Nanogenerators for blue energy

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Ocean energy, with its abundant reserves, has garnered significant attention as a renewable energy source, due to its potential to address global energy challenge and mitigate environmental deterioration effectively. However, this immense potential has remained largely untapped due to the limitations of traditional energy technologies. The emerging triboelectric nanogenerator (TENG) technology, with demonstrated advantages over existing power-generation schemes, appears to be a potential game changer for harnessing low-frequency ocean wave energy. Here, we provide a comprehensive review of recent progress in harvesting blue energy with TENGs, starting from the overall development venation of the TENG technology in blue energy applications. We thoroughly discuss the current research status and associated key issues, ranging from the structural design and performance optimization of TENGs to the system integration for water wave energy harvesting. Finally, we identify the challenges and opportunities of nanogenerator-based blue energy harvesting and applications. As technologies continue to evolve at an accelerated pace, we anticipate significant performance advancement for the TENGs in future. We are confident that the TENGs will play a transformative role in ocean energy harvesting, creating substantial industrial values and societal benefits as humanity continues to unlock the vast potential of oceans.

Introduction

Oceans occupying more than 70% of the earth′s surface area contain abundant and clean renewable energy, and the total average power generated by oceans globally is estimated to be 76.6 TW.[1] Ocean energy, with its renewable and environmentally friendly nature, has attracted considerable interest, particularly in light of the growing global concern over carbon emissions and the urgent need for sustainable, carbon-neutral energy solutions. Among the five forms of ocean energy, the ocean wave energy is the key direction of ocean energy development. The total wave power worldwide breaking around the coastlines can reach 3 TW, of which roughly 1 TW is technically exploitable. For open ocean areas, the wave power can reach 20–30 TW.[2] Despite years of R&D, the wave energy harvesting and conversion are still in the early stage of conceptual design and prototype validation, lacking substantial breakthroughs to overcome technical barriers for practical applications. Current wave energy conversion is mainly realized with the traditional electromagnetic generators (EMGs),[3] where the wave energy is first captured as the mechanical energy of device, and then transferred to the EMGs through a transmission module. Such technical path is complex, with low overall efficiency and high maintenance and operation costs, and the device reliability cannot be ensured,[4,5] which greatly limit the large-scale development and utilization of wave energy.

Compared to the EMG, the emerging triboelectric nanogenerator (TENG) invented by Wang et al. based on the coupling of triboelectrification and electrostatic induction,[6] exhibit obvious advantages of high power density, high efficiency, lightweight, and low fabrication costs, etc.[7,8] The TENG technology offers a new approach for the conversion of wave energy to electricity, potentially advantageous in large-scale wave energy harvesting. Since the invention of the TENG, many efforts have been made to design effective device structures and optimize the output performance of TENGs for water wave energy harvesting.[9–12] A TENG driven by the Maxwell′s displacement current[13] has significant advantages in collecting disordered, low-frequency, and high-entropy ocean energy,[14,15] providing a subversive technical path for efficient development and utilization of ocean energy. In 2014, Wang proposed the idea of using three-dimensional (3D) TENG networks to harvest large-scale

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ocean blue energy.[16] The TENG network composed of millions of enclosed TENG units linked as fishing nets, can harvest the ocean energy from the water surface or underwater to generate electricity. In theory, a substantial amount of electricity can be generated when individual TENGs work constructively to enhance the network outputs. However, significant scientific and engineering challenges must still be addressed to enable large-scale, practical implementation of this concept.[17]

This article highlights a comprehensive review of recent advancements in blue energy harvesting using TENGs, covering critical aspects such as structural design and performance optimization of TENGs for blue energy harvesting, construction of TENG networks and system integration, and future perspectives. In the first segment of the review, the overall development venation of the TENG technology for blue energy harvesting is introduced. In the subsequent section, the latest progress of typical TENG structural designs and performance optimization approaches for water wave energy harvesting is elaborated. Next, the related works regarding the networking of TENG units and power management on TENG units and networks for blue energy are summarized. Finally, crucial perspectives and challenges are discussed for future research on TENG-based blue energy harvesting.

