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Review

Toward the blue energy dream by triboelectric nanogenerator networks

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ABSTRACT

Widely distributed across the globe, water wave energy is one of the most promising renewable energy sources, while little has been exploited due to various limitations of current technologies mainly relying on electromagnetic generator (EMG), especially its operation in irregular environment and low frequency ($<$ 5 Hz). The newly developed triboelectric nanogenerator (TENG) exhibits obvious advantages over EMG in harvesting energy from low-frequency water wave motions, and the network of TENGs was proposed as a potential approach toward large-scale blue energy harvesting. Here, a review is given for recent progress in blue energy harvesting using TENG technology, starting from a comparison between the EMG and the TENG both in physics and engineering design. The fundamental mechanism of nanogenerators is presented based on Maxwell's displacement current. Approaches of water wave energy harvesting by liquid-solid contact electrification TENG are introduced. For fully enclosed TENGs, the structural designs and performance optimizations are discussed, based on which the TENG network is proposed for large-scale blue energy harvesting from water waves. Furthermore, the energy harvested by TENG from various sources such as water wave, human motion and vibration etc, is not only new energy, but more importantly, *the energy for the new era* – the era of internet of things.

1. Introduction

1.1. Ocean energy harvesting

Ocean covers more than 70% of the earth's surface and there are exceedingly abundant resources in water. The ocean energy is regarded as an important renewable and clean energy source, which has been estimated to be totally over 75 TW (1 terawatt = 10^{12} W) around the world [1,2]. Large-scope commercial applications of ocean energy, if possible, will bring huge changes for global energy structure, political balance, and economic and society developments. Ocean energy is typically regarded as having five specific forms, *i.e.*, tidal energy, water wave energy, ocean current energy, temperature gradient energy, and salinity gradient energy [3], among which ocean wave energy referring to the kinetic and potential energy from ocean surface waves exhibits advantages of high power density and wide distribution. The global power by waves breaking around the coastlines worldwide has been estimated to be about 2–3 TW [3], and if wave energy is harvested on open oceans, the global wave power is estimated to be one order of magnitude larger [4,5]. Therefore, the wave energy is one of the key directions of ocean energy development. However, it has rarely been exploited due to lack of economical energy scavenging technologies [6,7].

Currently, ocean energy companies are testing some designs to capture the energy from ocean tides or ocean waves [8,9]. A facility with a pair of 16-metre-long propellers attached to a central tower that is anchored to the channel floor, built by Marine Current Turbines, and a seabed-mounted turbines with an only moving central rotor designed by OpenHydro are typical examples of capturing tidal energy (see Fig. 1) [9]. For the ocean wave energy, Carnegie Wave Energy in Australia built bobbing buoys, in which the wave motions drive the sea-floor pumps to circulate fluid through a closed loop extending roughly 3 km to an onshore generator. Pelamis Wave Power in UK prepared connected floating buoys by applying the hydraulic pumps at joints to circulate the fluids to an onshore generator driving by the waves. Today's wave energy conversion starts from the extraction of large-area wave energy and translation into mechanical energy, and then relies on the electromagnetic generator (EMG) to generate electricity. The EMG made up of bulky, heavy magnets, metal coils, and turbines cannot naturally float on the water surface unless supported by a floating platform or fixed to the sea bed, which is very expensive and technically difficult [10–12]. The coils and magnets easily suffer seawater corro-

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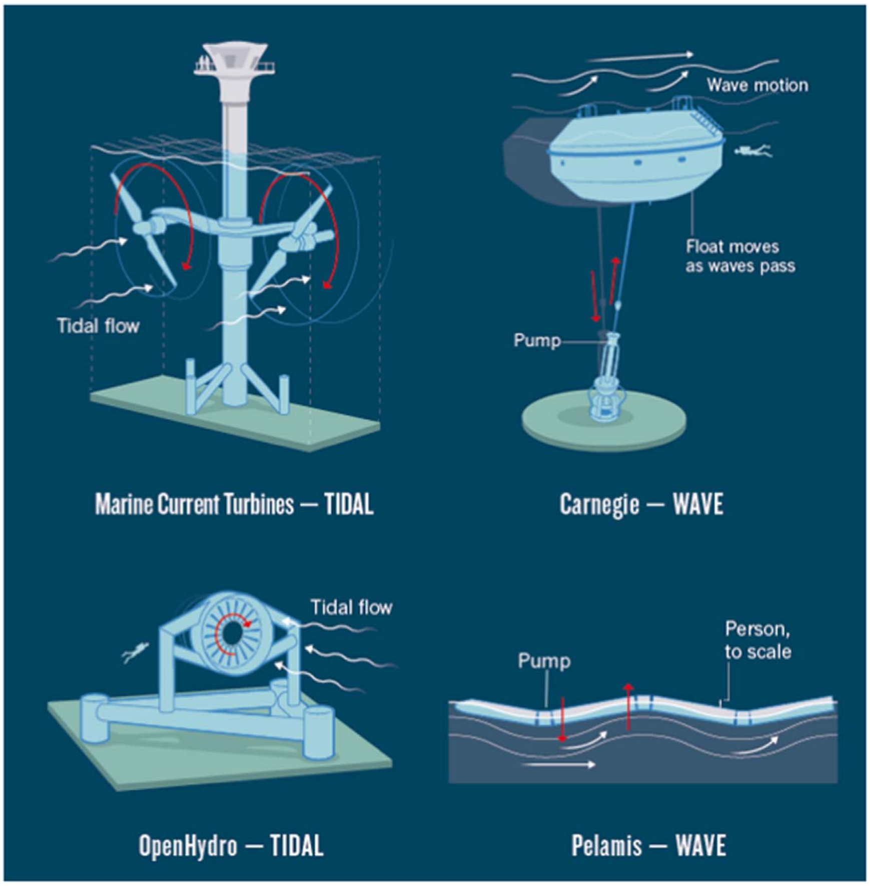

Fig. 1. Typical designs to capture the energy from ocean tides or ocean waves using EMGs currently built by ocean energy companies. Reproduced with permission from Nature Publishing Group [9].

sion, and the turbines have low efficiency at ocean wave frequency and motion modes. Due to these challenges, current ocean wave energy apparatuses exhibit unsatisfactory energy harvesting efficiency and high cost. So far, the research is mainly at the early stage of proto developing and testing, and there's not a large-scale commercial wave energy facility in the world.

1.2. Triboelectric nanogenerator

The nanogenerator was first developed by Wang and coworker in 2006 to harvest ambient mechanical energy based on the piezoelectric effect, opening up a new field of energy conversion and application [13]. In January 2012, the triboelectric nanogenerator (TENG) was invented as a powerful technology for converting mechanical energy into electricity based on the coupling of triboelectrification and electrostatic induction [14], with unique merits of high power density, high efficiency, low weight and low fabrication cost [15–18]. Since its birth, various TENGs with different structures and functions have been developed [19–23], which gradually innovates human's idea about energy harvesting. So far, the area power density for a single TENG device reaches as high as $500\ \mathrm{W\,m^{-2}}$ in special cases, and an instantaneous energy conversion efficiency of 70% has been demonstrated [24,25], which can meet the power demands of many small electronics. This technology exhibits universality in mechanical energy harvesting, and has been applied to harvest energy from a variety of sources, such as human walking, mechanical vibration, rotation, wind, tides, water waves, and so on [26–34]. Furthermore, the energy harvested by TENG from various sources is not only new energy, but *the energy for the new era* – the era of internet of things. The TENG could provide a new strategy for wave energy conversion and have huge potential toward large-scale *blue energy* harvesting from the ocean [35], which represents the energy offered by water wave, tide and ocean related.

Here, recent progress in blue energy harvesting with TENG technology is reviewed. The review focuses on the technological comparison between EMG and TENG, typical TENG technologies in blue energy harvesting, and future perspectives in large-scale blue energy. In the first segment of the review, the operation principles, fundamental physics mechanisms, and output performances for the EMG and the TENG are systematically compared. The theoretical origin of the TENG is Maxwell's displacement current, as is much distinct from that of the EMG, and the killer application of the TENG in harvesting low-frequency energy such as water wave energy is demonstrated. In the subsequent section, we primarily devote to elaborating on the latest progress of TENG devices as a new technology for water motion energy harvesting, including the liquid-solid contact electrification TENG, fully enclosed TENG, and TENG networks. Lastly, some perspectives and challenges for future development of TENG technology toward the blue energy dream are discussed.

