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Review

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Advanced ocean wave energy harvesting: current progress and future trends

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Abstract: With a transition towards clean and low-carbon renewable energy, against the backdrop of the fossil-energy crisis and rising pollution, ocean energy has been proposed as a significant possibility for mitigating climate change and energy shortages for its characteristics of clean, renewable, and abundant. The rapid development of energy harvesting technology has led to extensive applications of ocean wave energy, which, however, has faced certain challenges due to the low-frequency and unstable nature of ocean waves. This paper overviews the debut and development of ocean wave energy harvesting technology, and discusses the potential and application paradigm for energy harvesting in the "intelligent ocean." We first describe for readers the mechanisms and applications of traditional wave energy converters, and then discuss current challenges in energy harvesting performance connected to the characteristics of ocean waves. Next, we summarize the progress in wave energy harvesting with a focus on advanced technologies (e.g., data-driven design and optimization) and multifunctional energy materials (e.g., triboelectric metamaterials), and finally propose recommendations for future development.

Key words: Ocean wave energy; Wave energy converters; Energy harvesting technology; Advanced energy materials; Intelligent ocean

1 Introduction

Nearly 40% of global population and 70% of industrial capital are located within 100 km of marine coastlines (UN, 2017). Because of proximity to these sites with high energy demand, ocean energy is recognized as a significant potential means of mitigating climate change and energy shortages. It is clean, renewable, and abundant (IRENA, 2020). Among the major ocean energy resources, wave energy has the outstanding merits of high density and wide distribution, which opens up the possibility of generating electrical power in most marine environments with a small converter unit volume (Khan et al., 2017). Wave energy suitable for harvesting is predominantly from wind-generated waves, whose average annual power flux ranges from 10 kW/m to 100 kW/m (Mei, 2012). Wind-generated waves are dominated by gravity and inertial forces. Thus, they can propagate a long way with low energy decay and continuous wind drive, meaning that wave energy is a stable renewable energy source (Folley, 2017). The global wave energy capacity is theoretically 29500 TWh per year, which would be sufficient to meet the entire global energy demand (Mørk et al., 2010). Wave energy distribution is generally consistent with that of wind energy, which is powerful in the latitudes of 30°–60° and weak near the equator and poles (Gunn and Stock-Williams, 2012).

Although the French granted the first wave energy converter (WEC) patent as early as 1799, wave energy harvesting did not receive much attention until the first oil crisis. Salter (1974) published a paper titled "Wave Power" in the prestigious journal *Nature*, immediately generating enthusiasm in the academic community. The first large-scale WEC, called Kaimei (Miyazaki and Masuda, 1980), the integration of WEC into breakwaters in Sakata (Goda et al., 1991) and Trivandrum (Ravindran and Koola, 1991), and the overtopping WEC prototype TAPCHAN (Mehlum, 1986), all emerged in this period. Since entering the

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21st century, the coastal countries have continued to actively deploy policies and funding for wave energy harvesting to fuel further development. The European Marine Energy Center in Orkney, Scotland, is now the most authoritative international testing and certification institution for marine energy installations (EMEC, 2020). The USA released the United States Marine Hydrokinetic Renewable Energy Technology Roadmap in 2010, and launched the construction of a national wave energy testing facility named PacWave in 2016 (DOE, 2016). Australia is also a maritime power with massive potential for wave energy harvesting, where the MK1, MK2, and MK3 developed by Oceanlinx have been connected to the grid successfully (Falcão and Henriques, 2016). China has achieved some important technologies, such as a wave energy aquaculture cage called Penghu and a 500 kW WEC called Zhoushan. Portugal, Japan, India, and Ireland are also at the frontier of wave energy harvesting (IEA-OES, 2021).

Wave energy is a high-grade energy source that contains both kinetic and potential energy, allowing almost any transmission mechanism to be feasible for wave energy conversion. Consequently, thousands of WECs have been invented (Kofoed, 2017), but few have seen successful commercialization. The current progress of wave energy harvesting faces certain challenges, mainly due to the trade-off dilemma between technology and cost. First, WECs are designed to resonate in order to maximize energy conversion; this leads to large motions that cause critical reliability and survivability issues. Next, ocean wave frequencies are generally low, so the matching natural frequency of a WEC should also be low; the relatively large equipment sizes required for this are expensive. In addition, waves are random and unstable, while WECs are designed for specific sea conditions; therefore, the large variations in waves cause critical efficiency issues. These challenges make the design considerations for WECs different from those for traditional offshore engineering structures. Many studies have been done on WECs to reduce costs and enhance performance, which is vital for promoting commercialization. Besides large-scale power production, specialized applications of wave energy harvesting are another option for achieving economic viability. On the one hand, WECs could be deployed at small islands, marine buoys, offshore construction sites, and other locations where traditional energy is expensive, unavailable, or inaccessible (Fadaeenejad et al., 2014; McLeod and Ringwood, 2022). On the other hand, they could be integrated into breakwaters, offshore wind farms, and fish culture, where multiple functions could share the cost and space (He et al., 2019; Nguyen et al., 2020).

There have been many review papers covering various aspects of wave energy harvesting, including its mechanisms and classification (Drew et al., 2009; Falcão, 2010; López et al., 2013), power-take-off (PTO) system and control strategies (Wang LG et al., 2018; Ahamed et al., 2020), modeling methods (Li and Yu, 2012; Penalba et al., 2017; Windt et al., 2018), reliability and survivability (Clark and DuPont, 2018; Coe et al., 2018), integration with offshore infrastructures (Pérez-Collazo et al., 2015; Mustapa et al., 2017; Clemente et al., 2021), mooring system (Davidson and Ringwood, 2017; Qiao et al., 2020), economic analysis (Astariz and Iglesias, 2015; Bhuiyan et al., 2022), and status of particular country/continent (Clément et al., 2002; Lehmann et al., 2017; Qiu et al., 2019). It must be acknowledged that traditional wave energy harvesting is not yet fully mature and needs a breakthrough that would enable it to handle the essential characteristics of sea conditions. In this regard, some advanced technologies have emerged in recent years. Triboelectric nanogenerators (TENGs) are a typical example that has significant advantages for collecting low-frequency energy, strengthening its practicality for wave energy harvesting (Wang et al., 2017; Zhang QY et al., 2021). Wang et al. (2015) reported a spherical TENG and Xu et al. (2019) designed a tower-like TENG with high power density for direction-independent energy acquisition. Artificial intelligence (AI)-based performance-oriented optimization has been used to realize the ideal theory-based control. With the development of metamaterials and AI techniques, many novel mechanisms and research methods have been applied to improve wave energy harvesting performance. Means of achieving high-efficiency wave energy harvesting include phase control or resonance formation. For example, Zou et al. (2022) found that deep reinforcement learning (DRL) control outperformed model-based control in the power production of direct-drive WEC systems. This review aims to inform readers about the mechanisms and applications of traditional WECs, existing challenges due to the nature of ocean waves, current progress in wave energy harvesting with a focus on advanced technologies and energy materials, and recommendations for future development.

2 Mechanisms of ocean waves and traditional applications

2.1 Mechanisms and characteristics of ocean waves

Although monochromatic waves have been commonly accepted for WEC performance testing, ocean waves are random and irregular. Generally, irregular wave theories are employed to reproduce real sea conditions, as follows:

$$\eta(x,\ t)=\sum_{n=1}^{\infty}a_n\cos(k_n x-\omega_n t+\varepsilon_n), \tag{1}$$

where the foot marker n presents the nth partial wave, a_n the wave amplitude, k_n the wavenumber, ω_n the angular frequency, x the distance, t the time, and ε_n the initial phase angle ranging in $[0, 2\pi]$. Wave characteristics vary significantly by season and region, making wave energy assessments increasingly important (Arinaga and Cheung, 2012). These assessments mainly depend on ocean buoy and satellite altimeter data in the early stages, and advanced wave models in the later stages. Rapidly developed wave models make it possible to accomplish local refinement assessments, even in marine areas without observation information (Gunn and Stock-Williams, 2012), which contribute considerably to pre-site selection of nearshore wave energy harvesting.

2.2 Applications of ocean waves in energy harvesting

As mentioned above, thousands of WECs have been invented so far. The working principles, operation modes, structural features, and deployment locations of WECs are remarkably diverse. Aside from a few exceptions, the conversion process in a WEC generally consists of three stages, and performance depends heavily on ocean wave conditions. Here, we will follow the classification method of Falcão (2010), which is widely accepted by the academic community. Most WECs can be categorized into three types: oscillating water column, oscillating body, and overtopping system. For three categories, wave energy is converted into pneumatic, kinetic, and potential energy, respectively, in the first conversion stage; accordingly, the PTO mechanism is mainly air turbine, hydraulic motor, and low head hydraulic turbine in the second conversion stage. As illustrated in Fig. 1, each category can be further divided into floating and fixed, and some WECs listed have undergone pilot or prototype testing.

2.2.1 Oscillating water column WECs

The oscillating water column (OWC) WEC was the earliest one developed, dating as far back as 1940. As illustrated in Fig. 2, a typical OWC WEC consists of a hollow pneumatic chamber with a large opening below water level. Air is trapped inside the hollow chamber above the internal water column to act as the conversion medium. Incoming waves cause the internal water column to oscillate and convert wave energy into pneumatic energy of trapped air. Then the oscillating pressure of the trapped air can drive an air turbine at the chamber top as the PTO and convert pneumatic energy into mechanical energy for electricity production (He et al., 2012, 2013; Heath, 2012). The oscillating trapped air is reciprocating. If traditional one-way turbines are used, complex valve systems are needed and will cause considerable energy loss, so self-rectifying turbines are more suitable and widely employed. The Wells turbine and impulse turbine are the two most commonly used self-rectifying turbines for OWC WEC (Falcão and Henriques, 2016).