Development venation of TENG technology in blue energy harvesting

Since the concept of TENG-based blue energy harvesting was proposed in 2014, the TENG technology has made great strides in water wave energy harvesting in the past 10 years, as summarized in **Figure** 1. The first work considered several TENG boxes with arched basic units,[10] in which the performance test results of a small TENG network and the theoretical predictions indicated the network could generate a high power of up to 1 MW per km^2 of sea area. Subsequent work involved multiple TENG structures for blue energy harvesting, designed and fabricated, which showed gradual improvements. The maximum output power density of the TENG for harvesting the water wave energy reached 13.2 W m^{-3} in 2017.[18] The output charge density of TENG devices achieved a significant breakthrough, reaching 1.02 mC m^{-2} in 2018.[19] During the same year, we developed a spherical TENG network driven by water wave energy and demonstrated its efficacy in a wave-generating tank of 120 m^2. Power management for water wave energy generation networks has also been improved remarkably, increasing the charging speed to capacitors by 100 times.[20] In 2020, a swing-structured TENG and its network were developed, which achieved an energy-conversion efficiency of 28.2%,[21] and an as-fabricated charge shuttling TENG could generate an effective output charge density of 1.85 mC m^{-2}, leading to a power density of 30.2 W m^{-3}.[22] In 2021, the power density increased further to 34.7 W m^{-3} using a bifilar-pendulum structure,[23] and the energy-conversion efficiency increased to 29.7% with the elastic connection and soft contact.[24] Currently, the anaconda-shaped TENG with high space utilization rate can reach the highest power density of 80.6 W m^{-3} under a low-amplitude water wave excitation.[25] It is worth noting that in 2023, we conducted field studies of TENG prototypes in real ocean environments to power offshore Internet of Things (IoT) nodes. As discussed, the TENG technology for blue energy has emerged from basic scientific

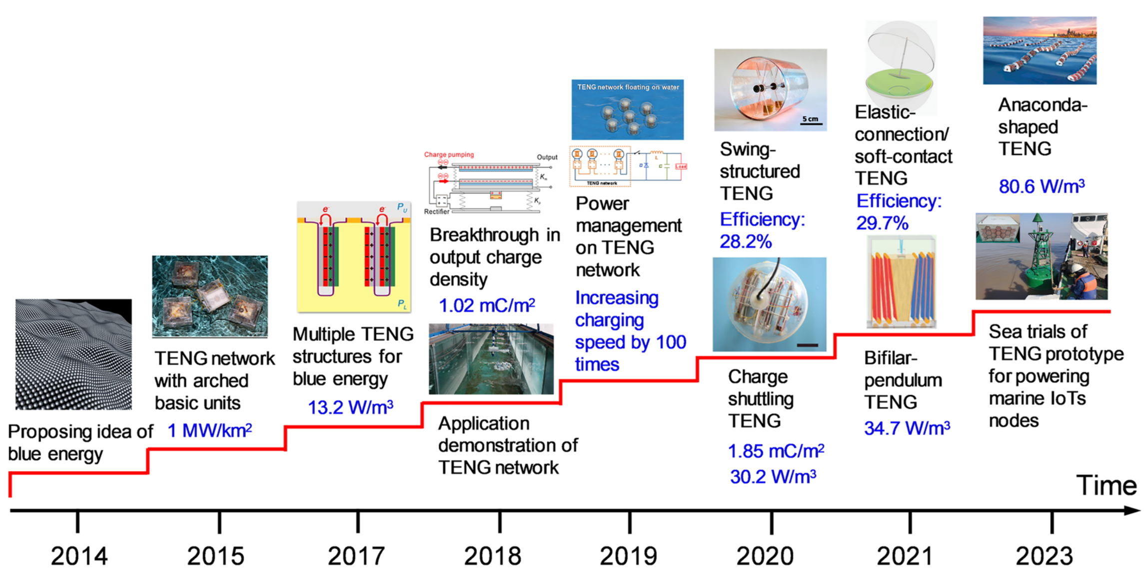

Figure 1. Development process of the triboelectric nanogenerator (TENG)-based blue energy harvesting in the last 10 years. Reprinted with permissions from Reference 16, © 2014 Royal Society of Chemistry; Reference 10, © 2015 American Chemical Society; Reference 18, © 2017 Elsevier; Reference 19, © 2018 Elsevier; Reference 20, © 2019 Wiley; Reference 21, © 2020 Wiley; Reference 22, © 2020 Springer Nature; Reference 23, © 2021 Wiley; Reference 24, © 2021 Wiley; Reference 25, © 2022 Elsevier.

principle studies to engineering prototypes. This technology is poised to advance from laboratory testing to sea trials.

Structural design and performance optimization of TENGs for blue energy

The TENGs have the advantage of converting low-level ambient mechanical energy into electricity, due to the potential difference between two surfaces induced by the repeated contact or friction between them. When the potential difference is applied to an external electrical circuit, an electric current flowing through the circuit is generated. Many TENG structures have been designed to demonstrate the working principle of using TENGs for water wave energy harvesting. The electric outputs have been optimized through various strategies toward real-world applications. Compared to general TENGs, the TENGs for harvesting water wave energy need to be specifically designed for enhancing the output performance, efficiency, and device durability. The structures should suit for the low-frequency character of water waves, and in terms of materials, moisture-resistant materials are more suitable for preparing the TENGs for water wave energy harvesting. In this section, the recent research progress is discussed, from the viewpoints of TENG structural designs, output performance optimization, and device efficiency and durability enhancement, and the hybrid energy technologies.