2. Comparison between electromagnetic generator and triboelectric nanogenerator

2.1. Operation principles

The classic technology for harvesting blue energy from the ocean is the propeller driven electromagnetic generator that is composed of magnets and metal coils (Fig. 2a), which is rather heavy and has a high mass density. In particular, water motion energy is an irregular energy with random oscillation directions, low oscillating frequency (< 2 Hz), and variable amplitude [36,37]. The EMG is not effective for harvesting such “random” energy [36].

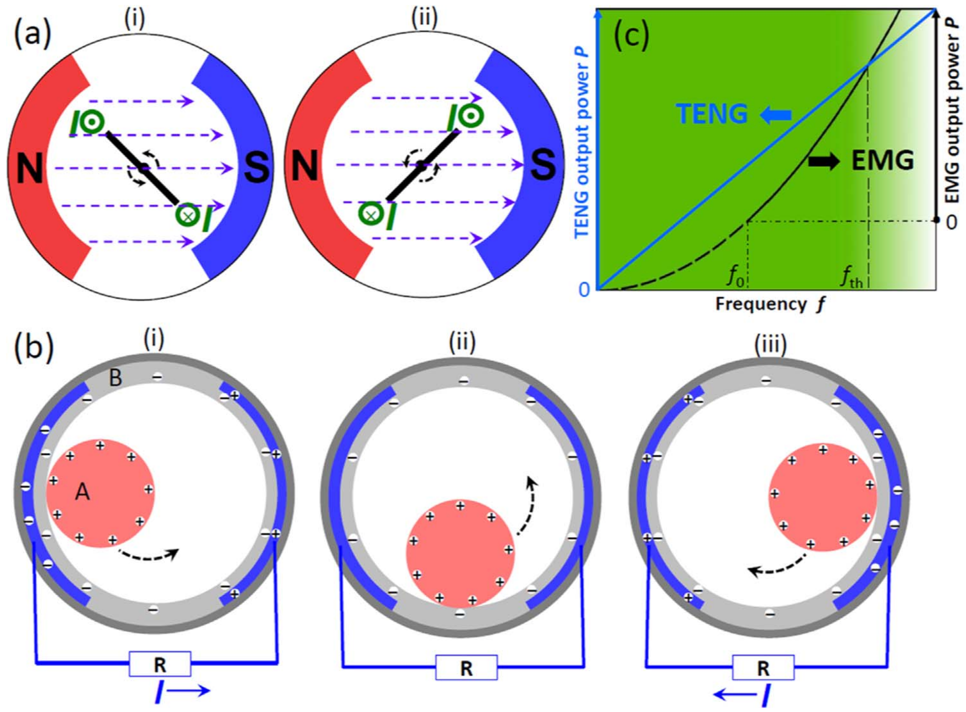

Fig. 2. Classical electromagnetic generator (EMG) vs triboelectric nanogeneraotor (TENG). (a) Working mechanism of an EMG based on electromagnetic induction as a metal coil cuts through the magnetic induction lines generated by a magnet. (b) Working mechanisms of a TENG by coupling of triboelectrificatioin effect and electrostatic induction. The contact between materials A and B creates surface electrostatic charges; the rolling of the ball changes the capacitance of the system, resulting in flow of electrons between the two electrodes to balance the electric potential drop (i, ii, iii). (c) Schematic illustration on the dependence of the output power of EMG and TENG on the operation frequency, indicating the killer applications of TENG for effectively harvesting low-frequency mechanical energy.

The basic principle of the TENG is illustrated in Fig. 2b. By conjunction of triboelectrification effect and electrostatic induction effect, physical contact between two dielectric materials causes triboelectric charges on the two surfaces (A and B in Fig. 2b(i)); a relative separation and/or sliding between the two as caused by mechanical motion results in an electric potential drop across the two electrodes built below the B dielectric material, which drives the electrons to flow between the two in order to balance the electrostatic system (Fig. 2b(ii)). The TENG can be made into fully packaged and sealed spherical ball/tube shape [38], so that no water infiltration into the sphere is possible and the growth of any bioproducts or contaminants outside of the sphere will not affect its performance for energy generation. The TENG can float on water surface with a full degree of freedom for rotation and movement in responding to water motion [38].

What are the advantages of using the TENG *vs* the EMG? Besides the light weight density and floating on water surface, TENG is much adaptive than EMG in responding to irregular and random mechanical motion, so that it is ideal for harvesting water wave energy. Most importantly, TENG has a high energy conversion efficiency at low frequency *(f)* [22,39]. The output voltage and current of an EMG are both proportional to the rotation frequency of the rotor, so that the output power is proportional to f^2. In contrast, the output voltage of the TENG is a constant that depends on the electrostatic charges built-up on the surface and the capacitance of the system, so that it is almost independence of the operation frequency, and its output current is proportional to f and so is its output power (Fig. 2c). There exists a critical frequency f_{th} (typically ~5 Hz), below which the output of TENG is larger than that of EMG if their sizes are the same. In addition, since the diode that is used for rectifying an AC into DC has a threshold operation voltage, which is typically ~0.5 V, it means that any current generated at low frequency with an output voltage of lower than ~0.5 V results in no effective output power, so that there exists another critical frequency f_0, above which EMG can give useful output power, and below which the output DC voltage is literally zero (see the y-axis label at the right-hand side in Fig. 2c). In contrast, TENG has a unique advantage that it usually has a high output voltage even at very low frequency, typically ~ 20–50 V. Thus, a small loss of 0.5 V by the diode leads almost no loss to the output power. Therefore, at low frequency of < 5 Hz, the output power of a TENG is much higher than that of an EMG, which is the dominant frequency range in which TENG is the only choice [40].

2.2. Fundamental physics mechanisms

The electromagnetic generator and the nanogenerator are two main technologies for converting the mechanical energy into electricity. Their theoretical foundations can trace back to fundamental Maxwell's equations, including Gauss's law, Faraday's law, and Ampère's circuital law [41]. Fig. 3 shows a comparison of theoretical foundation between the EMG and the nanogenerator. The EMG invented by Faraday in 1831 applies a varying magnetic field to generate current, whose power generation process is the Lorentz force induced electron flow in a conductor. The output current is directly related to the time-variation of the magnetic field: $\frac{\partial \boldsymbol{B}}{\partial t}$. This means that the time variation of the magnetic field results in the current of the EMG (see the left-hand side of Fig. 3).

However, for the nanogenerator proposed by Zhong Lin Wang in 2006 and TENG in 2012 [13,14], the current is generated by varying polarization field induced by surface polarization charges, which is one important part of the Maxwell's displacement current. From the fundamental physics, the EMG and the nanogenerator are distinctly different, but they are unified by the Maxwell's equations. The displacement current was first postulated by Maxwell in 1861 to ensure the continuity equation for electric charges [42]. The Maxwell's displacement current is defined as

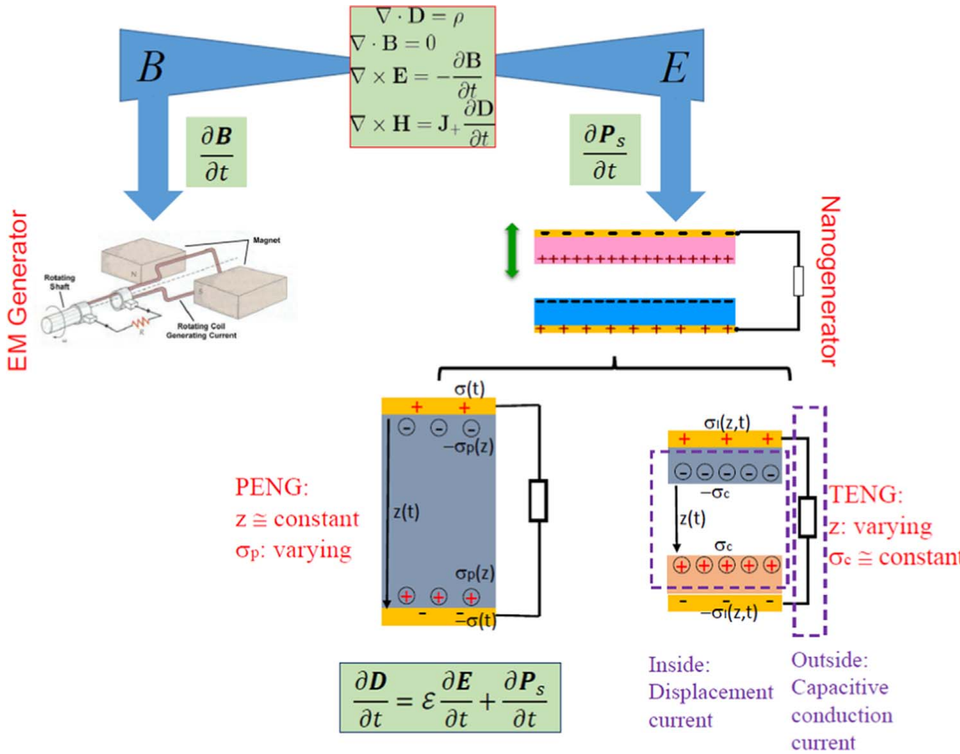

Fig. 3. A comparison of theoretical foundation between the EMG and the nanogenerator. The EMG applies a varying magnetic field to generate current ($\frac{\partial B}{\partial t}$), while the nanogenerator is based on the varying polarization field induced by surface polarization charges ($\frac{\partial P_S}{\partial t}$), which is the fundamental difference between the EMG and nanogenerators. The nanogenerator represents a completely new and different mechanism for power generation. One may or may not use nanomaterials for the nanogenerators, but it is still called nanogenerators. The working mechanisms of piezoelectric nanogenerator (PENG) and TENG are also illustrated, and the theoretical origin of nanogenerators is the Maxwell's displacement current (see text).