Due to their operating principle and structural simplicity, OWC WECs have the most refined design, and are suitable for both stand-alone and integrated use (He and Huang, 2014, 2016, 2017; He et al., 2023). OWC WECs which have undergone pilot or prototype testing include the Sakata in Japan (Goda et al., 1991), the Might Whale in Japan (Ogata et al., 2002), the Pico in Portugal (Falcão et al., 2020), the LIMPET in the UK (Alcorn and Beattie, 2001), the LeanCon in Denmark (LEANCON, 2015), the OE Buoy in Ireland (Alcorn et al., 2014), the MK3 in Australia (Falcão and Henriques, 2016), the Mutriku Plant in Spain (Torre-Enciso et al., 2009), the SparBuoy in the UK (Falcão and Henriques, 2014), the GreenWAVE in Australia (Appleyard, 2015), the Yongsoo plant in Korea (Liu et al., 2016), the REWEC3 in Italy (Arena et al., 2013), the Uniwave200 in Australia (WSE, 2021), and the Drakoo in China (Hann-Ocean, 2022).

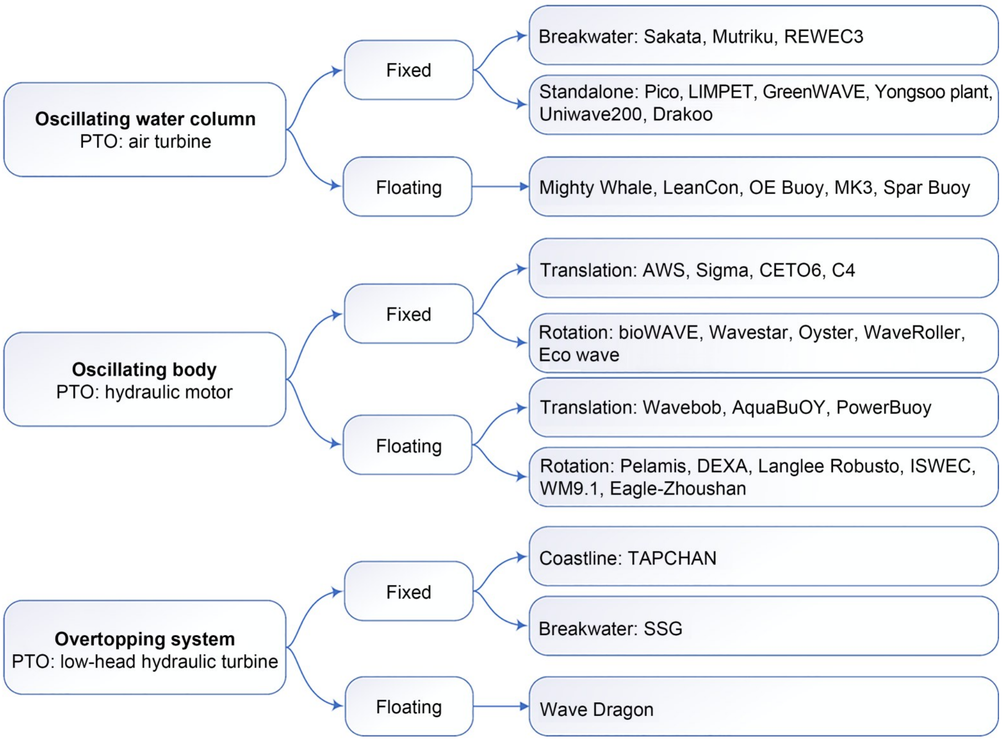

Fig. 1 Classification of WECs. Reprinted from (Falcão, 2010), Copyright 2010, with permission from Elsevier

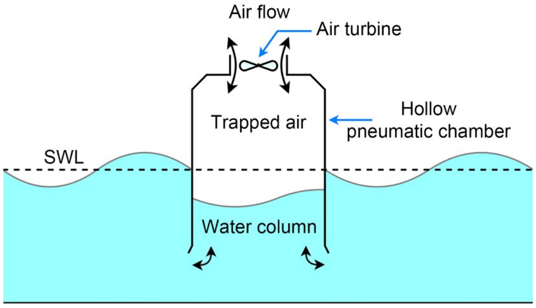

Fig. 2 Schematic diagram of OWC WEC (SWL: still water level)

2.2.2 Oscillating body WECs

A rigid body can move in six degrees of freedom. The oscillating body is a broad concept. As illustrated in Fig. 3, the oscillating body in this WEC design can have diverse shapes and move in various degrees of freedom. Incoming waves cause the body to oscillate and convert wave energy into kinematic energy of the body. Then, the motions of the oscillating body can drive a hydraulic motor as the PTO and convert kinematic energy into mechanical energy for electricity production (Xu et al., 2022). Based on its relationship to wave direction and motion modes, the oscillating body can be subcategorized as point absorber, attenuator, and oscillating water surge converter. The motions of oscillating bodies are random and unstable, so hydraulic motors and transmission systems are generally employed to achieve continuous and stable mechanical energy (Albert et al., 2017).

Although their long-term operability and durability are in doubt due to the movable components in the seawater, oscillating body WECs are considered some of the most economical and efficient (Li and Yu, 2012; Guo et al., 2021). Those which have undergone pilot or prototype testing include the Wavebob in Ireland (Tarrant and Meskell, 2016), the AquaBuOY in the USA (Weinstein et al., 2004), the AWS in Portugal (Prado and Polinder, 2013), the Pelamis in the UK (EMEC, 2004), the OPT PowerBuoy in the USA (Gerber and Taylor, 2003), the Sigma in Montenegro (SIGMA-ENERGY, 2018), the bioWAVE in Australia (Zhang and Aggidis, 2018), the Wavestar in Denmark (Wave Star, 2012), the DEXA in Denmark (Zanuttigh et al., 2013), the Oyster in the UK (Whittaker and Folley, 2012), the Langlee Robusto in Spain (LANGLEE, 2013), the ISWEC in Italy (ENI, 2022), the CETO6 in Australia (Carnegie, 2017), the WaveRoller in Portugal (AW-ENERGY, 2022), the WM9.1 in Cyprus (SWEL, 2022), the Eco Wave in Gibraltar (EWP, 2016), the

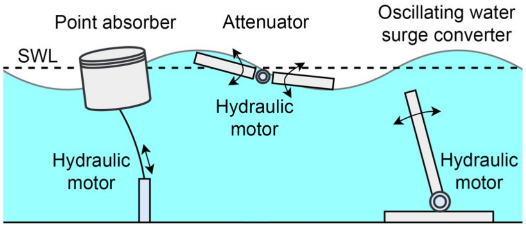

Fig. 3 Schematic diagram of oscillating body

C4 in Sweden (CorPower Ocean, 2018), and the Eagle-Zhoushan in China (IEA-OES, 2021).

2.2.3 Overtopping system WECs

The overtopping system is unique in various WECs and the principle is more similar to that behind hydroelectric power. As illustrated in Fig. 4, a typical overtopping system WEC consists of a reservoir with a sloping access. Incoming waves climb up the sloping access into the reservoir and convert wave energy into potential energy in the water stored in the reservoir. Then the head difference between internal and external water levels can drive a low head hydraulic turbine as the PTO and convert potential energy into mechanical energy for electricity production (Contestabile et al., 2017). The overtopping process is highly nonlinear. Occurrences of wave runup and breaking cause large energy loss, so the conversion efficiency of this design is low. However, overtopping system WECs can convert the random and unstable energy of waves into stable potential energy in the reservoir (Pérez-Collazo et al., 2015), and can use the mature axial flow turbines of hydroelectric power stations.

Overtopping system WECs have high requirements for reservoir capacity and deployment topography, so there are relatively few of them in operation. Models which have undergone pilot or prototype testing include the TAPCHAN in Norway (Mehlum, 1986), the Wave Dragon in Denmark (Tedd and Kofoed, 2009), and the SSG in Norway (Margheritini et al., 2009).

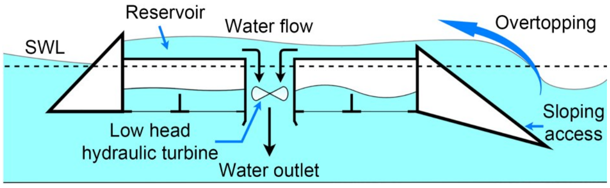

Fig. 4 Schematic diagram of overtopping system WEC

2.3 Performance and comparison

To date, none of the existing WECs has achieved economic viability. There is no predominant WEC design like the three-bladed horizontal-axis turbine in the wind energy sector. The wave energy sector is still making great efforts towards more efficient technologies and economic applications (Aderinto and Li, 2018). There is a wide variety of WEC concepts, with highly individual manufacturing, transportation installation, and operation costs. Due to the lack of data, it is hard to quantitatively compare different WEC concepts within the same framework at this time, and only a relatively general assessment can be obtained. In terms of efficiency, Babarit (2015) set up a database of capture width ratio (CWR) for WECs and performed a statistical analysis on the mean CWR for each type of WEC, as shown in Table 1. In order to carry out a comprehensive evaluation of performance, the scarce and precious data from some WECs that have undergone sea trials were collected by Xie et al. (2017) and Zhang YX et al. (2021). The latter group proposed a multi-index evaluation model including aspects of energy capture, technology-cost economics, reliability, environmental friendliness and adaptability. Their evaluation indicated that the oscillating body WEC offered the most benefits,

Table 1 Mean CWR and main issues for each type of WEC

Type of WEC	PTO	CWR	Main issues	
Oscillating water column	Air turbine	29%	Multiple chambers; air compression; efficiency of air turbine	Integration; array layout optimization; mooring system; control strategy local adaptation; environmental implications
Oscillating body	Hydraulic motor	16% (translation); 37% (rotation)	Reliability; multiple degrees of freedom	
Overtopping system	Low-head hydraulic turbine	17%	Design of sloping access and reservoir; parameter optimization of outlet pipe and PTO	

owing to its efficiency and environmental friendliness. The major drawback of the OWC WEC, on the other hand, is clearly the weak performance of the air turbines.