TENG structures for blue energy harvesting

To date, various TENG structures for harvesting the water wave energy have been designed and developed, which are mainly divided into two categories: enclosed-waterproof structures and liquid–solid interface electrification structures. The primary design principles of the enclosed-waterproof structures are to facilitate the motion of internal movable component relative to the stator when the device shell is excited by the water waves. The influences of the humidity and water spills can be largely reduced by the waterproof sealing. The enclosed-waterproof structures include the shell-ball structure,[9] wavy-electrode structure,[26,27] 3D electrode spherical structure,[28] air-driven membrane structure,[18] bifilar-pendulum structure,[23] anaconda-shaped structure,[25] buoy structure,[29,30] and the single-pendulum/tumbler coupling structure,[31] etc., as shown in **Figure** 2a. The bifilar-pendulum structure

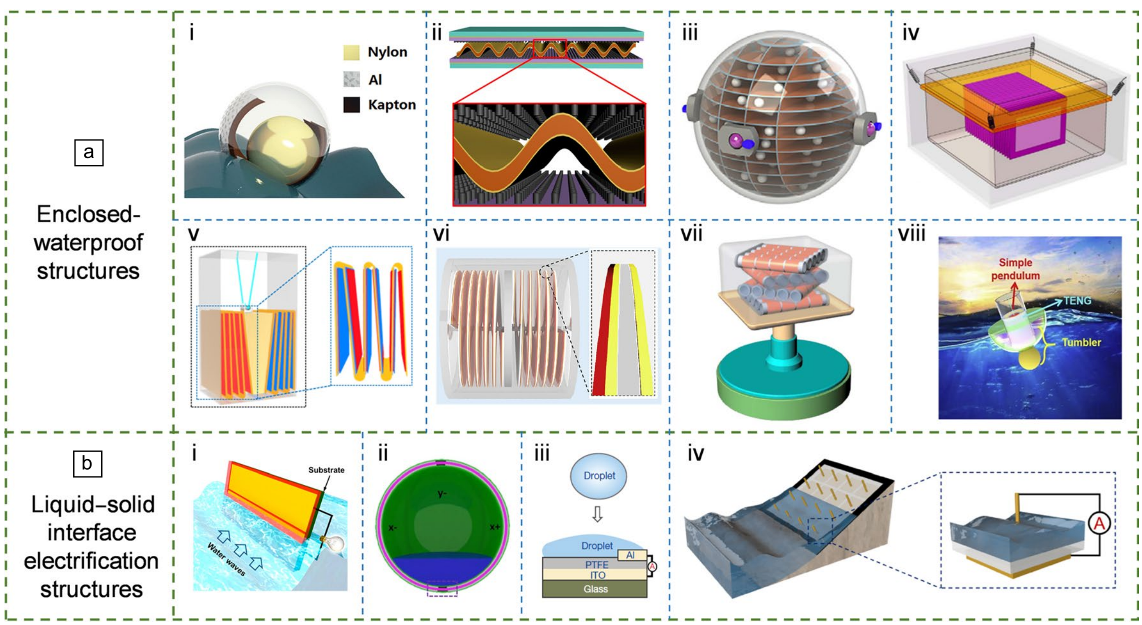

Figure 2. Two categories of triboelectric nanogenerator (TENG) structures designed for water wave energy harvesting. (a) Enclosed-waterproof TENG structures. (i) Shell-ball structure. Reprinted with permission from Reference 9. © 2015 Wiley. (ii) Wavy-electrode structure. Reprinted with permission from Reference 26. © 2014 American Chemical Society. (iii) Three-dimensional electrode spherical structure. Reprinted with permission from Reference 28. © 2019 Elsevier. (iv) Air-driven membrane structure. Reprinted with permission from Reference 18. © 2017 Elsevier. (v) Bifilar-pendulum structure. Reprinted with permission from Reference 23. © 2021 Wiley. (vi) Anaconda-shaped structure. Reprinted with permission from Reference 25. © 2022 Elsevier. (vii) Buoy structure. Reprinted with permission from Reference 30. © 2018 Elsevier. (viii) Single-pendulum/tumbler coupling structure. Reprinted with permission from Reference 31. © 2021 Elsevier. (b) Liquid–solid interface electrification TENG structures. (i) TENG based on the asymmetric screening of electrostatic charges at liquid–solid interface. Reprinted with permission from Reference 32. © 2014 American Chemical Society. (ii) Three-dimensional spherical water-based TENG. Reprinted with permission from Reference 34. © 2017 Elsevier. (iii) Field-effect transistor-like droplet TENG. Reprinted with permission from Reference 35. © 2020 Springer Nature. (iv) Bulk effect liquid–solid TENG. Reprinted with permission from Reference 36. © 2021 Elsevier.