$$J_D = \frac{\partial \boldsymbol{D}}{\partial t} = \varepsilon_0 \frac{\partial \boldsymbol{E}}{\partial t} + \frac{\partial \boldsymbol{P}}{\partial t} \tag{1}$$

where $\boldsymbol{E}$ is the electric field, $\boldsymbol{P}$ is the polarization field, $\boldsymbol{D}$ is the electric displacement field, and ε_0 is the vacuum permittivity. The first term $\varepsilon_0 \frac{\partial \boldsymbol{E}}{\partial t}$ not only unifies the electric field and magnetic field, but also gives the birth of electromagnetic wave, laying the physical foundation of wireless communication. For an isotropic media, $\boldsymbol{P} = (\varepsilon - \varepsilon_0)\boldsymbol{E}$, $\boldsymbol{D} = \varepsilon\boldsymbol{E}$, where ε is the permittivity of the dielectrics, so the displacement current becomes $J_D = \varepsilon \frac{\partial \boldsymbol{E}}{\partial t}$.

However, in a media with the presence of surface polarization charges, *e.g.*, piezoelectric material or triboelectric materials, the contribution to the displacement current from the polarization density of surface electrostatic charges cannot be ignored. The displacement current can be written as

$$J_D = \frac{\partial \boldsymbol{D}}{\partial t} = \varepsilon \frac{\partial \boldsymbol{E}}{\partial t} + \frac{\partial \boldsymbol{P}_S}{\partial t} \tag{2}$$

where the first term is the induced current by the varying electric field, and the second term is the current caused by the polarization field of surface electrostatic charges. The second term is the theoretical origin of nanogenerators. In other words, the nanogenerators are the applications of displacement current in energy and sensors.

In the nanogenerator family, piezoelectric nanogenerator (PENG) applies the piezoelectric polarization charges and the generated time-varying electric field to drive the electrons to flow through the external circuit. As shown in Fig. 3, when an insulator piezoelectric material covered by two electrodes on its two surfaces suffers a vertical mechanical deformation, piezoelectric polarization charges are generated at the two ends of the material. The polarization charge density σ_p can be increased by increasing the applied force, and the electrostatic potential created by the polarization charges is balanced by the flow of electrons between two electrodes through a load. The displacement current inside the material is the same as the output current derived from a capacitive model with nearly constant thickness z, but a varying surface charge density σ_p during straining.

For the TENG, electrostatic charges with opposite signs are generated on the surfaces of two dielectrics after the physical contact. The surface charge density σ_c gets saturation after several contact cycles. The electrostatic field built by the triboelectric charges drives electrons to flow through the external load. We have derived the output characteristics of the TENG from both the displacement current inside the material and a capacitive model in an external circuit, and obtained consistent results [41]. The internal circuit is dominated by the displacement current, and the observed current in the external circuit is the capacitive conduction current. The internal circuit and external circuit can meet at the two electrodes. Therefore, the displacement current is the intrinsic physical core of current generation, and the capacitive model in an external circuit is the external manifestation of displacement current. In TENG, the surface charge density is fixed but the capacitance of the system changes during mechanical triggering.

To illustrate the theory for TENG, we start from a simple configuration of contact-separation mode composed of two media with dielectric permittivities of ε_1 and ε_2 and thicknesses of d_1 and d_2, respectively. If the triboelectricity introduced surface charge density is $\sigma_c(t)$, and the density of free electrons on surfaces of the electrode is $\sigma_I(z, t)$, which is the function of the gap distance $z(t)$ between the two media. As shown at the bottom-right of Fig. 3, the electric fields in the two media and in the gap are $E_z = \sigma_I(z, t)/\varepsilon_1$, $E_z = \sigma_I(z, t)/\varepsilon_2$, $E_z = (\sigma_I(z, t) - \sigma_c)/\varepsilon_0$. The potential drop between the two electrodes is

$$V = \sigma_I(z, t)[d_1/\varepsilon_1 + d_2/\varepsilon_2] + z[\sigma_I(z, t) - \sigma_c]/\varepsilon_0 \tag{3}$$

Under short-circuit condition, $V = 0$,

$$\sigma_I(z, t) = \frac{z\sigma_c}{d_1\varepsilon_0/\varepsilon_1 + d_2\varepsilon_0/\varepsilon_2 + z} \tag{4}$$

Therefore, the displacement current inside the media is

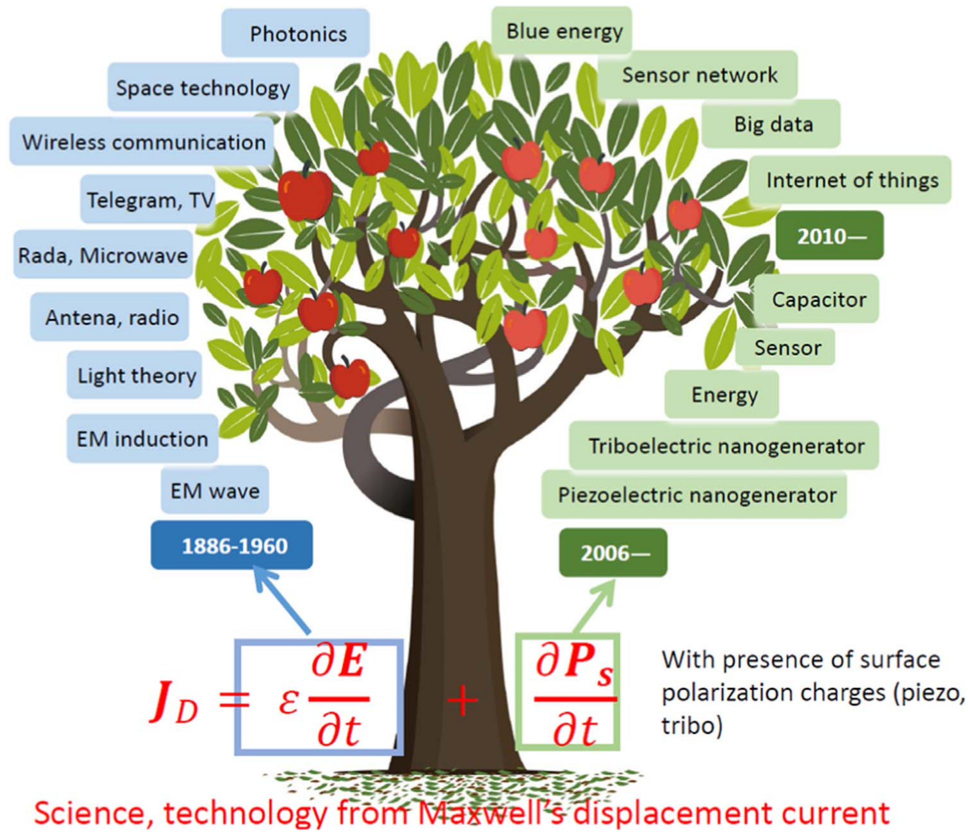

Fig. 4. Major fundamental science, technologies and practical impacts that have been derived from the two components of the Maxwell's displacement current. The left-hand side is the derived electromagnetic wave theory that has impacted the development of the world in the last century in communication; the right-hand side is the new technologies derived from displacement current for energy and sensors that are likely to impact the world for the future.

$$J_D = \frac{\partial \boldsymbol{D}_z}{\partial t} = \frac{\partial \sigma_I(z, t)}{\partial t} = \sigma_c \frac{dz}{dt} \frac{d_1\varepsilon_0/\varepsilon_1 + d_2\varepsilon_0/\varepsilon_2}{[d_1\varepsilon_0/\varepsilon_1 + d_2\varepsilon_0/\varepsilon_2 + z]^2} + \frac{d\sigma_c}{dt} \frac{z}{d_1\varepsilon_0/\varepsilon_1 + d_2\varepsilon_0/\varepsilon_2 + z} \quad (5)$$

In Eq. (5), the first term means that the magnitude of the displacement current is proportional to the speed at which the two media contact/separate (dz/dt); the second term is related to the rate at which the surface charge density building up. In general, after contacting for about 10 times, σ_c reaches saturation, and the second term vanishes.