However, the economic feasibility of a WEC depends more on the local wave energy resources in most cases, and thus, local adaptation is essential to design. By way of example, 25 kW/m is the representative wave energy flux along the coasts of Europe and the USA, while it may be much smaller in China (Mustapa et al., 2017). Amrutha and Sanil Kumar (2022) investigated the performance of a few WECs in the wave conditions of the Indian shelf seas, and recommended a kind of pontoon (oscillating body) WEC. Castro-Santos et al. (2020) found that the Wave Dragon (overtopping system) WEC offered good value in the wave conditions of the north of Spain. Xie et al. (2017) preferred a point absorber or duck-type (oscillating body) WEC for areas with low wave energy flux, like China. Focusing on the areas with the world's highest wave power, Rusu and Onea (2017) made a performance assessment of ten WECs based on their technical specifications. In addition to local adaptation, control strategy plays a significant role in the performance optimization of WECs in random and unstable wave conditions (Ringwood et al., 2014; Li et al., 2021). Damping control, reactive control, latching/unlatching, and model predictive control are the most common control strategies; they can be used to adjust the dynamic response of WECs and greatly improve energy harvesting performance of WECs (Maria-Arenas et al., 2019).

Many studies have been done on the oscillating water column, oscillating buoy, and overtopping system. A comprehensive evaluation of the performance of various existing WECs has become critical. It will help significantly in converging on a predominant model for WECs and focus further in-depth research.

3 Current progress in ocean wave energy harvesting

In this section, we review the promising direction of data-driven exploration as well as applications of advanced multifunctional materials and structures in ocean wave energy harvesting. We also give an overview of the emerging integrated ocean wave energy harvesting systems. Data-driven technique, in principle, takes advantage of given data to unveil the relationships behind complex inputs and corresponding outputs; this relies greatly on algorithms to accomplish tasks in material exploration and application without step-by-step instructions (Himanen et al., 2019; Schleder et al., 2019; Qu et al., 2021). Ever since its debut in the context of rapid development of computer technologies, data-driven technique has been extensively used in various fields such as material exploration (Tian et al., 2021; Cai et al., 2022) and structural optimization (Barri et al., 2021; He et al., 2021; Wei et al., 2021; Da et al., 2022; Jiao et al., 2023). In the specific domain of ocean wave energy harvesting, data-driven technique has demonstrated its superiority in predicting energy harvesting performance and efficiency by using AI algorithms (Gioia et al., 2022). Due to its ability to identify the unknown connections between inputs and outputs, AI has become an effective alternative to traditional statistical tools. AI algorithms are superior to these tools in computational efficiency, especially for issues in exploring and applying energy materials (Li et al., 2020; Sha et al., 2020; Liu Y et al., 2021). Therefore, AI has been applied to address the current questions surrounding new energy materials and performance prediction (Jha et al., 2017; Chen et al., 2020; Rahman et al., 2021; He et al., 2022). Three main contributions of AI have been reported in exploring and applying energy materials, including material discovery (Cai et al., 2020; Lu, 2021), structural optimization (Wang et al., 2015; Yu et al., 2019; Dudem et al., 2020), and performance-oriented inverse design (Peng et al., 2019).

3.1 Exploration and application paradigms of advanced energy materials

To this end, the typical application paradigms of AI in advanced energy materials can be categorized into data collection and representation, algorithm determination, and model development (Zhou et al., 2019; Barnett et al., 2020; Das et al., 2020), as shown in Fig. 5. In order to collect and represent data, AI algorithms are trained by the existing data on ocean wave energy harvesting. It is therefore necessary to maintain the quality and quantity of the data pool. For example, ocean waves typically consist of tens of thousands of low frequency cyclic fluctuations, which usually create 30% waste data (i.e., data noise) in the pool (Jiao, 2021). Thus, initial data preprocessing is important in exploring energy materials by AI (Gibert et al., 2016; Epps et al., 2021). Identifying and correcting errors is critical to reducing the possibility of misleading AI models. During algorithm determination, the raw data are preprocessed due to the huge amount of data collected in ocean wave energy harvesting strongly influencing the accuracy and efficiency of AI models. Given its high error-tolerance when handling noisy and incomplete data, AI is able to establish nonlinear relationships between inputs and outputs, and therefore, determine the dominant parameters of energy materials, in order to obtain advanced energy materials with high energy harvesting efficiency for ocean wave environment (Kalidindi et al., 2016; Gomes et al., 2019). During model development, AI is able to unveil the featurization between the input and output variables and develop a suitable model to guide the discovery of energy materials; and, more importantly, improve their applications in ocean wave energy harvesting. In general, the more suitably the raw data are represented and the more effectively the AI algorithms are determined, the more accurately and efficiently advanced energy materials can be explored (Sahu et al., 2018; Jiao and Alavi, 2021).

3.2 Data-driven design and optimization of energy devices

Due to the structural complexity of energy devices, data-driven tools have been extensively used in their structural design and optimization. The frequency and amplitude of ocean waves make it necessary to take advantage of structure to trigger energy materials for high efficiency energy harvesting, as shown in Fig. 6a. For example, starting with arbitrary population of initial designs, evolutionary computation compares and optimizes the designs with respect to the predefined

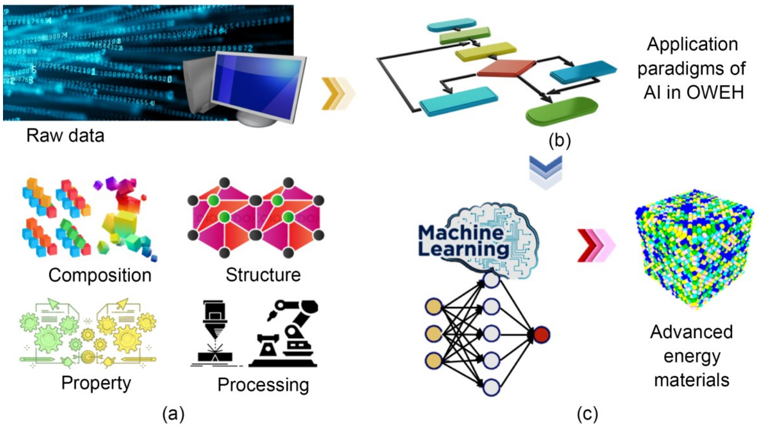

Fig. 5 Application paradigms of AI in advanced energy materials: (a) data collection and representation; (b) algorithm determination; (c) model development. OWEH: ocean wave energy harvesting

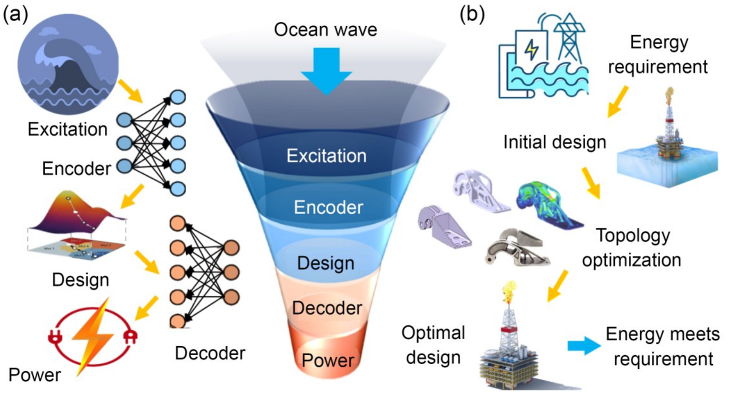

Fig. 6 Data-driven design and optimization of energy devices: (a) structural design to assist in efficiently triggering energy materials in response to ocean waves; (b) illustration of AI-enabled inverse design of energy devices in ocean wave energy harvesting

fitness evaluation function of ocean wave energy harvesting performance, and the designs with the best energy performance have the best chance to be the design parents for the next generation (Sirigu et al., 2020; Yang et al., 2022). Next, the selected designs are arbitrarily transformed into new designs based on crossover, recombination, or mutation operations. Eventually, the fittest design with the best energy harvesting response is determined from millions of possible designs generated during the evolutionary process.

While existing data-driven design and optimization studies have primarily focused on determining the best structural designs with respect to the evaluation function of ocean wave energy harvesting performance, the entire concept of AI for performance-oriented inverse design of novel energy devices is still in its infancy (Tang et al., 2020). One of the most vital issues in optimizing the energy harvesting performance of these devices is finding a way to establish appropriate predictor variables; and the next step toward AI-enabled inverse design of energy devices is to obtain optimal structures by directly considering the required energy harvesting performance response, as shown in Fig. 6b. In this strategy, a set of design constraints can be passed to a topology-optimization algorithm to generate the initial energy device geometries, and AI then explores a suite of new designs that outperform the initial patterns used for its training. As a consequence, AI-based structural design and optimization significantly enhance the experiential nature of design prototyping (Salehi and Burgueño, 2018; Wu et al., 2021).

3.3 Data-driven integrated ocean wave energy harvesting systems

Integrated ocean wave energy harvesting systems driven by advanced data technology have four layers: environment, software, hardware, and application, as shown in Fig. 7. The environment layer refers to external ocean wave conditions that can be used to trigger the energy harvesting system. Although data-driven technique cannot control these ambient conditions, it can design and optimize the materials and structures in the energy devices to assist in tailoring the entire energy harvesting system, which is important as ocean waves are typically low frequency and low amplitude. To trigger the energy materials under certain external excitations (e.g., ocean waves) and effectively generate electrical power, AI can be used to analyze the environment characteristics of ocean waves in this layer (Candella, 2019; Lou et al., 2021). Second, the software layer performs data preprocessing and AI model development. The raw energy harvesting data for certain energy materials and structures under ocean waves must first be processed through signal preprocessing, mining, and/or amplifying to improve data quantity and quality. AI models can then be developed after data analysis and interpretation to predict the generated electrical voltage (Mellit and Kalogirou, 2008; Hossain et al., 2017). The third layer, hardware, consists of designing and optimizing the structure of the energy harvesting devices under ocean waves. Due to the technological issues in energy harvesting from ocean waves, it is generally necessary to

Fig. 7 Data-driven integrated ocean wave energy harvesting systems: (a) environmental, software, hardware, and application layers; (b) extended functions in energy platforms and networks. Freq: frequency; amp: amplitude; envrn: environment; mater: material; struct opt: structural optimization

optimize energy devices for low frequency and low amplitude ocean wave excitations. In addition, it is necessary to protect the hardware package from the harsh ocean environment (Akyildiz et al., 2005; Calvente, 2018). Finally, the application layer refers to power storage, management, and real-time charging. One must store the generated electrical power for energy shortage in situ. Ocean equipment is typically designed with multifunctional devices (e.g., for monitoring, wireless communication, and computation), which requires in situ energy shortage management of these devices and functionalization of real-time charging (Shi et al., 2019; Cao et al., 2021).