adopts a soft-contact working mode, ultrathin and micro-/nanostructured dielectric materials, and reasonable space utilization of multilayered structures, which delivers an ultrahigh output power density of 200 W m^{-3}.[23] It can also exhibit outstanding performance in low-frequency water waves. Then the anaconda-shaped TENG raising the space utilization rate to 93.75% has generated the highest power density under the water wave triggering, up to now.[25] Moreover, the single-pendulum/tumbler coupled structure can achieve the effective harvesting of omnidirectional and full frequency band wave energy.[31] Ventura et al. prepared a buoy-type TENG based on a rolling spherical structure, and obtained the optimal device structure according to the hydrodynamic characteristics of the floating body,[29] opening up a new perspective for the marine applications of nanogenerators. Another buoy-based TENG was designed by Jung for collecting vibration energy from random water waves in barren seas,[30] which can generate stable outputs through harvesting water wave energy of various mixed amplitudes and frequencies from various directions.

In terms of water wave energy harvesting by liquid–solid interface electrification, dripping water droplets or fluctuating water bodies are usually utilized to interact with hydrophobic dielectric surfaces, inducing the triboelectrification, and generating electricity through electrostatic induction during the water motion process. Several representative structures for the liquid–solid TENGs are shown in Figure 2b. Asymmetric screening effect of electrostatic charges at the liquid–solid interface was adopted to fabricate a TENG that can directly interact with water waves by Zhu et al.[32] A water tank TENG and a 3D spherical water-based TENG were, respectively, fabricated to collect water motion energy.[33,34] Wang et al. invented a field-effect transistor-like TENG that can harvest energy from impacting water droplets, enabling rapid transfer of a large amount of generated charges.[35] With just a 100-μL water droplet hitting the device surface from a height of 15 cm, it can generate a voltage of 140 V and a current of 200 μA. Subsequently, a liquid–solid interface TENG based on the volume effect was designed,[36] which broke the limitations of surface effect through the design of external 3D electrodes and achieved a current output of 4 mA.

Output performance optimization of TENGs

Despite various TENG structures capable of harvesting water wave energy, the output performance of the TENGs need to be further optimized for meeting the needs of practical applications. Currently, multiple approaches have been developed to optimize the output performance of TENG devices, focusing on the enhancement of the output charge density and power density. The representative examples in the related research are shown in **Figure** 3a. The first approach is the frequency amplification by designing structures for storing the potential energy, such as the spring or pendulum structure. The spring can convert low-frequency water wave motions into high-frequency vibrations, and increase the electric energy by 1.5 times.[37] The spring structure was further integrated into a spherical shell, delivering an output power of 7.96 mW for a single sphere.[38] Another frequency-amplifying structure, the pendulum structure, exhibits similar characteristics of increasing the output frequency and output energy through the sustained electrical energy generation after the triggering.[21,39] It was further narrated that using a vacuum environment and ferroelectric materials can increase the output charge density by one order of magnitude and raise the maximum output power density by two orders of magnitude.[40] Moreover, charge pumping and charge shuttling strategies were adopted to realize an ultrahigh effective output charge density for the TENG under normal environmental conditions.[19,22] In addition, a soft-contact spherical structure was applied to increasing the contact area, thereby enhancing the TENG output performance greatly, which can improve the maximum transferred charges by 10 times relative to the hard-contact structure.[41]

Device efficiency and durability enhancement

Besides the output performance optimization, attempts have been made to enhance the energy-conversion efficiency and device durability. Typical strategies for raising the efficiency and durability are shown in Figure 3b. First, the previously mentioned frequency-multiplied structures such as the spring- or pendulum structure, can not only increase the electric outputs, but also enhance the energy-conversion efficiency. A spring and flexible dielectric fluffs were incorporated into a pendulum to create a swing-structured TENG by Lin et al.,[24] achieving a high vibration energy-to-electric energy-conversion efficiency of 29.7%, due to the charge replenishment of the dielectric fluffs during the swing process. Furthermore, the output voltage of the TENG almost keeps unchanged after 2,000,000 cycles, and the strong device durability is ascribed to the noncontact/soft-contact combined working mode. Second, a kind of fur-brush TENG using animal furs such as rabbit furs was fabricated to harvest the water wave or flow energy.[42–45] When utilizing two low-friction charge brushes, including the rabbit fur-brush and fluorinated ethylene propylene (FEP) roller brush, a double charge supplement TENG was obtained,[46] in which the output performance and device durability are both enhanced. The normalized output current presents an attenuation of only 5% after 110 h (3,960,000 cycles). Third, using the polymer rollers to construct a stacked-disc rolling TENG and a lateral-rolling swing-structured TENG.[47,48] The rolling friction can significantly decrease the material wear and lead to the enhanced device durability. For the lateral-rolling TENG, the attenuation of output current is below 1.6% after 1,260,000 cycles. Finally, Lin et al. integrated a transmission mechanism with a radial-arrayed TENG to maximize the sustainable operation with less material wear and damage.[49] The listed durability improving strategies are all mainly focused on the decrease of the friction resistance during the operation process of TENGs.