If there is an external load R, from the Ohm's law, the transport equation of the TENG is:

$$RA\frac{d\sigma_I(z, t)}{dt} = z\sigma_c/\varepsilon_0 - \sigma_I(z, t)[d_1/\varepsilon_1 + d_2/\varepsilon_2 + z/\varepsilon_0] \quad (6)$$

From above, we know the theoretical origin of nanogenerators is the Maxwell's displacement current. The major fundamental science, technologies and practical impacts derived from the two components of the Maxwell's displacement current are presented in Fig. 4. In fact, the first component of displacement current $\varepsilon\frac{\partial E}{\partial t}$ gives the birth of electromagnetic wave theory, and the electromagnetic induction causes the emergence of antenna, radio, telegram, TV, Radar, microwave, wireless communication, and space technology from 1886 to 1930s. In the 1960s, the electromagnetic unification produces the theory of light, laying the physical theory foundation for the invention of laser and development of photonics. In addition, the control and navigation of airplane, shipping, and spacecraft, as well as the technology progress of the electric power and microelectronics industry, cannot be separated from Maxwell. Therefore, the first component of displacement current has driven the development of the world in communication technology in the last century.

In parallel, the second term $\frac{\partial P_S}{\partial t}$ in the displacement current based on the media polarization gives the birth of piezoelectric nanogenerator and triboelectric nanogenerator from 2006, which greatly promotes the developments of new energy technology and self-powered sensors, which is referred to be the energy for new era – the era of internet of things and sensor networks. Our nanogenerators for energy could have extensive applications in IoT, sensor networks, blue energy and even big data which will impact the world for the future. By tracing back to 150 years ago, our nanogenerators can be regarded as another important application of Maxwell's displacement current in energy and sensors after the electromagnetic wave theory and technology. For the foreseeable future, the "tree" drawing nutrition from the first largest equations for physics will grow stronger, which possibly leads the technological innovation and changes the human society.

Base on the distinctly different physics mechanism**s** between the nanogenerator and EMG, Fig. 5 provides a comparison between the EMG and the TENG from the mechanisms, advantages and disadvantages. It is necessary to emphasize again that the EMG based on electromagnetic induction generates current through the mechanism of resistive free electron conduction driven by Lorentz force, while the TENG based on the contact electrification and electrostatic induction adopts the mechanism of capacitive displacement current arising from time-dependent electrostatic induction and slight motion of bonded electrostatic charges [41]. The EMG is heavy, costly but durable. By contrast, the TENG is lightweight and cost-effective, but has low durability. The comparison about the output performance of the two generators will be discussed in the next subsection.

2.3. Output performances

Zi et al. reported a systematic comparative study on low-frequency mechanical energy harvesting by a TENG and an EMG both in the

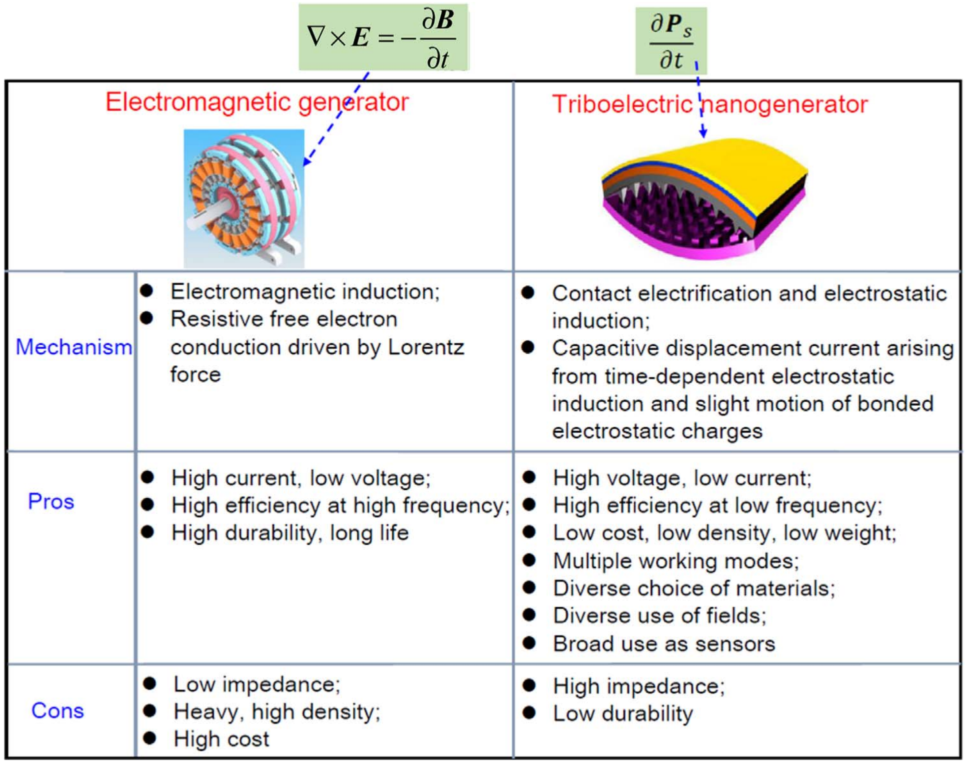

Fig. 5. A comparison between the EMG and the TENG from the mechanisms, advantages and disadvantages.
Reproduced with permission from Elsevier [41].

contact-separation (CS) mode and freestanding-sliding (FS) mode [40], as shown in Fig. 6. The CS mode TENG relies on the contact electrification between Cu and fluorinated ethylene propylene (FEP) film attached by Cu electrode on its backside, and the CS EMG was achieved by contact separation between one set of Cu coils and a square magnet. The FS TENG consists of a freestanding FEP film and two Cu films deposited in parallel onto an acrylic, and the FS EMG has a square magnet moving above two sets of copper coils. They measured the optimized average output power *versus* frequency experimentally for the EMG and the TENG, as shown in Fig. 6c-d. The power density of TENG is proportional to the frequency, but that of EMG is proportional to the square of the frequency, regardless of the motion mode. Therefore, there exists a threshold frequency below which the output power of TENG is higher than that of EMG. Besides, they carried out experiments of lighting LED and found that a certain frequency is required to light up the LED for the EMG due to the threshold voltage of LED, resulting in a higher current of TENG than EMG at a quite small frequency. They demonstrated the possible killer application of TENG to harvest low-frequency mechanical energy such as ocean wave energy for large-scale power generation (blue energy).

The output characteristics of EMG and TENG were also compared by Zhang et al. from the theoretical equations and experimental validations [43]. As shown in Fig. 7a, the output voltage of rotating EMG based on the electromagnetic induction has a similar expression with the output current of rotating TENG based on contact electrification and electrostatic induction. That indicates that the TENG has a comparative and symmetric relationship with the EMG in theory. The resistive output characteristics of EMG and TENG were measured and the TENG was found to have much higher matching impedance than EMG (Fig. 7b). It was concluded that the TENG can be considered as a current source with a large internal resistance, while the EMG is equivalent to a voltage source with a small internal resistance. Then they designed a hybrid generator in which two generators have a common rotational axis based on two different electricity generating principles (Fig. 7c), and characterized two conjunction operation modes in parallel and series (Fig. 7d). The parallel and serial connections between rectified EMG with a serial resistance and rectified TENG with a parallel resistance were both demonstrated as effective conjunction approaches to getting the maximum power close to the theoretical value. The comparison and conjunction operation established the basis of TENG as a new energy technology that could be parallel or possibly equivalently important as the traditional EMG for general power applications at large-scale.