Note that integrated ocean wave energy harvesting systems are commonly designed with multiple components over a relatively large application zone, which critically relies on data communication through wireless technologies such as wireless gateways, the internet-of-things (IoT), or the intelligent cloud (Shaikh and Zeadally, 2016; Sanislav et al., 2018). Furthermore, there is significant power dependence because energy harvesting systems are connected with human-computer interaction or with certain terminal software such as user interfaces (UIs), user portals, or customized cloud interfaces. In general, novel functionalities of integrated ocean wave energy harvesting systems require electronic devices, which results in more severe energy shortage.

4 Future trends of ocean wave energy harvesting in the intelligent ocean

Ocean engineering, especially large-scale equipment and construction, relies heavily on electrical power. Therefore, it consumes large amounts of electricity and also provides the most application scenarios for energy harvesting technologies (Zuo and Tang, 2013; Wang Y et al., 2020). Reliable green energy is viewed as a key issue that critically affects sustainable development of the entire domain of ocean engineering. To address this energy shortage, energy harvesting has opened a promising venue for next-generation electrical power. Ocean waves are seen as an excellent source of electricity energy, which has led to extensive research and practical directions for ocean wave energy harvesting. However, as explained above, ocean waves have certain limitations that cause technological challenges for energy harvesting, i.e., low frequency and low amplitude fluctuation (Safaei et al., 2019; Wang et al., 2021). Energy harvesting efficiency is inadequate under typical conditions. Data-driven material exploration and structural design are powerful tools to address the challenges of ocean waves, and therefore, we believe that enhancement of ocean wave excitation will be a future trend in ocean wave energy harvesting. AI has attracted significant research attention in ocean wave energy harvesting in recent years, mainly due to the inadequacy of physics-based models developed using first principles (Dong et al., 2020; Jiang et al., 2021). In physics, modeling of materials through what is known as first principles has become a major research area. The approach involves putting in place only certain basic physical constants to obtain the fundamental properties of a system, rather than using experimental parameters. However, the nature of first principles results in potential oversimplification or assumptions, as otherwise the entire system is likely to be too complex to model or solve. Compared to traditional modeling approaches that typically use physical principles to design energy devices for use in ocean waves, AI has the capability to comprehend and handle high dimensional feature spaces (Wang T et al., 2020). According to the objectives and applications, AI in ocean wave energy harvesting can be categorized into the fields of technology (i.e., AI model design and optimization) and utility (i.e., AI-enabled energy harvesting performance) (Khorsand et al., 2020; Liu L et al., 2021). The former is mainly achieved using machine learning (ML) algorithms (Kibria et al., 2018; Guo et al., 2021), and the latter includes the functionalities of reasoning, programming, artificial life, evolutionary computation, and constraint satisfaction (Erden et al., 2008; Gottlob and Szeider, 2008; Lu et al., 2018; Zhan et al., 2022). The application paradigms of AI ocean wave energy harvesting can be divided into three steps. The first is identifying the key indicators that dominate the performance of the energy device; the second is processing the energy harvesting data and establishing the AI model accordingly; and the final step is conducting performance-oriented inverse design to determine the structural and material properties of the energy device.

“Intelligent ocean” refers to not only internet-based information technologies, but also green energy solutions that are customized, portable, efficient, and sustainable, such as ocean wave energy harvesting (Ahmadi et al., 2019; Zhang Q et al., 2021). Wave energy is a critical energy source in the intelligent ocean, and has been used to power various marine devices and equipment for both ocean engineering and ocean technology (Rui et al., 2020; Zhao et al., 2021). From an ocean engineering perspective, ocean structural health monitoring (O-SHM) systems are joint applications of various advanced sensors, control systems, and communication technologies in the intelligent ocean. They require reliable power to remotely charge these sensors and monitor control platforms, while continuously analyzing the generated big data (Zhang et al., 2017; Xi et al., 2019). Efficiently charging the sensors for the specific working environment (e.g., type and amplitude of mechanical energy) ensures precise monitoring of the real-time working conditions of ocean engineering structures (Wang XF et al., 2015; Wang LG et al., 2018; Zhang YX et al., 2021; Li et al., 2022). From an ocean technology perspective, ocean wave energy is one of the main power sources for maintaining the functionality of various marine equipment and devices, such as deep sea mining equipment, wind energy equipment, and ocean exploration devices. Wireless communication systems play an important role in maintaining connection and communication in the intelligent ocean, and they need highly reliable power supplies to maintain the processing of massive data (Liserre et al., 2010; López et al., 2013; Li et al., 2019). Ocean wave energy harvesting can be used to generate electrical power for the relatively high energy consumption needed for wireless communication. Fig. 8 illustrates the potential applications of ocean wave energy in ocean engineering and technology for the intelligent ocean. The traditional immobile, centralized energy supply systems have become incompatible with the current requirements of customized remote equipment and devices (Bandodkar et al., 2016; Guk et al., 2019). As a consequence, ocean wave energy is anticipated to serve as an important and powerful component in the intelligent ocean. Potential applications are envisioned in the ocean engineering domain, such as road detection (e.g., roads, bridges, and facilities), smart supervision systems (e.g., self-diagnosing wireless local area network (WLAN), smart surveillance closed-circuit television (CCTV), and smart traffic signal systems), and all-in-one portable devices for real-time feedback on working conditions. Potential applications have also been proposed in the ocean technology domain, for example self-powered unmanned aerial vehicles (UAVs) (Khoshnoud et al., 2020), autonomous underwater vehicles (AUVs) (Townsend, 2016), mining equipment (Jasiulek et al., 2016), wind energy equipment (Pan et al., 2019), and ocean exploration equipment (Valdez et al., 2011).

5 Conclusions

Ocean wave energy has attractive potential for generating electrical power from the marine environment, and this potential has been exploited by different

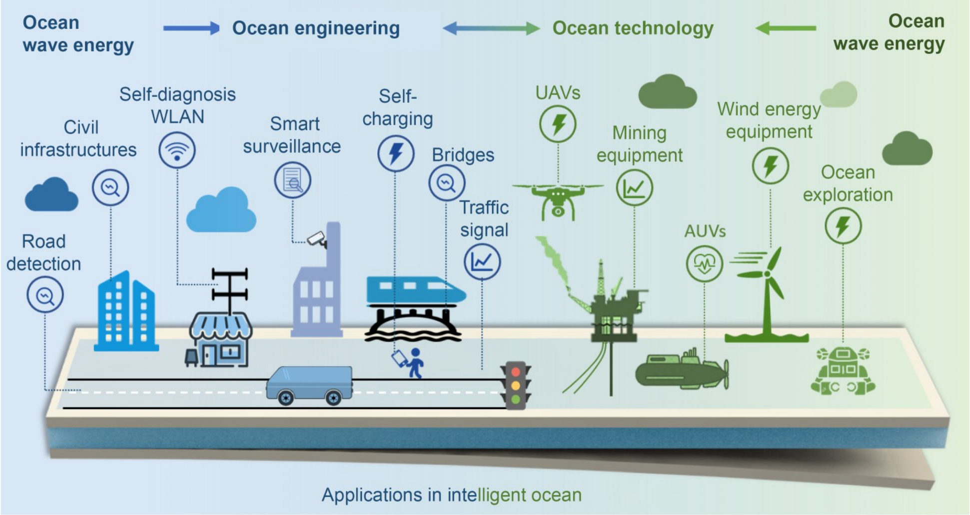

Fig. 8 Vision for ocean wave energy harvesting in the intelligent ocean

energy harvesting devices in recent years. However, traditional wave energy converters face certain challenges due to their intrinsic characteristics as well as the low frequency and unstable nature of ocean waves, leading to a trade-off dilemma between technology and cost. This review article provides readers with an overview of the mechanisms and applications of traditional wave energy converters, the existing challenges in energy harvesting performance, and current progress on next-generation ocean wave energy harvesting driven by the advanced energy materials and technologies. We first covered the mechanisms of traditional wave energy converters: the oscillating water column, oscillating body, and overtopping system; and described cases, whether fixed or floating, that have undergone pilot or prototype testing. Next, we summarized the research direction of AI-based exploration and the potential applications of advanced multifunctional materials and structures in ocean wave energy harvesting. The description of various applications of AI concluded with material discovery, structural optimization, and performance-oriented inverse design. Integrated ocean wave energy harvesting systems enabled by advanced energy materials and structures involve four development stages: environment, software, hardware, and application. Eventually, we envision future development trends that involve applying ocean wave energy harvesting in the intelligent ocean from perspectives of ocean engineering and ocean technology. Intelligent ocean engineering relies heavily on joint application of various advanced sensors, control systems, and communication technologies in ocean structural health monitoring systems. Ocean wave energy harvesting can efficiently charge sensors for the specific working environment, allowing precise monitoring of real-time working conditions of structures. Intelligent ocean technology is dependent on power sources to maintain the functionality of various marine equipment and devices, and ocean wave energy harvesting could be a powerful alternative to generate electrical power.

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Conflict of interest

Fang HE, Yibei LIU, Jiapeng PAN, Xinghong YE, and Pengcheng JIAO declare that they have no conflict of interest.