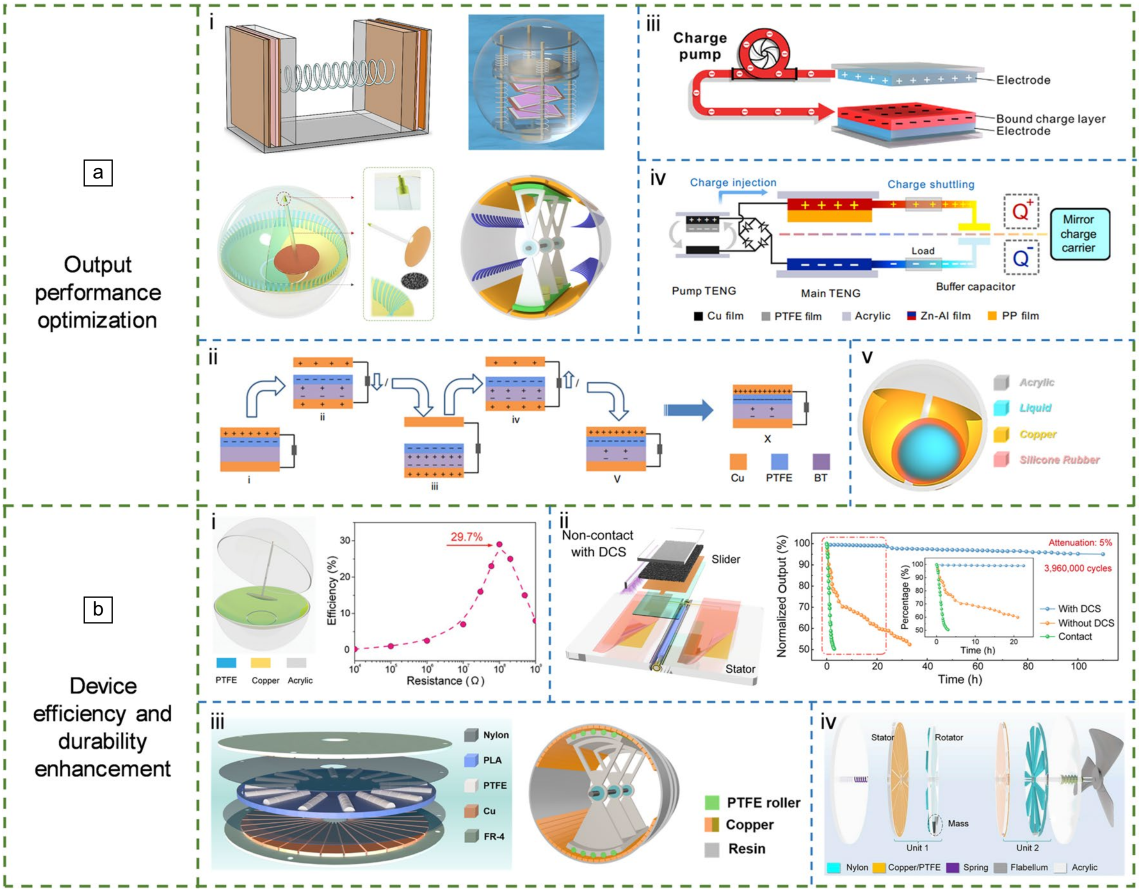

Figure 3. (a) Approaches for enhancing the output performance of triboelectric nanogenerators (TENGs). (i) Introducing a spring or pendulum structure. Reprinted with permission from Reference 37, © 2017 Elsevier; Reference 38, © 2018 Wiley; Reference 39, © 2019 Elsevier; Reference 21, © 2020 Wiley. (ii) Using vacuum environment and ferroelectric materials. Reprinted with permission from Reference 40. © 2017 Springer Nature. (iii) Charge pumping. Reprinted with permission from Reference 19. © 2018 Elsevier. (iv) Charge shuttling. Reprinted with permission from Reference 22, © 2020 Springer Nature. (v) Designing soft-contact structure. Reprinted with permission from Reference 41. © 2019 Elsevier. (b) Strategies for improving the device efficiency and durability. (i) Designing a spherical swing-structured TENG in an elastic-connection and soft-contact mode. Reprinted with permission from Reference 24. © 2021 Wiley. (ii) Using animal furs to construct double charge supplement (DCS) fur-brush TENG. Reprinted with permission from Reference 46. © 2022 Wiley. (iii) Introducing polymer rollers to fabricate a stacked-disc rolling or lateral-rolling swing-structured TENG. Reprinted with permission from Reference 47, © 2024 Wiley; Reference 48, © 2024 Wiley. (iv) Integrating a transmission mechanism with a radial-arrayed TENG. Reprinted with permission from Reference 49. © 2020 Elsevier.

