Harvesting the power of the oceans: Advancements, challenges, and the promising future of wave energy

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Abstract. This dissertation explores the pivotal domain of wave energy, delving into its historical evolution, technological advancements, and economic prospects. In response to escalating environmental challenges and the imperative to address climate change, the pursuit of sustainable and ecologically benign energy sources has gained prominence. Wave energy emerges as a compelling frontier within the realm of renewable energy, tapping into the perpetual undulations of oceans. The study traces the conceptual antecedents of wave energy from the 19th century to its current status as a burgeoning renewable energy source. Significant strides in technology during the 1990s and 2010s marked a shift towards optimizing energy conversion efficiencies, exploring novel materials, and refining wave energy converter designs. The dissertation analyzes diverse wave energy converter types, their operational principles, and their potential applications. Despite challenges such as environmental impact, operational reliability, and high capital costs, the unwavering commitment of researchers positions Wave Energy as a sanguine contender in the renewable energy landscape. The economic outlook for wave energy is promising, with global potential estimated at 2 billion kilowatts, fostering socio-economic benefits and contributing to carbon emission reduction. By presenting a comprehensive examination of wave energy, this dissertation underscores its significance in the pursuit of sustainable, environmentally friendly, and reliable energy solutions.

Keywords: Wave Energy, Renewable Energy, Wave Energy Converters, Technological Advancements in Wave Energy

1. Introduction

In light of escalating environmental challenges and the pressing imperative to mitigate the repercussions of climate change, the pursuit of sustainable and ecologically benign sources of energy has ascended to the forefront of priority areas. Amidst the quest for sustainable and innovative remedies to this exigency, wave energy has emerged as a compelling frontier within the realm of renewable energy. The perpetual undulations of the oceans proffer an abundant reservoir of electricity that remains substantially untapped, thereby underscoring the significance of proficient and effective harnessing of oceanic energy—a domain of pronounced research interest. The extraction of kinetic energy inherent in oceanic waves presents a distinctive prospect for diversifying our energy portfolio whilst concurrently curbing emissions of greenhouse gases. Nevertheless, wave energy, being a resource demanding a substantial degree of technical prowess, currently manifests an exploitation rate notably inferior to that of other

renewable energy sources. This disparity partly attests to the considerable latent potential enshrined in wave energy.

The earliest conceptual antecedents of wave energy trace back to the latter part of the 19th century, when pioneers and scholars first mooted the notion of transmuting the rhythmic cadence of waves into utilizable energy. However, the limitations posed by technological constraints and the preeminence of traditional fossil fuels engendered a stagnation of significant advancement. The energy crisis of the 1970s served to rejuvenate interest in alternative energy avenues, including wave power. This epoch witnessed the commencement of investigations into diverse mechanisms for capturing wave energy, encompassing oscillating water columns and point absorbers. Experimental prototypes were deployed across assorted locations to amass data and assess feasibility.

The 1990s marked a phase of prodigious strides in wave energy technology. Research institutions, academic establishments, and private enterprises embarked upon the development of more sophisticated prototypes, subsequently subjecting them to empirical scrutiny under authentic circumstances. This juncture marked a shift in emphasis towards the optimization of energy conversion efficiencies, as well as the exploration of novel materials and the refinement of wave energy converter designs.

The subsequent decade, the 2010s, witnessed a proliferation of pilot initiatives and demonstration installations dedicated to wave energy converters. Nations, especially those endowed with extensive coastlines and potent maritime currents, embarked on substantial investments in testing infrastructures and licenses for the deployment of more expansive apparatuses. This phase was characterized by an overarching objective to affirm the reliability, endurance, and propensity for grid integration of the technology. In recent years, wave energy has garnered prominence as a pivotal constituent of a diversified repertoire of renewable energy resources. Collaborative endeavors between governmental bodies, research establishments, and private enterprises have crystallized with the objective of amalgamating wave energy converters with pre-existing renewable energy grids. This integration endeavors to mitigate the intermittent nature inherent in certain renewable energy sources, proffering a steady and anticipatable oceanic energy stream. As technological acumen advances, researchers continue to probe novel configurations, enhanced materials, and more efficacious energy transmutation mechanisms. Furthermore, strides in control systems and predictive modeling have augmented the prognostic precision and optimization of wave energy extraction.