3. Blue energy harvesting by triboelectric nanogenerator

Ocean waves are one of the most abundant energy sources on earth, but harvesting such energy is rather challenging due to the limitations of traditional electromagnetic generators, especially at low frequency. The TENG is much more effective than the EMG for harvesting energy in the frequency range of < 5 Hz due to its distinct mechanism, which is ideally suited for our daily life and the nature, such as the ocean waves [40]. In contrast with heavy weight and high cost of the EMG, the TENG provides a lightweight, cost-effective approach for converting water wave energy into electricity, which is greatly desired as a key to solve the above problems. Since the invention and fast development of TENG, lots of efforts have been made in harvesting water-based energy by designing various prototypes [44–69]. In this section, the recent research progress in blue energy harvesting by the TENG is discussed, from the viewpoints of liquid-solid contact electrification TENG, fully enclosed TENG and TENG network.

3.1. Liquid-solid contact electrification TENG

Due to the novel working mechanism of TENG, the water itself can be one triboelectric material interacting with insulating polymer films. Lin et al. first developed a TENG in 2013 to harvest the water wave energy based on the liquid-solid contact electrification [44]. Fig. 8a presents the schematic device structure of the designed TENG, in which the periodic contact and separation between polydimethylsilox-

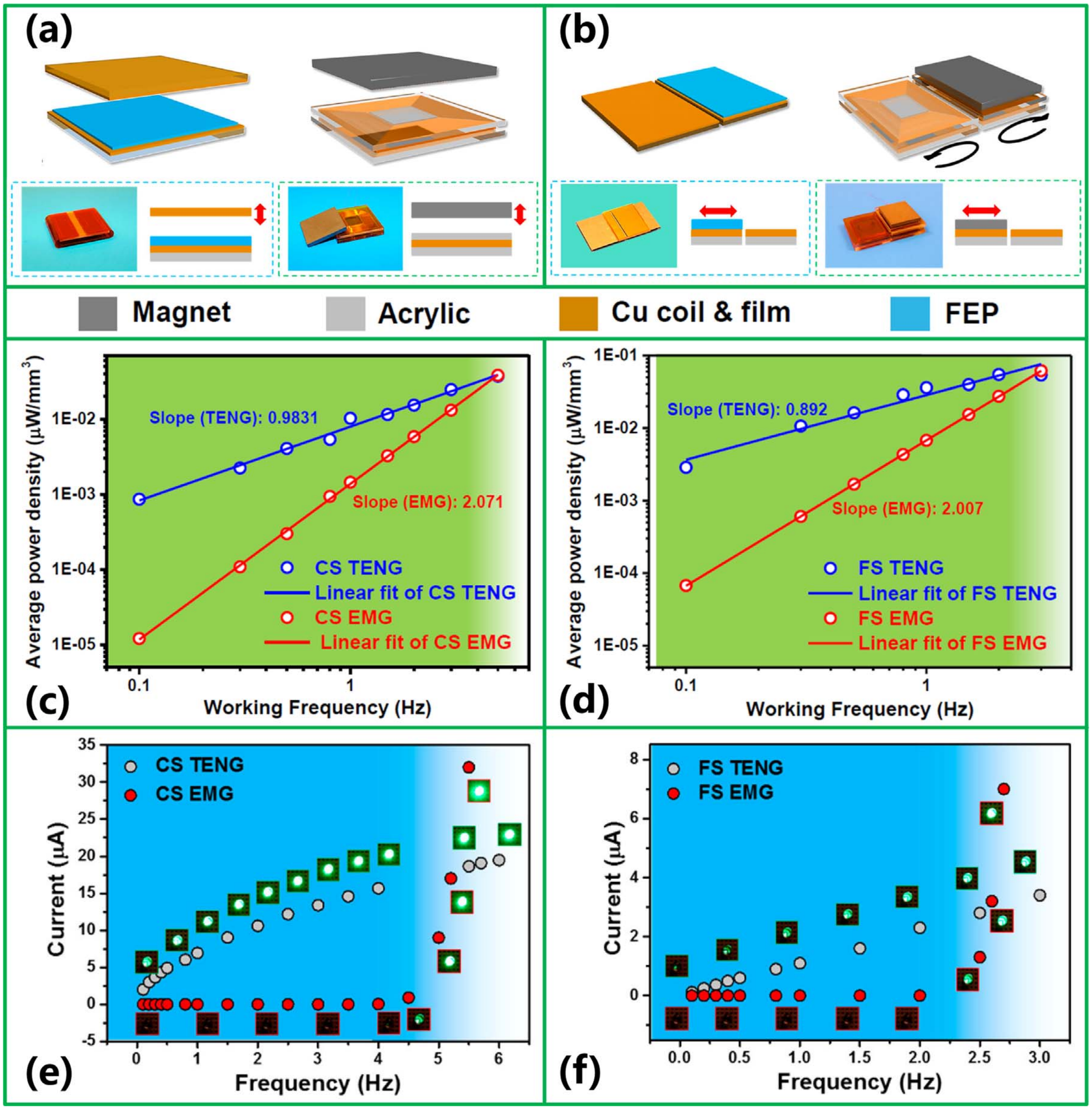

Fig. 6. Output performance comparison between the TENG and the EMG. (a-b) Schematic structures of fabricated CS mode and FS mode TENG and EMG. (c-d) The average output power density with respect to the frequency for the TENG and the EMG, respectively. (e-f) Current through an LED as driven by CS mode and FS mode TENG and EMG devices with photos of the lighting LED for a visual indication of the generated power.
Reproduced with permission from American Chemical Society [40].

ane (PDMS) film and water produces a potential difference between the electrodes, driving the electron flow through the external circuit and generating the current. The movement of the PDMS film contacting and separating from water would generate a water wave, disturbing the contact area with the PDMS film. The frequency response tests indicate that the optimized output power density of this TENG reached up to 50 mW m^{-2} at 5 Hz. Then they prepared a TENG with a super-hydrophobic nanostructured polytetrafluoroethylene (PTFE) layer contacting with water to harvest the water-related energy from flowing water and water drops (Fig. 8b) [45]. Before the contact with the TENG, the water drop already contains triboelectric charges on its surface because of the friction with air/pipes. When the water drop approaches the PTFE film, a potential difference created between the Cu electrode and ground drives the electron transfer from ground to the Cu electrode. Once the water drop moves off the PTFE surface, an opposite electric potential difference induces the electrons to flow back. This is the electricity generation process of typical water-based TENG.

Subsequently, Zhu et al. reported a liquid-solid electrification TENG directly interacting with the water waves by applying asymmetric screening of triboelectric charges on a nanostructured hydrophobic thin film surface, as shown in Fig. 8c [46]. The TENG consists of a FEP film and two parallel strip-shaped electrodes with a fine gap deposited on one side of FEP, while the other side of the FEP film is modified with nanowire structures. The repetitive emerging-submerging process with traveling water waves drives the alternating flow of electrons between electrodes. An integrated TENG with a scaled-up design was further tested to harvest the energy from ambient water motions, including surface waves and falling drops, as shown in Fig. 8c4-c5. The TENG has six strip-shaped electrodes and five basic units formed by any pair of adjacent electrodes. With parallel connection of rectified electric output of each pair, the TENGs can produce sufficient output power for driving an array of LEDs when placed in traveling waves created in a large container, or beneath a sprinkler head with sprayed water droplets. The TENG interacting with water waves produces pulses of current, while the TENG interacting with water droplets generates continuous direct current due to the numerous droplets and the merging of a large number of current pulses.