Hybrid energy-harvesting technologies

In order to maximize the comprehensive utilization of various energy forms or energy technologies, and enhance the energy-conversion efficiency, hybrid generators combining TENGs and other energy-harvesting technologies have been designed. For example, coupling the TENGs with solar cells and wind turbines to collect hybrid energy can take full advantages of various technologies for complex application scenarios; the TENGs can be hybridized with the EMGs to jointly harvest ocean blue energy. Wang's group developed a composite system based on the TENG and EMG, which can collect the kinetic energy of ocean waves and currents.[50] Subsequently, a concentric cylindrical device structure was designed for harvesting broad frequency band wave energy.[51] Zhao et al. reported a multilayered soft-brush triboelectric-electromagnetic hybrid generator for point absorber-based wave energy conversion,[52] in which the soft-brush structure greatly improves the device output performance and durability. The unidirectional transmission mechanism is easy to achieve continuous and high outputs, and fully enclosed magnetic-coupling is convenient for hybrid power generation. Additionally, a soft-contact triboelectric-electromagnetic hybrid generator was constructed using the rabbit fur brushes and swing structure,[53] which can output at least 60 current pulses under one triggering of water waves.

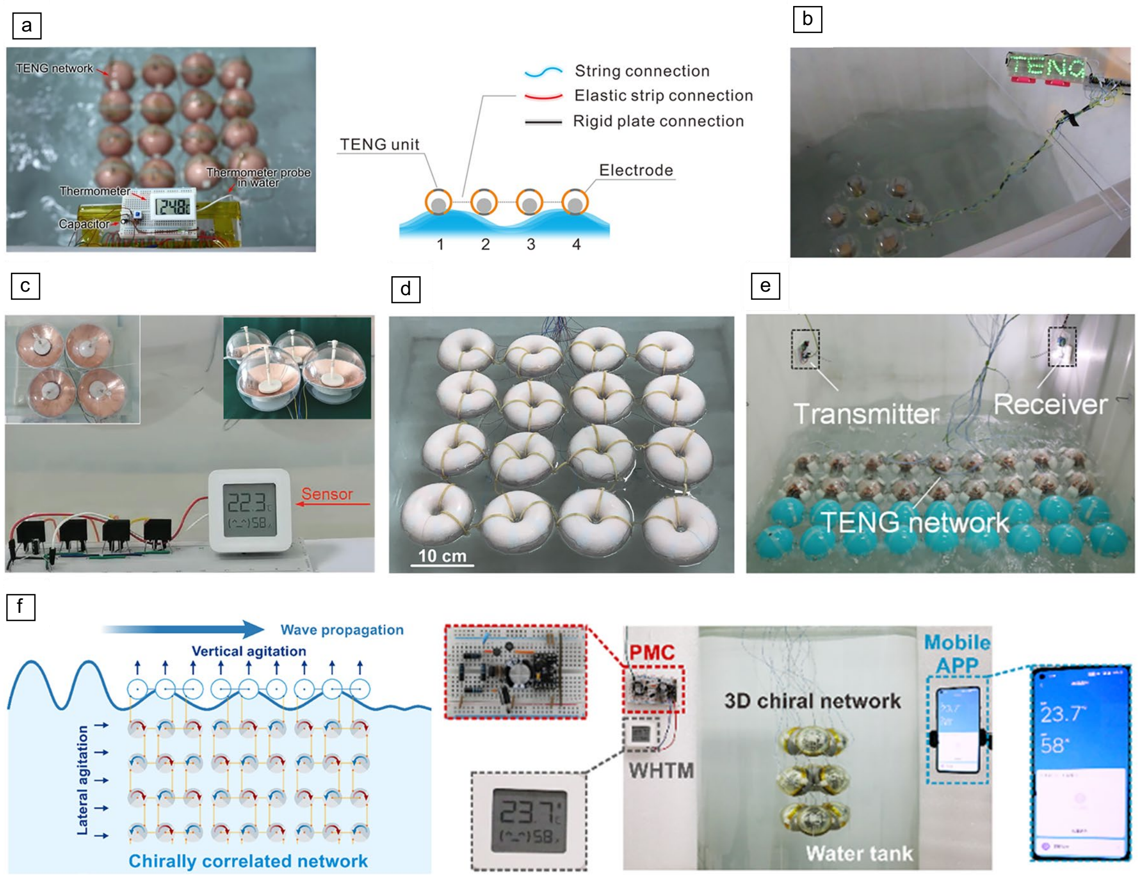

Figure 4. Construction and performance testing of triboelectric nanogenerator (TENG) networks. (a) Network of shell-ball structure units. Reprinted with permission from Reference 12. © 2018 American Chemical Society. (b) Spherical spring-assisted TENG network. Reprinted with permission from Reference 20. © 2019 Wiley. (c) Pendulum-like spherical TENG network. Reprinted with permission from Reference 24. © 2021 Wiley. (d) Torus structured TENG network. Reprinted with permission from Reference 54. © 2019 Elsevier. (e) Macroscopic self-assembly network based on 3D electrode spherical units. Reprinted with permission from Reference 28.© 2019 Elsevier. (f) Three-dimensional chiral TENG network. PMC, power management circuit; WHTM, wireless hygro-thermometer. Reprinted with permission from Reference 55. © 2023 Royal Society of Chemistry.