Throughout its developmental trajectory, the harnessing of wave energy has remained beleaguered by multifarious challenges, including the formidable maritime milieu, intricate technological exigencies, and the pronounced costs associated with research, development, and deployment. Notwithstanding these impediments, the unwavering commitment of scientists, engineers, and policymakers to the pursuit of sustainable energy solutions has yielded substantial headway, consequently positioning wave energy as a sanguine contender within the ambit of the renewable energy domain. The ensuing paper will undertake a comprehensive scrutiny of the captivating domain of wave energy, delving into its foundational principles, evolutionary technological strides, ecological footprints, prospective economic trajectories, and its role within the broader tapestry of worldwide endeavors toward renewable energy. By unleashing the latent energy enshrined within oceanic expanses, wave energy not only signifies a stride towards an unsullied energy prospect but also stands as a resounding testament to the potentialities of human resourcefulness.

2. Wave Energy Theory

2.1. Wave Energy Converter Overview

Wave energy converters (WECs) represent an exciting frontier in the quest for sustainable energy sources. These ingenious devices are commonly categorized according to their operational principles, deployment sites, and power generation systems. They are strategically positioned along coastlines, in nearshore regions, and even offshore to harness the full potential of wave energy.

In 2009, Drew, Plummer, and Sahinkaya reported an astounding array of over 1,000 wave energy collector designs documented in patents and publications. These designs can be broadly categorized into

three distinct types based on their fundamental operating mechanisms: oscillating water columns (OWCs), oscillating body systems, and overflow devices. Furthermore, wave energy converters are commonly classified into six primary categories: Point Absorbers, Terminators, Attenuators, Oscillating Surge, Underwater Differential Pressure, and Rotating Mass Devices.

2.2. Wave Energy Converter Classification and Working Principle

Rotating Mass Devices typically exploit resonance to capture energy from periodic waves, with power generation peaking when the incident wave frequency aligns with the device's natural resonant frequency. It's worth noting that various wave energy harvesters exhibit distinct characteristics and advantages, leading to a range of applications [1].

The Point-absorbing wave energy converter is characterized by its floating structure with horizontal dimensions smaller than its vertical dimensions, allowing it to harness wave energy at a single point. This design offers several advantages, including a compact size, cost-effectiveness, and a straightforward structure [2]. In a typical point absorber configuration, one end of the absorber remains fixed or relatively stationary, while the other end exhibits vertical motion in response to the oscillation of wave crests and troughs. This reciprocating motion serves to either pump fluid or drive a linear generator, thus generating usable power [3].

Surface attenuators function in a manner akin to point-type wave-absorbing buoys by employing multiple interconnected floating sections oriented perpendicular to the incident waves. The interaction of waves induces a bending motion that powers a hydraulic pump, resulting in electricity generation [4]. These devices are often characterized by their modular design and their reliance on joint bending as a means to produce electricity.

Pelamis devices are semi-submersible articulated structures that consist of interconnected cylindrical sections joined by articulated joints. These devices employ hydraulic cylinders to pump high-pressure fluid, which, in turn, drives hydraulic motors. These motors are responsible for driving generators, ultimately generating electricity while effectively mitigating wave-induced joint motion.

The Oscillating Surge design prototype harnesses the oscillation of ocean waves as they move back and forth. These devices are typically submerged, often placed on the seabed in shallow waters or even in more challenging locations near breakwaters. In this design, the articulated joint responds to the motion of the waves by pivoting, causing the oscillating surge to vibrate in a back-and-forth manner. The resulting motion of the flap acts like a large lever arm, which can be mechanically connected to either a generator for electricity production or a pump for fluid pressurization.

Submerged differential pressure comes in two distinct variations. The first type involves positioning the device on or near the seafloor, capitalizing on pressure fluctuations caused by waves passing overhead. These pressure fluctuations induce bending in flexible materials, such as airbags, and the resulting compression of fluid drives a turbine or other power output device. The second type is reminiscent of a point absorber, albeit submerged underwater. In this configuration, buoyant underwater floats are set in motion by passing waves, and this reciprocating motion is effectively transformed into energy through the utilization of a linear generator [3].

Rotating mass wave energy converters are generally surface-based devices that rely on an internal weight rotating around a fixed point to drive a rotating alternator. These devices exploit the rocking motion induced by the waves, which leads to shifts in the hull's center of buoyancy and center of gravity. As the ship's longitudinal pitch and sway vary, the rotating mass adjusts around its axis in search of a new center point. This continuous rotation of the mass aims to achieve equilibrium while simultaneously generating electricity.