References

Aderinto T, Li H, 2018. Ocean wave energy converters: status and challenges. *Energies*, 11(5):1250. https://doi.org/10.3390/en11051250

Ahamed R, McKee K, Howard I, 2020. Advancements of wave energy converters based on power take off (PTO) systems: a review. *Ocean Engineering*, 204:107248. https://doi.org/10.1016/j.oceaneng.2020.107248

Ahmadi MH, Ghazvini M, Alhuyi Nazari M, et al., 2019. Renewable energy harvesting with the application of nanotechnology: a review. *International Journal of Energy Research*, 43(4):1387-1410. https://doi.org/10.1002/er.4282

Akyildiz IF, Pompili D, Melodia T, 2005. Underwater acoustic sensor networks: research challenges. *Ad Hoc Networks*, 3(3):257-279. https://doi.org/10.1016/j.adhoc.2005.01.004

Albert A, Berselli G, Bruzzone L, et al., 2017. Mechanical design and simulation of an onshore four-bar wave energy converter. *Renewable Energy*, 114:766-774. https://doi.org/10.1016/j.renene.2017.07.089

Alcorn R, Blavette A, Healy M, et al., 2014. FP7 EU funded CORES wave energy project: a coordinators' perspective on the Galway bay sea trials. *Underwater Technology*, 32(1):51-59. https://doi.org/10.3723/ut.32.051

Alcorn RG, Beattie WC, 2001. Power quality assessment from a wave-power station. Proceedings of the 16th International Conference and Exhibition on Electricity Distribution, p.ISOPE-I-01-086. https://doi.org/10.1049/cp:20010828

Amrutha MM, Sanil Kumar V, 2022. Evaluation of a few wave energy converters for the Indian shelf seas based on available wave power. *Ocean Engineering*, 244:110360. https://doi.org/10.1016/j.oceaneng.2021.110360

Appleyard LD, 2015. Design and construction of greenWAVE Energy Converter for shallow waters off south Australia. *Journal of Civil Engineering and Architecture*, 9:1179-1184.

https://doi.org/10.17265/1934-7359/2015.10.005

Arena F, Romolo A, Malara G, et al., 2013. On design and building of a U-OWC wave energy converter in the Mediterranean sea: a case study. ASME 32nd International Conference on Ocean, Offshore, and Arctic Engineering, V008T09A102.
https://doi.org/10.1115/omae2013-11593

Arinaga RA, Cheung KF, 2012. Atlas of global wave energy from 10 years of reanalysis and hindcast data. *Renewable Energy*, 39(1):49-64.
https://doi.org/10.1016/j.renene.2011.06.039

Astariz S, Iglesias G, 2015. The economics of wave energy: a review. *Renewable and Sustainable Energy Reviews*, 45:397-408.
https://doi.org/10.1016/j.rser.2015.01.061

AW-ENERGY, 2022. Waveroller.
https://aw-energy.com/waveroller

Babarit A, 2015. A database of capture width ratio of wave energy converters. *Renewable Energy*, 80:610-628.
https://doi.org/10.1016/j.renene.2015.02.049

Bandodkar AJ, Jeerapan I, Wang, J, 2016. Wearable chemical sensors: present challenges and future prospects. *ACS Sensors*, 1(5):464-482.
https://doi.org/10.1021/acssensors.6b00250

Barnett JW, Bilchak CR, Wang YW, et al., 2020. Designing exceptional gas-separation polymer membranes using machine learning. *Science Advances*, 6(20):eaaz4301.
https://doi.org/10.1126/sciadv.aaz4301

Barri K, Jiao PC, Zhang QY, et al., 2021. Multifunctional meta-tribomaterial nanogenerators for energy harvesting and active sensing. *Nano Energy*, 86:106074.
https://doi.org/10.1016/j.nanoen.2021.106074

Bhuiyan MA, Hu P, Khare V, et al., 2022. Economic feasibility of marine renewable energy: review. *Frontiers in Marine Science*, 9:988513.
https://doi.org/10.3389/fmars.2022.988513

Cai JZ, Chu X, Xu K, et al., 2020. Machine learning-driven new material discovery. *Nanoscale Advances*, 2(8):3115-3130.
https://doi.org/10.1039/D0NA00388C

Cai WB, Abudurusuli A, Xie CW, et al., 2022. Toward the rational design of mid-infrared nonlinear optical materials with targeted properties via a multi-level data-driven approach. *Advanced Functional Materials*, 32(23):2200231.
https://doi.org/10.1002/adfm.202200231

Calvente FDR, 2018. Wireless Sensors for Health Monitoring of Marine Structures and Machinery. PhD Thesis, Munster Technological University, Ireland.

Candella RN, 2019. Characteristics of ocean waves off Fortaleza, CE, Brazil, extracted from 1-year deep-water measured data. *Ocean Dynamics*, 69(10):1239-1251.
https://doi.org/10.1007/s10236-019-01293-z

Cao XL, Xiong Y, Sun J, et al., 2021. Piezoelectric nanogenerators derived self-powered sensors for multifunctional applications and artificial intelligence. *Advanced Functional Materials*, 31(33):2102983.
https://doi.org/10.1002/adfm.202102983

Carnegie, 2017. CETO Technology.
https://www.carnegiece.com/ceto-technology

Castro-Santos L, Bento AR, Guedes Soares C, 2020. The economic feasibility of floating offshore wave energy farms in the north of Spain. *Energies*, 13(4):806.
https://doi.org/10.3390/en13040806

Chen A, Zhang X, Zhou Z, 2020. Machine learning: accelerating materials development for energy storage and conversion. *InfoMat*, 2(3):553-576.
https://doi.org/10.1002/inf2.12094

Clark CE, DuPont B, 2018. Reliability-based design optimization in offshore renewable energy systems. *Renewable and Sustainable Energy Reviews*, 97:390-400.
https://doi.org/10.1016/j.rser.2018.08.030

Clément A, McCullen P, Falcão A, et al., 2002. Wave energy in Europe: current status and perspectives. *Renewable and Sustainable Energy Reviews*, 6(5):405-431.
https://doi.org/10.1016/S1364-0321(02)00009-6

Clemente D, Rosa-Santos P, Taveira-Pinto F, 2021. On the potential synergies and applications of wave energy converters: a review. *Renewable and Sustainable Energy Reviews*, 135:110162.
https://doi.org/10.1016/j.rser.2020.110162

Coe RG, Yu YH, van Rij J, 2018. A survey of WEC reliability, survival and design practices. *Energies*, 11(1):4.
https://doi.org/10.3390/en11010004

Contestabile P, Iuppa C, di Lauro E, et al., 2017. Wave loadings acting on innovative rubble mound breakwater for overtopping wave energy conversion. *Coastal Engineering*, 122:60-74.
https://doi.org/10.1016/j.coastaleng.2017.02.001

CorPower Ocean, 2018. Projects.
https://corpowerocean.com/projects/

Da DC, Chan YC, Wang LW, et al., 2022. Data-driven and topological design of structural metamaterials for fracture resistance. *Extreme Mechanics Letters*, 50:101528.
https://doi.org/10.1016/j.eml.2021.101528

Das S, Pegu H, Sahu KK, et al., 2020. Machine learning in materials modeling—fundamentals and the opportunities in 2D materials. *In*: Yang EH, Datta D, Ding JJ, et al. (Eds.), Synthesis, Modeling, and Characterization of 2D Materials, and Their Heterostructures. Elsevier, Amsterdam, the Netherland, p.445-468.
https://doi.org/10.1016/B978-0-12-818475-2.00019-2

Davidson J, Ringwood JV, 2017. Mathematical modelling of mooring systems for wave energy converters—a review. *Energies*, 10(5):666.
https://doi.org/10.3390/en10050666

Falcão AFO, 2010. Wave energy utilization: a review of the technologies. *Renewable and Sustainable Energy Reviews*, 14(3):899-918.
https://doi.org/10.1016/j.rser.2009.11.003

DOE (US Department of Energy), 2016. Energy Department Announces Investment in Wave Energy Test Facility.
https://www.energy.gov/articles/energy-department-announces-investment-wave-energy-test-facility

Dong K, Peng X, Wang ZL, 2020. Fiber/fabric-based piezoelectric and triboelectric nanogenerators for flexible/stretchable and wearable electronics and artificial intelligence. *Advanced*

Materials, 32(5):1902549.
https://doi.org/10.1002/adma.201902549

Drew B, Plummer AR, Sahinkaya MN, 2009. A review of wave energy converter technology. *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy*, 223(8):887-902.
https://doi.org/10.1243/09576509jpe782

Dudem B, Dharmasena RDIG, Graham SA, et al., 2020. Exploring the theoretical and experimental optimization of high-performance triboelectric nanogenerators using microarchitectured silk cocoon films. *Nano Energy*, 74: 104882.
https://doi.org/10.1016/j.nanoen.2020.104882

EMEC (The European Marine Energy Centre Limited), 2004. Pelamis Wave Power.
https://www.emec.org.uk/about-us/wave-clients/pelamis-wave-power

EMEC (The European Marine Energy Centre Limited), 2020. Emec Achieves World's First Ocean Energy Retl Designation.
https://www.emec.org.uk/press-release-emec-achieves-worlds-first-ocean-energy-retl-designation-2/

ENI (Ente Nazionale Idrocarburi), 2022. ISWEC: Energy from the Sea.
https://www.eni.com/en-IT/operations/iswec-eni.html

Epps RW, Volk AA, Reyes KG, et al., 2021. Accelerated AI development for autonomous materials synthesis in flow. *Chemical Science*, 12(17):6025-6036.
https://doi.org/10.1039/D0SC06463G

Erden MS, Komoto H, van Beek TJ, et al., 2008. A review of function modeling: approaches and applications. *AI EDAM*, 22(2):147-169.
https://doi.org/10.1017/S0890060408000103

EWP (Eco Wave Power), 2016. Eco Wave Power-Gibraltar.
https://www.ecowavepower.com/gibraltar

Fadaeenejad M, Shamsipour R, Rokni SD, et al., 2014. New approaches in harnessing wave energy: with special attention to small islands. *Renewable and Sustainable Energy Reviews*, 29:345-354.
https://doi.org/10.1016/j.rser.2013.08.077

Falcão AFO, Henriques JCC, 2014. Model-prototype similarity of oscillating-water-column wave energy converters. *International Journal of Marine Energy*, 6:18-34.
https://doi.org/10.1016/j.ijome.2014.05.002

Falcão AFO, Henriques JCC, 2016. Oscillating-water-column wave energy converters and air turbines: a review. *Renewable Energy*, 85:1391-1424.
https://doi.org/10.1016/j.renene.2015.07.086

Falcão AFO, Sarmento AJNA, Gato LMC, et al., 2020. The pico OWC wave power plant: its lifetime from conception to closure 1986-2018. *Applied Ocean Research*, 98:102104.
https://doi.org/10.1016/j.apor.2020.102104

Folley M, 2017. The wave energy resource. *In*: Pecher A, Kofoed JP (Eds.), Handbook of Ocean Wave Energy. Springer, Cham, Germany, p.43-79.
https://doi.org/10.1007/978-3-319-39889-1_3

Gerber JS, Taylor GW, 2003. Installation of a scaleable wave energy conversion system in Oahu, Hawaii. The Thirteenth International Offshore and Polar Engineering Conference, p.ISOPE-I-03-054.