Construction of TENG networks and system integration

Networking of TENG units for large-scale blue energy

Based on the array integration of TENG units, TENG networks with different structures have been constructed to harvest ocean blue energy over a larger scale, and the optimization of their output performance has been carried out. The progress of related research work is shown in **Figure** 4. Since the first TENG network for water wave energy harvesting based on the box-like units with internal arched structures,[10] the network design of shell-ball structure units has made significant progress.[12] A TENG network composed of 16 spherical units can produce a peak power of 5.93 mW and an average power of 2.04 mW at 3 Hz. The functions and roles of the network connection manner in the water wave energy collection were elucidated, where flexible string and elastic strip connections can have better effects than the rigid connection, providing a preliminary solution for large-scale wave energy harvesting. Moreover, TENG networks with internal spring,[20] pendulum structures,[24] and torus structures[54] were fabricated to convert water wave energy into electrical energy, successfully powering small portable electronic devices. Next, based on a 3D electrode spherical structure unit with a diameter of 8 cm, Yang et al. constructed a demonstration network of 18 units, delivering an average power density of 2.05 W m^{-3} in the water waves,[28] for self-powered sensing and wireless signal transmission. The ocean environment tests of such ball-based network were carried out in the Guangxi Beibu Gulf, verifying the power-generation capacity of the TENG network in real sea conditions. In addition, inspired by metamaterial's structure, Li et al. reported a 3D chiral TENG network adopting a distributed architecture with chiral connections between unbalanced units, which can be configured to different scales and depths to harvest water wave energy in all directions.[55]

Power management of the TENGs and networks for blue energy

Due to the large impedance and unbalanced load matching, the water wave-driven TENGs and their networks have difficulties in directly powering electronics or charging storage units.[56–58] Therefore, effective power management on the TENG or network outputs is essential to break through such bottleneck and successfully power electronics. A universal power management strategy for TENGs was proposed by Zhang et al.,[56] and a power-management module was developed. Based on this module, 85% of the energy from the TENGs can be autonomously released, and stable and continuous voltage output can be obtained on the load resistor after voltage reduction. By utilizing this power-management module, effective managements of the output energy of an integrated spherical TENG for multidirectional wave energy harvesting and a spherical spring-assisted multilayered TENG network were achieved,[20,59] resulting in a nearly 100-fold increase in stored energy when charging a capacitor or supercapacitor. And a kind of charge excitation module using the switch of serial and parallel connections between capacitors for TENGs was designed.[60,61] After integration, the output current of a single spherical unit was increased by 208 times under the water wave excitations, reaching 25.1 mA, and the power arrived at 25.8 mW.[60] Through the power management on the TENG network consisting of seven charge excitation spherical TENG units, wireless communication between the network and mobile phone can be realized. At the same time, a systematic study was conducted on the integrated power pack of TENG-power management–energy storage.

Summary and perspectives

In this article, the overall development venation of TENG technology for blue energy harvesting in the past 10 years was first introduced. Next, the current research progress in blue energy harvesting using the TENGs was summarized, focusing on structural designs of various enclosed-waterproof structures and liquid–solid interface electrification structures for water wave energy collection, and the optimization of output performance and device efficiency/durability. Among them, the anaconda-shaped TENG generates the highest power density of 80.6 W m^{-3} under low-amplitude water wave excitation currently, and the pendulum and flexible brush structure improve the energy-conversion efficiency of the TENG to 29.7 percent. Multiple TENG networks were constructed and the research works on optimizing their output performance under water wave triggering and managing the outputs were reviewed. The TENG network based on 3D electrode spherical units delivers an average power density of 2.05 W m^{-3}. The networking of multiple TENG units and the system integration of power generation–power management–energy storage provide a promising solution for future large-scale blue energy harvesting.