In addition to the above structural designs, some other prototypes

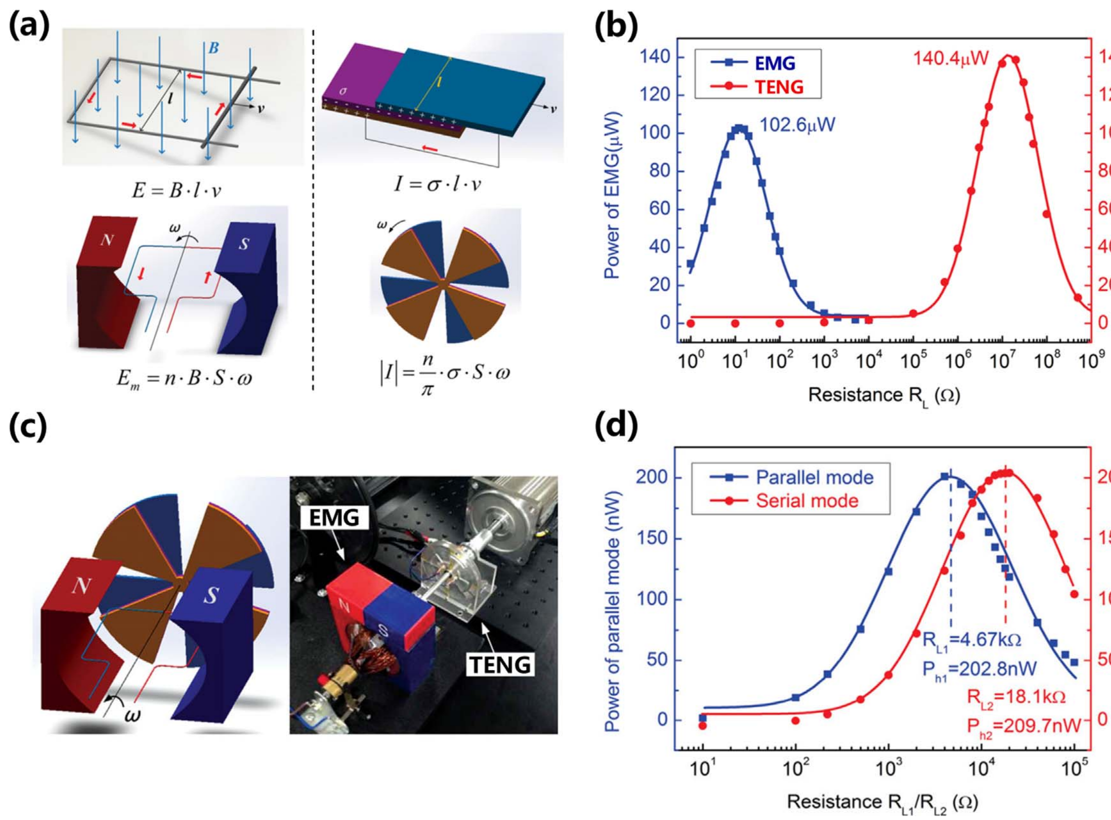

Fig. 7. (a) Theoretical comparison of EMG and TENG. (b) Output power of the rotating rectified EMG and rectified TENG with different load resistances. (c) Schematic diagram and photograph of the hybrid rotating EMG and TENG, and their conjunction operations. (d) Relationship between the output power and the load resistance in both parallel and serial modes.
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were also proposed for water-related energy harvesting by applying the liquid-solid contact electrification [47–49]. Lin et al. fabricated a dual-mode TENG containing a superhydrophobic TiO_2 layer with hierarchical micro/nanostructures to simultaneously harvest the electrostatic and mechanical energies of flowing water [47]. Then Cheng et al. designed a dual-mode TENG consisting of a water-TENG part and a disk-TENG part [48]. The water-TENG with 8 wheel blades covered by PTFE film in a single-electrode mode was used to harvest the electrostatic energy from flowing water. The flowing water impacting on the wheel blades also caused the rotation motion of disk-TENG that can harvest the water kinetic energy. The short-circuit current of the water-TENG and disk-TENG at a water flow rate of $54\ \mathrm{mL\ s^{-1}}$ can

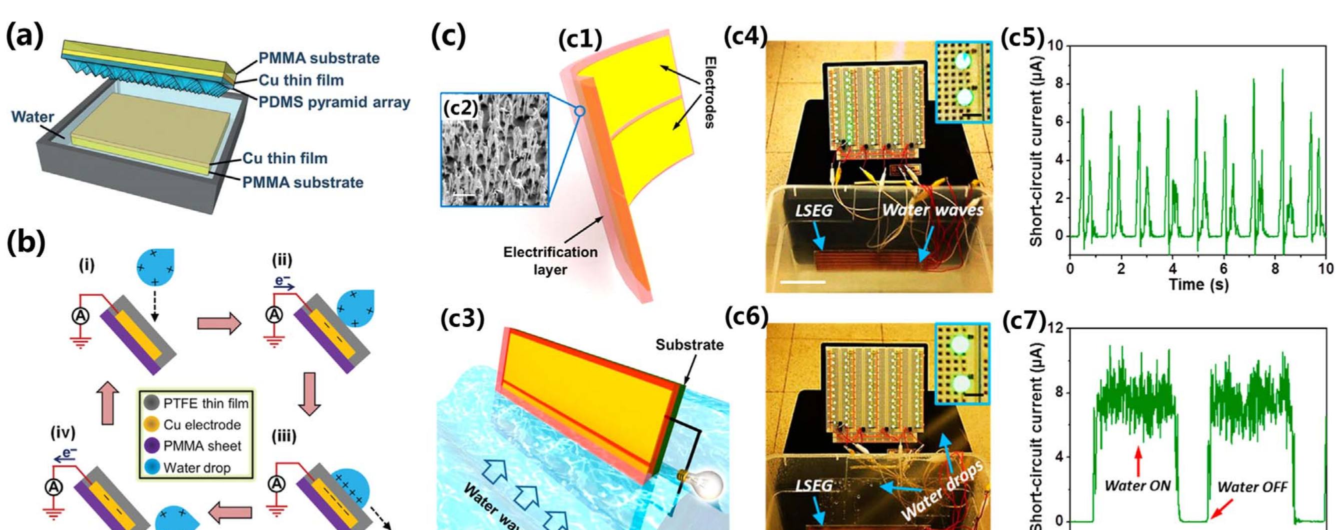

Fig. 8. (a) Schematic device structure of the TENG based on the contact electrification between micro-patterned PDMS film and water. (b) Schematic working mechanism of the water-based TENG with a hydrophobic PTFE layer. (c) Schematic structure and working principle of the liquid-solid electrification TENG by applying the asymmetric screening effect of triboelectric charges on a nanostructured hydrophobic thin film surface. The up-and-down movement of the surrounding water body induces electricity between the two electrodes. The photos of the integrated TENG in powering LED bulbs by harnessing water waves and water drops, and the output current are also shown.
(a) Reproduced with permission from Wiley [44]. (b) Reproduced with permission from Wiley [45]. (c) Reproduced with permission from American Chemical Society [46].

reach 12.9 and 3.8 μA, respectively. Besides the water flow, the electrostatic and mechanical energies from water waves were also simultaneously collected by a dual-mode TENG composed of an interfacial electrification enabled TENG and an impact TENG with internal wavy-electrode structure [49]. These works show the potential applications of the liquid-solid contact electrification TENG onshore/offshore and even in rainy areas. However, in real seawater environment, the polymer films directly contacting with the water are easily corroded by the seawater, so the researches about harvesting the water wave energy are mainly focused on the fully enclosed TENG as discussed in the next subsection.

3.2. Fully enclosed TENG for water wave energy harvesting

Water wave energy is an abundant energy source for large-scale applications that is much less dependent on seasonality, day or night, weather, and temperature conditions [7,50]. Because the environment humidity can have a great influence on the output performance of TENG utilizing solid-solid contact electrification, the TENG should be fully enclosed to work under harsh conditions especially in the presence of water. So far, several prototypes of fully enclosed TENG have been reported and optimized for harvesting the water wave energy [51–69]. This section will provide typical examples.

3.2.1. Wavy-electrode structure

Wen et al. invented a TENG based on a wavy-structured Cu-Kapton-Cu film sandwiched between two flat nanostructured PTFE films for harvesting energy from impacting/compressing /mechanical vibration using the triboelectrification effect [51]. The schematic of device structure and magnified schematic of the wavy core contacting with the nanostructures on the PTFE films are shown in Fig. 9a. When suffering an external impact force, the TENG with the wavy-electrode structure can convert vertical impact into lateral extension, leading to the sliding electrification between the electrodes and PTFE films. After impact it is self-restorable due to its elasticity, so the wavy electrodes will retract to the initial state. The repetitive pressing and releasing cause the charge transfer between flat electrodes and wavy electrodes and generate alternating current. Such TENG was proved to have the ability to harvest the impact energy of water waves when it was sealed into a thin rubber pocket and fixed to the side wall of a bathtub, as shown in Fig. 9b. As triggered by water waves, the LEDs can be lighted up. The experiments demonstrated that the output voltage of single device could reach 30 V, and the output current reached 6 μA at the artificial wave conditions with a wave height of 0.2 m and a wave speed of 1.2 m s^{-1} (Fig. 9c-d).

The wavy-structured TENG can serve as a unit of an integrated device for effectively harvesting water wave energy. Zhang et al. fabricated a regular dodecahedron device integrated with 12 sets of multilayer wavy-structured TENGs (Fig. 9e) [52]. The wavy-structured TENG is composed of a wavy Cu-Kapton-Cu film and two FEP thin films sputtered with metal electrodes as a sandwich structure. Agitated by the water wave motion, a hard ball inside the dodecahedron device was used to continually strike the multilayer wavy-structured TENGs to convert the water wave energy into electricity. The rectified output voltage and current of the sealed device in water was measured to be about 260 V and 220 μA, respectively, as shown in Fig. 9f-g. This work presents the potential of TENG with wavy-electrode structure to harvest large-scale water wave energy.