Gibert K, Sànchez-Marrè M, Izquierdo J, 2016. A survey on pre-processing techniques: relevant issues in the context of environmental data mining. *AI Communications*, 29(6): 627-663.
https://doi.org/10.3233/AIC-160710

Gioia DG, Pasta E, Brandimarte P, et al., 2022. Data-driven control of a pendulum wave energy converter: a Gaussian process regression approach. *Ocean Engineering*, 253:111191.
https://doi.org/10.1016/j.oceaneng.2022.111191

Goda Y, Nakada H, Ohneda H, et al., 1991. Results of field experiment of a wave power extracting caisson breakwater. *Proceedings of Civil Engineering in the Ocean*, 7: 143-148.
https://doi.org/10.2208/prooe.7.143

Gomes CP, Selman B, Gregoire JM, 2019. Artificial intelligence for materials discovery. *MRS Bulletin*, 44(7):538-544.
https://doi.org/10.1557/mrs.2019.158

Gottlob G, Szeider S, 2008. Fixed-parameter algorithms for artificial intelligence, constraint satisfaction and database problems. *The Computer Journal*, 51(3):303-325.
https://doi.org/10.1093/comjnl/bxm056

Guk K, Han G, Lim J, et al., 2019. Evolution of wearable devices with real-time disease monitoring for personalized healthcare. *Nanomaterials*, 9(6):813.
https://doi.org/10.3390/nano9060813

Gunn K, Stock-Williams C, 2012. Quantifying the global wave power resource. *Renewable Energy*, 44:296-304.
https://doi.org/10.1016/j.renene.2012.01.101

Guo K, Yang ZZ, Yu CH, et al., 2021. Artificial intelligence and machine learning in design of mechanical materials. *Materials Horizons*, 8(4):1153-1172.
https://doi.org/10.1039/D0MH01451F

Hann-Ocean, 2022. Hann-Ocean Energy Launches 3rd-Gen Drakoo Wave Energy Converter in Shengsi, China.
http://www.hann-ocean.com/index.php/publications/news-detail.html?u=1y642gH3tbY24942

He F, Huang ZH, 2014. Hydrodynamic performance of pile-supported OWC-type structures as breakwaters: an experimental study. *Ocean Engineering*, 88:618-626.
https://doi.org/10.1016/j.oceaneng.2014.04.023

He F, Huang ZH, 2016. Using an oscillating water column structure to reduce wave reflection from a vertical wall. *Journal of Waterway, Port, Coastal, and Ocean Engineering*, 142(2):04015021.
https://doi.org/10.1061/(ASCE)WW.1943-5460.0000320

He F, Huang ZH, 2017. Characteristics of orifices for modeling nonlinear power take-off in wave-flume tests of oscillating water column devices. *Journal of Zhejiang University-SCIENCE A (Applied Physics & Engineering)*, 18(5):329-345.
https://doi.org/10.1631/jzus.A1600769

He F, Huang ZH, Law AWK, 2012. Hydrodynamic performance of a rectangular floating breakwater with and without pneumatic chambers: an experimental study. *Ocean*

Engineering, 51:16-27.
https://doi.org/10.1016/j.oceaneng.2012.05.008

He F, Huang ZH, Law AWK, 2013. An experimental study of a floating breakwater with asymmetric pneumatic chambers for wave energy extraction. *Applied Energy*, 106: 222-231.
https://doi.org/10.1016/j.apenergy.2013.01.013

He F, Zhang HS, Zhao JJ, et al., 2019. Hydrodynamic performance of a pile-supported OWC breakwater: an analytical study. *Applied Ocean Research*, 88:326-340.
https://doi.org/10.1016/j.apor.2019.03.022

He F, Lin Y, Pan JP, et al., 2023. Experimental investigation of vortex evolution around oscillating water column wave energy converter using particle image velocimetry. *Physics of Fluids*, 35(1):015151.
https://doi.org/10.1063/5.0135927

He MX, Lyu X, Zhai YJ, et al., 2021. Multi-objective optimal design of periodically stiffened panels for vibration control using data-driven optimization method. *Mechanical Systems and Signal Processing*, 160:107872.
https://doi.org/10.1016/j.ymssp.2021.107872

He ZY, Guo WM, Zhang P, 2022. Performance prediction, optimal design and operational control of thermal energy storage using artificial intelligence methods. *Renewable and Sustainable Energy Reviews*, 156:111977.
https://doi.org/10.1016/j.rser.2021.111977

Heath TV, 2012. A review of oscillating water columns. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 370(1959):235-245.
https://doi.org/10.1098/rsta.2011.0164

Himanen L, Geurts A, Foster AS, et al., 2019. Data-driven materials science: status, challenges, and perspectives. *Advanced Science*, 6(21):1900808.
https://doi.org/10.1002/advs.201900808

Hossain S, Ong ZC, Ismail Z, et al., 2017. Artificial neural networks for vibration based inverse parametric identifications: a review. *Applied Soft Computing*, 52:203-219.
https://doi.org/10.1016/j.asoc.2016.12.014

IEA-OES (International Energy Agency-Ocean Energy Systems), 2021. IEA-OES Annual Report: an Overview of Ocean Energy Activities in 2020. International Energy Agency, Lisbon, Portugal.

IRENA (International Renewable Energy Agency), 2020. Innovation Outlook: Ocean Energy Technologies. Technical Report, IRENA, Abu Dhabi, The United Arab Emirates.

Jasiulek D, Stankiewicz K, Woszczyński M, 2016. Intelligent self-powered sensors in the state-of-the-art control systems of mining machines. *Archives of Mining Sciences*, 61(4):907-915.
https://doi.org/10.1515/amsc-2016-0060

Jha SK, Bilalovic J, Jha A, et al., 2017. Renewable energy: present research and future scope of artificial intelligence. *Renewable and Sustainable Energy Reviews*, 77: 297-317.
https://doi.org/10.1016/j.rser.2017.04.018

Jiang JX, Liu SG, Feng LF, et al., 2021. A review of piezoelectric vibration energy harvesting with magnetic coupling based on different structural characteristics. *Micromachines*, 12(4):436.
https://doi.org/10.3390/mi12040436

Jiao PC, 2021. Emerging artificial intelligence in piezoelectric and triboelectric nanogenerators. *Nano Energy*, 88: 106227.
https://doi.org/10.1016/j.nanoen.2021.106227

Jiao PC, Alavi AH, 2021. Artificial intelligence-enabled smart mechanical metamaterials: advent and future trends. *International Materials Reviews*, 66(6):365-393.
https://doi.org/10.1080/09506608.2020.1815394

Jiao PC, Zhang H, Li WT, 2023. Origami tribo-metamaterials with mechanoelectrical multistability. *ACS Applied Materials & Interfaces*, 15(2):2873-2880.
https://doi.org/10.1021/acsami.2c16681

Kalidindi SR, Brough DB, Li S, et al., 2016. Role of materials data science and informatics in accelerated materials innovation. *MRS Bulletin*, 41(8):596-602.
https://doi.org/10.1557/mrs.2016.164

Khan N, Kalair A, Abas N, et al., 2017. Review of ocean tidal, wave and thermal energy technologies. *Renewable and Sustainable Energy Reviews*, 72:590-604.
https://doi.org/10.1016/j.rser.2017.01.079

Khorsand M, Tavakoli J, Guan HW, et al., 2020. Artificial intelligence enhanced mathematical modeling on rotary triboelectric nanogenerators under various kinematic and geometric conditions. *Nano Energy*, 75:104993.
https://doi.org/10.1016/j.nanoen.2020.104993

Khoshnoud F, Esat II, de Silva CW, et al., 2020. Self-powered solar aerial vehicles: towards infinite endurance UAVs. *Unmanned Systems*, 8(2):95-117.
https://doi.org/10.1142/S2301385020500077

Kibria MG, Nguyen K, Villardi GP, et al., 2018. Big data analytics, machine learning, and artificial intelligence in next-generation wireless networks. *IEEE Access*, 6:2328-32338.
https://doi.org/10.1109/ACCESS.2018.2837692

Kofoed JP, 2017. The wave energy sector. *In*: Pecher A, Kofoed JP (Eds.), Handbook of Ocean Wave Energy. Springer, Cham, Germany, p.17-42.
https://doi.org/10.1007/978-3-319-39889-1_2

LANGLEE, 2013. Langlee Wave Power-Langlee Technology.
http://www.langleewp.com/?q=langlee-technology

LEANCON, 2015. The LEANCON Wave Energy Device.
http://www.leancon.com/

Lehmann M, Karimpour F, Goudey CA, et al., 2017. Ocean wave energy in the United States: current status and future perspectives. *Renewable and Sustainable Energy Reviews*, 74:1300-1313.
https://doi.org/10.1016/j.rser.2016.11.101

Li H, Huang CG, Soares CG, 2022. A real-time inspection and opportunistic maintenance strategies for floating offshore wind turbines. *Ocean Engineering*, 256:111433.
https://doi.org/10.1016/j.oceaneng.2022.111433