2.3. The Future of Wave Energy Converters

Wave energy harvesters face challenges, including potential environmental impact, operational reliability in extreme ocean conditions, intermittency, high capital costs, competition from other renewable sources, regulatory complexities, and variable wave resources by location. Additionally,

public perception and acceptance can impact project feasibility. Addressing these issues is essential for advancing wave energy as a sustainable and economically viable energy source.

3. Wave Energy Development and Technology Advancement

3.1. History of Wave Energy

The history of wave energy research dates back to the late 18th century when the first wave energy patent was sought by Girard and his sons in France [5]. However, after World War I, the focus shifted to oil as the primary energy source, causing a decline in interest in wave energy [5].

In the late 1940s, Japan's Yoshio Masuda began researching wave energy and invented an oscillating water column power generation device, initially used for navigation buoys [5]. Additionally, individuals like Stephen Salter from Scotland and Kiell Budal from Norway joined the wave energy research field [5].

3.2. Current Development of Wave Energy in Various Regions

Today, with a global emphasis on renewable energy, various countries, including the United Kingdom, the United States, Australia, Denmark, and Spain, have initiated wave energy projects [6]. However, due to the early stage of research, challenges like device reliability and energy conversion efficiency persist [6].

Among them, various countries are also actively promoting the development of related wave energy. In China, the history of wave energy research and utilization has its roots dating back to the 1960s. It was during this time that China embarked on projects related to wave energy power generation (Development History and Key Technologies of Wave Energy Utilization, 2018). Through years of accumulated technological knowledge and the growth of scientific research teams, China has made substantial progress in wave energy power generation technology. As of 2022, China's installed wave energy capacity has reached 1.52 MW [5].

In January 2019, the U.S. Department of Energy announced that it was seeking to raise \$25 million in funding, including Oscilla Power, the University of Maine, Atargis Energy, Columbia Power Technologies and many other companies. Projects such as Triton WEC Oscillae Power, CycWEC Atargis Energy and Columbia Power Technologies' "RAY" series are underway.

Japan has always been a leader in the research and application of ocean energy power generation technology and has assembled more than 1,500 ocean energy power generation devices. Research institutions such as Okinawa Institute of Science and Technology, Hiroshima University, and Toyota Institute of Technology are all involved in research on ocean energy power generation. Notable projects include a combination of turbines and tetrahedrons for capturing and harvesting ocean energy, an ocean power station installed in Iwate Prefecture, and an ocean energy system based on wind turbines.

Europe is the global leader in ocean energy power generation technology, with nearly 60% of ocean energy power generation companies. The European Commission has finalized the Horizon 2020 project to increase the capabilities of ocean energy power converters. Universities such as Plymouth University and Uppsala University are engaged in research focusing on linear generators and optimized systems. Companies such as AWS Ocean Energy (Scotland), CorPower Ocean (Sweden) and Ocean Harvesting Technologies have developed point-to-point ocean energy converters with variable power [7].

Adding to the global progress, Wave for Energy, a company from Italy's Politecnico di Torino, achieved a significant milestone. They developed Italy's first full-scale device for generating electricity from ocean waves, moored off the coast of Pantelleria Island, Italy, in 2015. The device initially operated independently before being connected to the island's grid, supplying energy to smaller Mediterranean islands. This achievement resulted from research efforts that began in 2006 by a team led by Giuliana Mattiazzo and Ermanno Giorcelli from the Department of Mechanical and Aerospace Engineering at Politecnico di Torino, marking a step toward industrializing Wave for Energy.

4. The Economic Future of Wave Energy

4.1. *The Future Potential of Wave Energy*

Wave energy, hailed as a prominent renewable resource, holds the promise of revolutionizing our approach to sustainable energy solutions, underpinned by its renewability, environmental friendliness, widespread applicability, and unwavering reliability. While it's undeniable that commercializing wave energy encounters certain hurdles, the continuous march of technological progress and the concurrent reduction of costs are set to catapult wave energy into the forefront of our energy landscape. Remarkably, global wave energy potential is estimated at an astounding 2 billion kilowatts, sufficient to power vital activities like national defense and remote ocean development, thereby bearing immense socio-economic significance by mitigating the expenses associated with marine resource development and augmenting national defense [2].