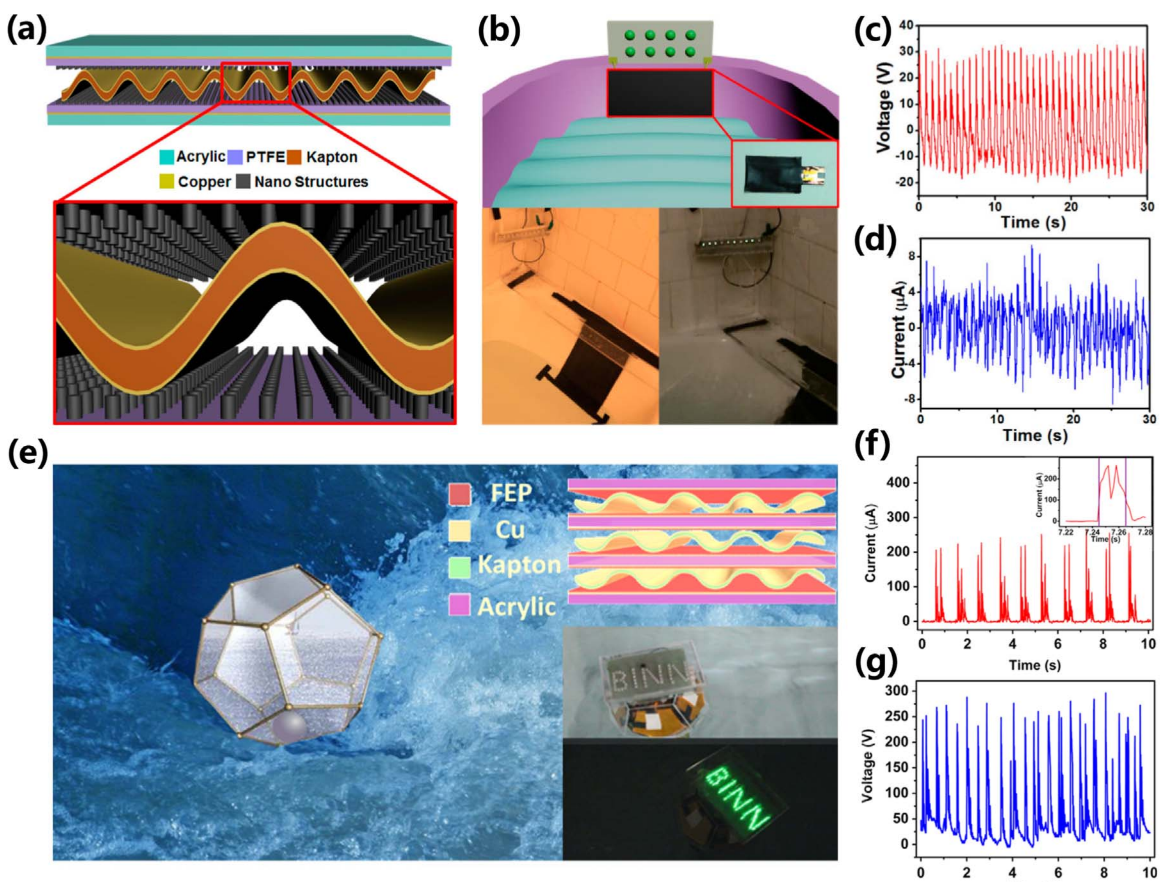

Fig. 9. (a) Schematic structure of the TENG device based on a wavy-structured film. (b) Experimental setup for the packaged TENG to collect water wave energy and light up LEDs. (c-d) Output voltage and current of the TENG triggered by water waves. (e) Schematic of an integrated dodecahedron device with multilayer wavy-structured TENGs, and photos of the device and lighting LEDs agitated by water wave motion. (f-g) Rectified output voltage and current of the sealed device in water.
(a-d) Reproduced with permission from American Chemical Society [51]. (e-g) Reproduced with permission from Elsevier [52].

In addition, a box-like TENG device composed of wavy-structured TENG walls and an enclosed ball was fabricated to harvest the water wave energy by Jiang et al. [53]. The theoretical model of wavy-structured TENG was constructed and the TENG structure was optimized to reach the highest output performance. They found that there exists an optimum ball size or mass to reach maximized output power and electric energy from the theoretical calculations and experimental validations. Then the charging system of such TENG device was characterized and optimized under the two cases of direct water wave impact and enclosed ball collision [54]. It could be found that under the direct water wave impact, the stored energy and maximum energy storage efficiency are controlled by deformation depth, while the stored energy and maximum efficiency can be optimized by the ball size under the enclosed ball collision. The two works provide useful guidance for improving the performance of TENGs toward effective water wave energy harvesting and storage.

3.2.2. Rolling spherical structure

A rolling-spherical freestanding-triboelectric-layer based nanogenerator (RF-TENG) was demonstrated to harvest energy from low-frequency water wave movements [38]. The RF-TENG fabricated by Wang et al. uses a rolling nylon ball to contact with a Kapton film in an enclosed spherical shell as shown in Fig. 10a. The backside of the Kapton film is attached by two arc stationary electrodes. This RF-TENG can float freely on the water surface without any support due to the fully enclosed structure design and light weight. When driven by a wave vibration, the freestanding ball can roll back and forth between two electrodes, providing alternating current in the external circuit. The ability of the RF-TENG to harvest the water wave energy was proved by lighting 70 LEDs driven in a wave system (Fig. 10b). Then the size of rolling ball was optimized to reach the maximized output from the viewpoints of theoretical calculations and experimental measurements (Fig. 10c). The experimental result that the transferred charge first increases then saturates with increasing ball size is roughly consistent with the theoretical prediction that an optimum ball diameter exists with a maximized transferred charge. Besides the structural optimization, the TENG has a nearly uniform and significant response characteristic within frequency range from 1.23 to 1.55 Hz, indicating that the effective resonance of this design can be reached with actual water waves (Fig. 10f). The optimized RF-TENG at a wave frequency of 1.43 Hz (the natural frequency of this oscillating structure) can deliver a short-circuit transferred charge of 24 nC and a short-circuit current of 1.2 μA (Fig. 10d-e).

Relative to other enclosed rolling-structured TENGs in single-electrode and attached-electrode modes [55–58], the freestanding design of the RF-TENG imparts it good charge transfer efficiency and high energy conversion efficiency. Therefore, the RF-TENG is particularly suitable for harvesting energy from irregular wave oscillations. The energy harvested can also be stored in electric double-layer supercapacitors and used to power small electronics, providing a feasible solution to the long-term, wide-area, *in-situ*, and real-time monitoring of water parameters, particularly in closed environments such as sealed pipelines [38].

3.2.3. Duck-shaped structure

Ahmed et al. designed a fully enclosed duck-shaped TENG for effectively scavenging energy from random and low-frequency water waves [59]. Fig. 11a-b present the schematic and photograph of the duck-shaped TENG. This design introduced the freestanding rolling mode and the pitch motion of a duck-shaped structure generated by incident waves, which was inspired by the well-known wave power harvesting device called Edinburgh duck [60]. The duck-shaped TENG device can rotate around an axis parallel to the incident waves, making the nylon balls roll back and forth on the nanostructured Kapton surface over the interdigitative copper electrodes. The alternating current was generated through the electrodes due to the repetitive pitch motion of duck structure. The frequency responses of output voltage and current for a multilayered duck-shaped TENG were also characterized, as shown in Fig. 11c-d. The maximum amplitudes of voltage and current reach 325 V and 65.5 μA at a wave frequency of 2.5 Hz. Subsequently, the load resistance dependency of the generated power was measured considering the amount of duck-shaped TENG units. The maximum peak power can increase up to 1.366 W m^{-2}, as the amount of units increases to 3, revealing the potential application of the duck-shaped TENG for being hybridized in a network of TENGs. A possible network with a series of duck units attached to two legs of a