Li JL, Lim K, Yang HT, et al., 2020. AI applications through the whole life cycle of material discovery. *Matter*, 3(2): 393-432.
https://doi.org/10.1016/j.matt.2020.06.011

Li L, Gao Y, Ning DZ, et al., 2021. Development of a constraint non-causal wave energy control algorithm based on artificial intelligence. *Renewable and Sustainable Energy Reviews*, 138:110519.
https://doi.org/10.1016/j.rser.2020.110519

Li SN, Qu WY, Liu CF, et al., 2019. Survey on high reliability wireless communication for underwater sensor networks. *Journal of Network and Computer Applications*, 148: 102446.
https://doi.org/10.1016/j.jnca.2019.102446

Li Y, Yu YH, 2012. A synthesis of numerical methods for modeling wave energy converter-point absorbers. *Renewable and Sustainable Energy Reviews*, 16(6):4352-4364.
https://doi.org/10.1016/j.rser.2011.11.008

Liserre M, Sauter T, Hung JY, 2010. Future energy systems: integrating renewable energy sources into the smart power grid through industrial electronics. *IEEE Industrial Electronics Magazine*, 4(1):18-37.
https://doi.org/10.1109/MIE.2010.935861

Liu L, Guo XG, Liu WX, et al., 2021. Recent progress in the energy harvesting technology—from self-powered sensors to self-sustained IoT, and new applications. *Nanomaterials*, 11(11):2975.
https://doi.org/10.3390/nano11112975

Liu Y, Esan OC, Pan ZF, et al., 2021. Machine learning for advanced energy materials. *Energy and AI*, 3:100049.
https://doi.org/10.1016/j.egyai.2021.100049

Liu Z, Hyun B, Jin JY, et al., 2016. OWC air chamber performance prediction under impulse turbine damping effects. *Science China Technological Sciences*, 59(4):657-666.
https://doi.org/10.1007/s11431-016-6030-5

López I, Andreu J, Ceballos S, et al., 2013. Review of wave energy technologies and the necessary power-equipment. *Renewable and Sustainable Energy Reviews*, 27:413-434.
https://doi.org/10.1016/j.rser.2013.07.009

Lou RR, Lv ZH, Dang SP, et al., 2021. Application of machine learning in ocean data. *Multimedia Systems*.
https://doi.org/10.1007/s00530-020-00733-x

Lu HM, Li YJ, Chen M, et al., 2018. Brain intelligence: go beyond artificial intelligence. *Mobile Networks and Applications*, 23(2):368-375.
https://doi.org/10.1007/s11036-017-0932-8

Lu ZH, 2021. Computational discovery of energy materials in the era of big data and machine learning: a critical review. *Materials Reports: Energy*, 1(3):100047.
https://doi.org/10.1016/j.matre.2021.100047

Margheritini L, Vicinanza D, Frigaard P, 2009. SSG wave energy converter: design, reliability and hydraulic performance of an innovative overtopping device. *Renewable Energy*, 34(5):1371-1380.
https://doi.org/10.1016/j.renene.2008.09.009

Maria-Arenas A, Garrido AJ, Rusu E, et al., 2019. Control strategies applied to wave energy converters: state of the art. *Energies*, 12(16):3115.
https://doi.org/10.3390/en12163115

McLeod I, Ringwood JV, 2022. Powering data buoys using wave energy: a review of possibilities. *Journal of Ocean Engineering and Marine Energy*, 8(3):417-432.
https://doi.org/10.1007/s40722-022-00240-3

Mei CC, 2012. Hydrodynamic principles of wave power extraction. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 370(1959):208-234.
https://doi.org/10.1098/rsta.2011.0178

Mehlum E, 1986. Tapchan. Hydrodynamics of Ocean Wave-Energy Utilization. Springer Berlin Heidelberg, Germany, p.51-55.
https://doi.org/10.1007/978-3-642-82666-5_3

Mellit A, Kalogirou SA, 2008. Artificial intelligence techniques for photovoltaic applications: a review. *Progress in Energy and Combustion Science*, 34(5):574-632.
https://doi.org/10.1016/j.pecs.2008.01.001

Miyazaki T, Masuda Y, 1980. Tests on the wave power generator "Kaimei". Offshore Technology Conference, Paper Number OTC-3689-MS.
https://doi.org/10.4043/3689-ms

Mørk G, Barstow S, Kabuth A, et al., 2010. Assessing the global wave energy potential. ASME 29th International Conference on Ocean, Offshore, and Arctic Engineering, p.447-454.
https://doi.org/10.1115/omae2010-20473

Mustapa MA, Yaakob OB, Ahmed YM, et al., 2017. Wave energy device and breakwater integration: a review. *Renewable and Sustainable Energy Reviews*, 77:43-58.
https://doi.org/10.1016/j.rser.2017.03.110

Nguyen HP, Wang CM, Tay ZY, et al., 2020. Wave energy converter and large floating platform integration: a review. *Ocean Engineering*, 213:107768.
https://doi.org/10.1016/j.oceaneng.2020.107768

Ogata T, Washio Y, Osawa H, et al., 2002. The open sea tests of the offshore floating type wave power device "mighty whale": performance of the prototype. Proceedings of the ASME 21st International Conference on Offshore Mechanics and Arctic Engineering, p.517-524.
https://doi.org/10.1115/OMAE2002-28335

Pan HY, Li H, Zhang TS, et al., 2019. A portable renewable wind energy harvesting system integrated S-rotor and H-rotor for self-powered applications in high-speed railway tunnels. *Energy Conversion and Management*, 196:56-68.
https://doi.org/10.1016/j.enconman.2019.05.115

Penalba M, Giorgi G, Ringwood JV, 2017. Mathematical modelling of wave energy converters: a review of nonlinear approaches. *Renewable and Sustainable Energy Reviews*, 78:1188-1207.
https://doi.org/10.1016/j.rser.2016.11.137

Peng JH, Yuan C, Ma RS, et al., 2019. Backmapping from multiresolution coarse-grained models to atomic structures of large biomolecules by restrained molecular dynamics simulations using Bayesian inference. *Journal of Chemical Theory and Computation*, 15(5):3344-3353.
https://doi.org/10.1021/acs.jctc.9b00062

Pérez-Collazo C, Greaves D, Iglesias G, 2015. A review of combined wave and offshore wind energy. *Renewable and Sustainable Energy Reviews*, 42:141-153.

https://doi.org/10.1016/j.rser.2014.09.032

Prado M, Polinder H, 2013. 9−Case study of the Archimedes wave swing (AWS) direct drive wave energy pilot plant. *In*: Mueller M, Polinder H (Eds.), Electrical Drives for Direct Drive Renewable Energy Systems. Woodhead Publishing, Philadelphia, the USA, p.195-218. https://doi.org/10.1533/9780857097491.2.195

Qiao DS, Haider R, Yan J, et al., 2020. Review of wave energy converter and design of mooring system. *Sustainability*, 12(19):8251. https://doi.org/10.3390/su12198251

Qiu SQ, Liu K, Wang DJ, et al., 2019. A comprehensive review of ocean wave energy research and development in China. *Renewable and Sustainable Energy Reviews*, 113: 109271. https://doi.org/10.1016/j.rser.2019.109271

Qu TM, Di SC, Feng YT, et al., 2021. Towards data-driven constitutive modelling for granular materials via micromechanics-informed deep learning. *International Journal of Plasticity*, 144:103046. https://doi.org/10.1016/j.ijplas.2021.103046

Rahman M, Shakeri M, Tiong SK, et al., 2021. Prospective methodologies in hybrid renewable energy systems for energy prediction using artificial neural networks. *Sustainability*, 13(4):2393. https://doi.org/10.3390/su13042393

Ravindran M, Koola PM, 1991. Energy from sea waves—the Indian wave energy programme. *Current Science*, 60(12): 676-680.

Ringwood JV, Bacelli G, Fusco F, 2014. Energy-maximizing control of wave-energy converters: the development of control system technology to optimize their operation. *IEEE Control Systems Magazine*, 34(5):30-55. https://doi.org/10.1109/MCS.2014.2333253

Rui PS, Zhang W, Zhong YM, et al., 2020. High-performance cylindrical pendulum shaped triboelectric nanogenerators driven by water wave energy for full-automatic and self-powered wireless hydrological monitoring system. *Nano Energy*, 74:104937. https://doi.org/10.1016/j.nanoen.2020.104937

Rusu L, Onea F, 2017. The performance of some state-of-the-art wave energy converters in locations with the worldwide highest wave power. *Renewable and Sustainable Energy Reviews*, 75:1348-1362. https://doi.org/10.1016/j.rser.2016.11.123

Safaei M, Sodano HA, Anton SR, 2019. A review of energy harvesting using piezoelectric materials: state-of-the-art a decade later (2008-2018). *Smart Materials and Structures*, 28(11):113001. https://doi.org/10.1088/1361-665X/ab36e4

Sahu H, Rao WN, Troisi A, et al., 2018. Toward predicting efficiency of organic solar cells via machine learning and improved descriptors. *Advanced Energy Materials*, 8(24): 1801032. https://doi.org/10.1002/aenm.201801032

Salehi H, Burgueño R, 2018. Emerging artificial intelligence methods in structural engineering. *Engineering Structures*, 171:170-189. https://doi.org/10.1016/j.engstruct.2018.05.084

Salter SH, 1974. Wave power. *Nature*, 249(5459):720-724. https://doi.org/10.1038/249720a0

Sanislav T, Zeadally S, Mois GD, et al., 2018. Wireless energy harvesting: empirical results and practical considerations for internet of things. *Journal of Network and Computer Applications*, 121:149-158. https://doi.org/10.1016/j.jnca.2018.08.002

Schleder GR, Padilha ACM, Acosta CM, et al., 2019. From DFT to machine learning: recent approaches to materials science–a review. *Journal of Physics: Materials*, 2(3): 032001. https://doi.org/10.1088/2515-7639/ab084b