Moreover, statistical projections affirm the rising prominence of wave energy, with the global wave energy market poised to surge at a commendable CAGR of 17.8% from 2020 to 2027. This upward trajectory is chiefly driven by the burgeoning demand for marine power generation and the imperative of satisfying the escalating electricity requisites of coastal communities. Illustrating this commitment to propelling wave energy into the mainstream, the U.S. Department of Energy has recently unveiled a substantial \$27 million investment in federal funding, strategically allocated to further the commercialization of wave energy technology. This allocation is divided into three pivotal segments: wave energy conversion technology testing, research and development, and wave energy converter design. Paralleling these endeavors, the United Kingdom is actively cultivating wave energy technology, with several enterprises engaged in the development of wave energy systems. The UK government has pledged a noteworthy \$10.37 million in public funding for wave energy development projects, underscoring the transformative potential of wave and tidal energy within the UK's energy matrix. Scotland, endowed with abundant marine resources along its coastline, has initiated the Wave Energy Scotland (WES) program to invigorate innovation and the commercialization of wave energy technologies, proudly supported by governmental funding, fostering several pioneering wave energy innovation projects [8].

The academic discourse, as encapsulated in the article titled "A review of wave energy technology from a research and commercial perspective," paints a compelling picture of wave energy's vast underutilized potential, with a global estimate ranging from 1 to 10 TW. This reservoir of untapped energy holds the key to substantial carbon emission reduction and the quenching of our ever-increasing energy thirst. In the grand tapestry of renewable energy sources, wave energy stands tall with its advantages, boasting higher energy density, increased energy utilization, lower environmental footprint, seamless integration into existing energy infrastructures for smoother power output, and heightened predictability. These attributes unequivocally position wave energy as a formidable contender in the energy landscape. Depending on the estimation method, global wave energy's theoretical potential hovers around 32,000 TWh/year, with an accessible resource base of approximately 3 TW. These numbers beckon a compelling commercialization narrative for wave energy in the power supply sector [9].

4.2. *Challenges for the Development of Wave Energy*

Nonetheless, the glaring incongruity lies in the current wave energy generation capacity, which stands at a meager 2.31 MW, indicating that wave energy technology is still at its nascent stages, grappling with a constellation of challenges, ranging from elevated costs to environmental exigencies and financial uncertainties. Realizing the commercialization of wave energy hinges upon bolstering research and development (R&D) initiatives, fostering technological maturity, cost diminution, and the attraction of both private and public investments. A diminishment in private and public investments could, paradoxically, be the very catalyst to galvanize wave energy technology development by incentivizing a surge in R&D activities [9].

Notwithstanding its tremendous potential, wave energy technology confronts a gamut of challenges, characterized by the pressing need for substantial investment and the establishment of a robust infrastructure, which, if not addressed proactively, could serve as impediments to the burgeoning wave energy market. Hence, an urgent infusion of R&D investments becomes imperative in order to surmount these barriers.

5. Conclusion

In conclusion, the exploration of wave energy stands as an exemplar of our commitment to sustainable energy solutions amidst escalating environmental challenges. The inexhaustible rhythm of ocean waves provides a vast and largely untapped reservoir of electricity, underscoring the need for proficient harnessing of this potent energy source. Wave energy has a compelling history, evolving from its conceptual origins in the 19th century to its current status as a burgeoning renewable energy frontier. The development of various wave energy converter designs, ranging from point absorbers to oscillating surge systems, has paved the way for a promising future.

Despite its remarkable potential, the path to wave energy commercialization is fraught with challenges, including environmental considerations, technological complexities, and cost barriers. However, the unwavering dedication of scientists, engineers, and policymakers to sustainable energy solutions has propelled wave energy into the spotlight. Collaborative efforts across nations and the integration of wave energy into existing renewable energy grids signify a significant step forward. As technological advancements continue to enhance the efficiency and predictability of wave energy conversion, the tide is turning in favor of this sustainable energy source.

Looking ahead, the economic outlook for wave energy is promising. With the global wave energy market projected to grow at an impressive rate, governments, research institutions, and private enterprises are investing in research, development, and commercialization efforts. The potential of wave energy to contribute to carbon emission reduction and meet the rising energy demands of coastal communities positions it as a formidable contender in the energy landscape. However, realizing its full potential requires substantial R&D investments and infrastructure development to address current challenges and unlock the vast oceanic energy resource. Wave energy, once harnessed to its full extent, offers a beacon of hope in our quest for sustainable, environmentally friendly, and reliable energy solutions.

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