If stimulated 2–3 times per second by water waves, each unit can generate a power of 10 mW or a power density of 10 W m^{-3}, the TENG networks covering 10 m of water depth at a sea area equal to the size of the state of Georgia can produce enough electricity for powering the world. In addition, above the TENG network, solar panels and wind turbines can be arranged to achieve collaborative collection of water wave energy, wind energy, and solar energy, enhancing the output power. The collected electrical

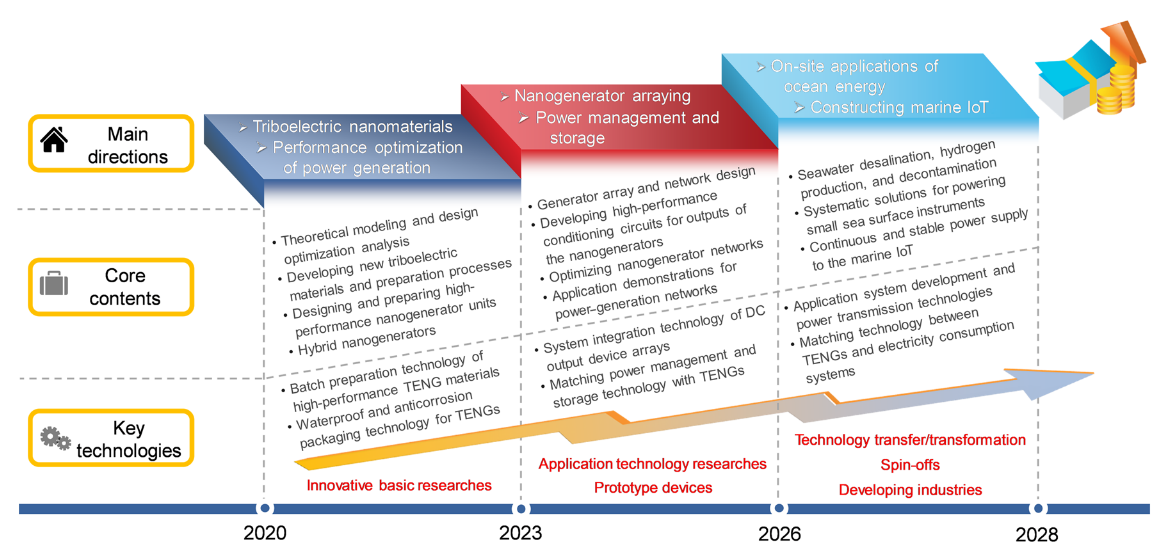

Figure 5. Proposed roadmap for the development of using triboelectric nanogenerators (TENGs) to harvest ocean blue energy from 2020 to 2028 toward future practical commercial applications.

energy can be used for floating platforms at sea or transmitted to land for integration into the power grids. If the blue energy dream can be realized, the social and economic effects are incalculable, which could induce an energy revolution and effectively promote the development of social productivity and the progress of human civilization. Toward the blue energy dream, there are still some core scientific and key technical issues that urgently need to be solved in the blue energy research based on the TENGs. Continuous and in-depth explorations are needed in terms of triboelectrification mechanism, ocean dynamics theory, model experiments, TENG network design and performance optimization, power management, etc., and practical experience needs to be accumulated. And the location and size of the power-generation grids require to be considered for minimizing the impacts on shipping, marine life, and ecology.

A roadmap for the development of using TENGs to harvest ocean blue energy from 2020 to 2028 toward future practical commercial applications is proposed, as shown in **Figure** 5. As we continue to conduct innovative basic research on triboelectric nanomaterials and optimization of power-generation performance, efforts have been expanded to applied technology research on nanogenerator arraying, power management and storage, and we will promote the industrialization of on-site applications of ocean energy such as continuous and stable power supply to the marine IoT. The ultimate objective is to realize the achievement transfer/transformation and industrialization of blue energy development from the basic and applied research. In summary, the most critical research topics in this field are as follows: (1) exploring new materials, structures, and power-generation mechanisms suitable for the marine environment, in order to improve the utilization efficiency of ocean blue energy; (2) elucidating the interaction mechanism between the power-generation device and the water fluids to construct a liquid–solid coupled multiphysics field theoretical system; (3) discussing the energy-management and storage solutions applicable to different types of power-generation devices, optimizing management and storage efficiency, and achieving the coupling of power generation–power management–energy storage; (4) utilizing complementarily multiple energy-conversion mechanisms to enhance the ocean energy collection capacity; (5) studying the durability and corrosion resistance of devices to improve their reliability and life, so as to provide systematic solutions for different ocean application requirements. *In situ* power solutions can be first provided for small offshore equipment and navigation positioning systems, and to further meet different application needs, building a mobile self-powered system and a new type of marine IoT will exhibit broad application prospects in fields of ocean equipment power supply, on-site ocean development, island power supply, offshore navigation positioning, and underwater or water surface monitoring.

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Author contributions

Z.L.W. contributed overall conception and framework of this review and guided the writing. T.J. contributed to the sections about the TENG development venation and structural designs. T.M. contributed to the section about the performance optimization of TENGs. R.Y. contributed to the section about the TENG network construction and system integration. All contributed to the Introduction and Summary sections.

Conflict of interest

On behalf of all authors, the corresponding authors state that there is no conflict of interest.

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