Sha WX, Guo YQ, Yuan Q, et al., 2020. Artificial intelligence to power the future of materials science and engineering. *Advanced Intelligent Systems*, 2(4):1900143. https://doi.org/10.1002/aisy.201900143

Shaikh FK, Zeadally S, 2016. Energy harvesting in wireless sensor networks: a comprehensive review. *Renewable and Sustainable Energy Reviews*, 55:1041-1054. https://doi.org/10.1016/j.rser.2015.11.010

Shi QF, He TYY, Lee C, 2019. More than energy harvesting–combining triboelectric nanogenerator and flexible electronics technology for enabling novel micro-/nano-systems. *Nano Energy*, 57:851-871. https://doi.org/10.1016/j.nanoen.2019.01.002

SIGMA-ENERGY, 2018. Sigma WEC. http://www.sigma-energy.si

Sirigu SA, Foglietta L, Giorgi G, et al., 2020. Techno-Economic optimisation for a wave energy converter via genetic algorithm. *Journal of Marine Science and Engineering*, 8(7):482. https://doi.org/10.3390/jmse8070482

SWEL, 2022. Sea Wave Energy Ltd.–Research. https://swel.eu/research

Tang YH, Kojima K, Koike-Akino T, et al., 2020. Generative deep learning model for inverse design of integrated nanophotonic devices. *Laser & Photonics Reviews*, 14(12): 2000287. https://doi.org/10.1002/lpor.202000287

Tarrant K, Meskell C, 2016. Investigation on parametrically excited motions of point absorbers in regular waves. *Ocean Engineering*, 111:67-81. https://doi.org/10.1016/j.oceaneng.2015.10.041

Tedd J, Kofoed JP, 2009. Measurements of overtopping flow time series on the wave dragon, wave energy converter. *Renewable Energy*, 34(3):711-717. https://doi.org/10.1016/j.renene.2008.04.036

Tian CX, Li TJ, Bustillos J, et al., 2021. Data-driven approaches toward smarter additive manufacturing. *Advanced Intelligent Systems*, 3(12):2100014. https://doi.org/10.1002/aisy.202100014

Torre-Enciso Y, Ortubia I, de Aguileta LL, et al., 2009. Mutriku wave power plant: from the thinking out to the reality. Proceedings of the 8th European Wave and Tidal Energy Conference, p.319-329.

Townsend NC, 2016. Self-powered autonomous underwater vehicles: results from a gyroscopic energy scavenging

prototype. *IET Renewable Power Generation*, 10(8):1078-1086.
https://doi.org/10.1049/iet-rpg.2015.0210

UN (United Nations), 2017. Factsheet: People and Oceans. New York, USA.

Valdez TI, Jones JA, Leland RS, et al., 2011. A Self-Powered Underwater Robot for Ocean Exploration and Beyond.
https://ntrs.nasa.gov/citations/20150005952

Wang LG, Isberg J, Tedeschi E, 2018. Review of control strategies for wave energy conversion systems and their validation: the wave-to-wire approach. *Renewable and Sustainable Energy Reviews*, 81:366-379.
https://doi.org/10.1016/j.rser.2017.06.074

Wang P, Tian XL, Peng T, et al., 2018. A review of the state-of-the-art developments in the field monitoring of offshore structures. *Ocean Engineering*, 147:148-164.
https://doi.org/10.1016/j.oceaneng.2017.10.014

Wang XF, Niu SM, Yin YJ, et al., 2015. Triboelectric nanogenerator based on fully enclosed rolling spherical structure for harvesting low-frequency water wave energy. *Advanced Energy Materials*, 5(24):1501467.
https://doi.org/10.1002/aenm.201501467

Wang T, Zhang C, Snoussi H, et al., 2020. Machine learning approaches for thermoelectric materials research. *Advanced Functional Materials*, 30(5):1906041.
https://doi.org/10.1002/adfm.201906041

Wang Y, Gao SW, Xu WH, et al., 2020. Nanogenerators with superwetting surfaces for harvesting water/liquid energy. *Advanced Functional Materials*, 30(26):1908252.
https://doi.org/10.1002/adfm.201908252

Wang YZ, Matin Nazar A, Wang JJ, et al., 2021. Rolling spherical triboelectric nanogenerators (RS-TENG) under low-frequency ocean wave action. *Journal of Marine Science and Engineering*, 10(1):5.
https://doi.org/10.3390/jmse10010005

Wang ZL, Jiang T, Xu L, 2017. Toward the blue energy dream by triboelectric nanogenerator networks. *Nano Energy*, 39:9-23.
https://doi.org/10.1016/j.nanoen.2017.06.035

Wave Star, 2012. History.
https://wavestarenergy.com/news/

Wei HD, Xiao LF, Liu MY, et al., 2021. Data-driven model and key features based on supervised learning for truncation design of mooring and riser system. *Ocean Engineering*, 224:108743.
https://doi.org/10.1016/j.oceaneng.2021.108743

Weinstein A, Fredrikson G, Parks MJ, et al., 2004. AquaBUoY-the offshore wave energy converter numerical modeling and optimization. Oceans '04 MTS/IEEE Techno-Ocean '04 (IEEE Cat. No.04CH37600), INSPEC Accession Number 8304710.
https://doi.org/10.1109/OCEANS.2004.1406425

Whittaker T, Folley M, 2012. Nearshore oscillating wave surge converters and the development of oyster. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 370(1959):345-364.
https://doi.org/10.1098/rsta.2011.0152

Windt C, Davidson J, Ringwood JV, 2018. High-fidelity numerical modelling of ocean wave energy systems: a review of computational fluid dynamics-based numerical wave tanks. *Renewable and Sustainable Energy Reviews*, 93:610-630.
https://doi.org/10.1016/j.rser.2018.05.020

WSE, 2021. Uniwave.
https://www.waveswell.com/technology/

Wu N, Bao B, Wang Q, 2021. Review on engineering structural designs for efficient piezoelectric energy harvesting to obtain high power output. *Engineering Structures*, 235:112068.
https://doi.org/10.1016/j.engstruct.2021.112068

Xi F, Pang YK, Liu GX, e al. , 2019. Self-powered intelligent buoy system by water wave energy for sustainable and autonomous wireless sensing and data transmission. *Nano Energy*, 61:1-9.
https://doi.org/10.1016/j.nanoen.2019.04.026

Xie D, Gu YJ, Yu ZW, et al., 2017. Performance analysis and comprehensive evaluation of wave energy power generation devices. *Journal of Hydroelectric Engineering*, 36(8):113-120.
https://doi.org/10.11660/slfdxb.20170813

Xu MY, Zhao TC, Wang C, et al., 2019. High power density tower-like triboelectric nanogenerator for harvesting arbitrary directional water wave energy. *ACS Nano*, 13(2):1932-1939.
https://doi.org/10.1021/acsnano.8b08274

Xu RJ, Wang H, Xi ZY, et al., 2022. Recent progress on wave energy marine buoys. *Journal of Marine Science and Engineering*, 10(5):566.
https://doi.org/10.3390/jmse10050566

Yang WX, Huang LL, Singamneni S, 2022. Generative design of structured materials for controlled frequency responses. *3D Printing and Additive Manufacturing*, in press.
https://doi.org/10.1089/3dp.2021.0241

Yu CH, Qin Z, Buehler MJ, 2019. Artificial intelligence design algorithm for nanocomposites optimized for shear crack resistance. *Nano Futures*, 3(3):035001.
https://doi.org/10.1088/2399-1984/ab36f0

Zanuttigh B, Angelelli E, Kofoed JP, 2013. Effects of mooring systems on the performance of a wave activated body energy converter. *Renewable Energy*, 57:422-431.
https://doi.org/10.1016/j.renene.2013.02.006

Zhan ZH, Zhang J, Lin Y, et al., 2022. Matrix-based evolutionary computation. *IEEE Transactions on Emerging Topics in Computational Intelligence*, 6(2):315-328.
https://doi.org/10.1109/TETCI.2020.3047410

Zhang H, Aggidis GA, 2018. Nature rules hidden in the biomimetic wave energy converters. *Renewable and Sustainable Energy Reviews*, 97:28-37.
https://doi.org/10.1016/j.rser.2018.08.018

Zhang NN, Tao CY, Fan X, et al., 2017. Progress in triboelectric nanogenerators as self-powered smart sensors. *Journal of Materials Research*, 32(9):1628-1646.
https://doi.org/10.1557/jmr.2017.162

Zhang Q, Liang QJ, Nandakumar DK, et al., 2021. Shadow enhanced self-charging power system for wave and solar

energy harvesting from the ocean. *Nature Communications*, 12(1):616.
https://doi.org/10.1038/s41467-021-20919-9

Zhang QY, Barri K, Kari SR, et al., 2021. Multifunctional triboelectric nanogenerator-enabled structural elements for next generation civil infrastructure monitoring systems. *Advanced Functional Materials*, 31(47):2105825.
https://doi.org/10.1002/adfm.202105825

Zhang YX, Zhao YJ, Sun W, et al., 2021. Ocean wave energy converters: technical principle, device realization, and performance evaluation. *Renewable and Sustainable Energy Reviews*, 141:110764.
https://doi.org/10.1016/j.rser.2021.110764

Zhao TC, Xu MY, Xiao X, et al., 2021. Recent progress in blue energy harvesting for powering distributed sensors in ocean. *Nano Energy*, 88:106199.
https://doi.org/10.1016/j.nanoen.2021.106199

Zhou T, Song Z, Sundmacher K, 2019. Big data creates new opportunities for materials research: a review on methods and applications of machine learning for materials design. *Engineering*, 5(6):1017-1026.
https://doi.org/10.1016/j.eng.2019.02.011

Zou SY, Zhou X, Khan I, et al., 2022. Optimization of the electricity generation of a wave energy converter using deep reinforcement learning. *Ocean Engineering*, 244:110363.
https://doi.org/10.1016/j.oceaneng.2021.110363

Zuo L, Tang XD, 2013. Large-scale vibration energy harvesting. *Journal of Intelligent Material Systems and Structures*, 24(11):1405-1430.
https://doi.org/10.1177/1045389X13486707