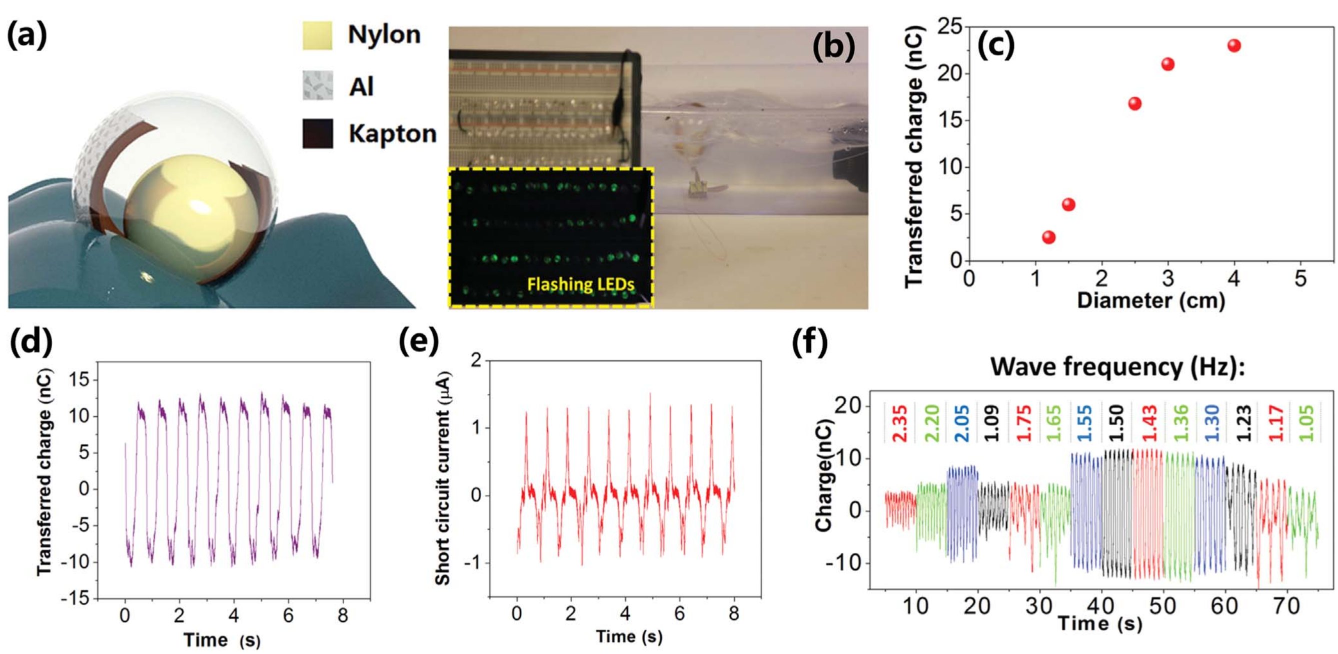

Fig. 10. (a) Schematic diagram of a RF-TENG device. (b) Photographs of the RF-TENG device operating in a water wave system. (c) Experimental transferred charge with respect to the ball diameter. (d-e) Measured short-circuit transferred charge and short-circuit current of an optimized RF-TENG at a wave frequency of 1.43 Hz. (f) The dependence of transferred charge on the wave frequency for the RF-TENG device with a ball diameter of 4 cm.
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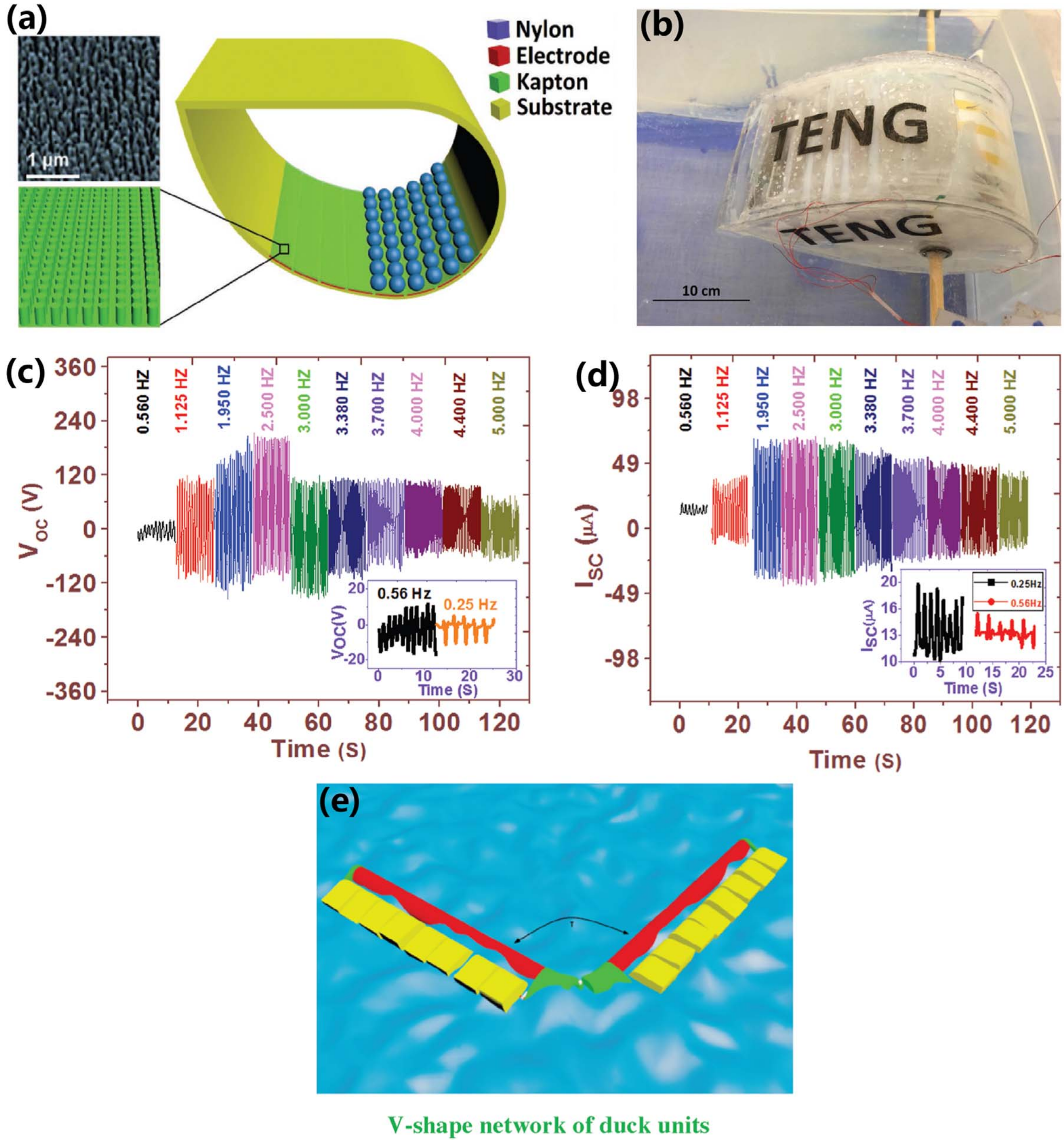

Fig. 11. (a-b) Schematic and photograph of the duck-shaped TENG. (c-d) Frequency responses of output voltage and current for a multilayered duck-shaped TENG. (e) Proposed V-shape network of duck units based on WEPTOS WEC model for water wave energy harvesting.
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floating structure (Fig. 11e), which is based on the WEPTOS WEC design [61], was proposed to harvest energy of water waves with high efficiency.

3.2.4. Air-driven membrane structure

In order to improve the output performance of TENGs, an integrated TENG array device based on air-driven membrane structures was designed by Xu et al. to effectively harvest water wave energy [62]. The device structure and working principle are shown in Fig. 12. In the device, the inner oscillator composed of TENG array, two air chamber walls and an acrylic separator is connected to the outer shell with elastic bands, forming a spring-levitated oscillator structure. For a detailed structure, the upper and lower TENG units are attached to the upper side and lower side of soft membranes respectively (Fig. 12b). The high-density TENG array based on vertical contact-separation mode generates current by applying repetitive reshaping of soft membranes under varying pressures (Fig. 12c). When the outer shell moves upwards with the water waves, the bottom of the lower air chamber is pressed by the shell, causing a larger pressure in the lower chamber (P_L) than that in the upper chamber (P_U). The pressure difference makes the upper units into contact state and the lower ones into fully separate state, inducing the electrons to flow between electrodes. On the other hand, when the shell moves downwards with the water waves, the case is opposite, and the electron flow and current directions become reversed.

Due to the innovative design of a spring-levitated oscillator structure and a mechanism to use air pressure to transfer and distribute harvested water wave energy, the device can drive a series of integrated TENG units effectively and simultaneously. The output measurements show that the peak short-circuit current of the device integrating 38 TENG units reaches 187 μA, and the short-circuit accumulative charges per cycle reaches 15 μC at a low frequency near

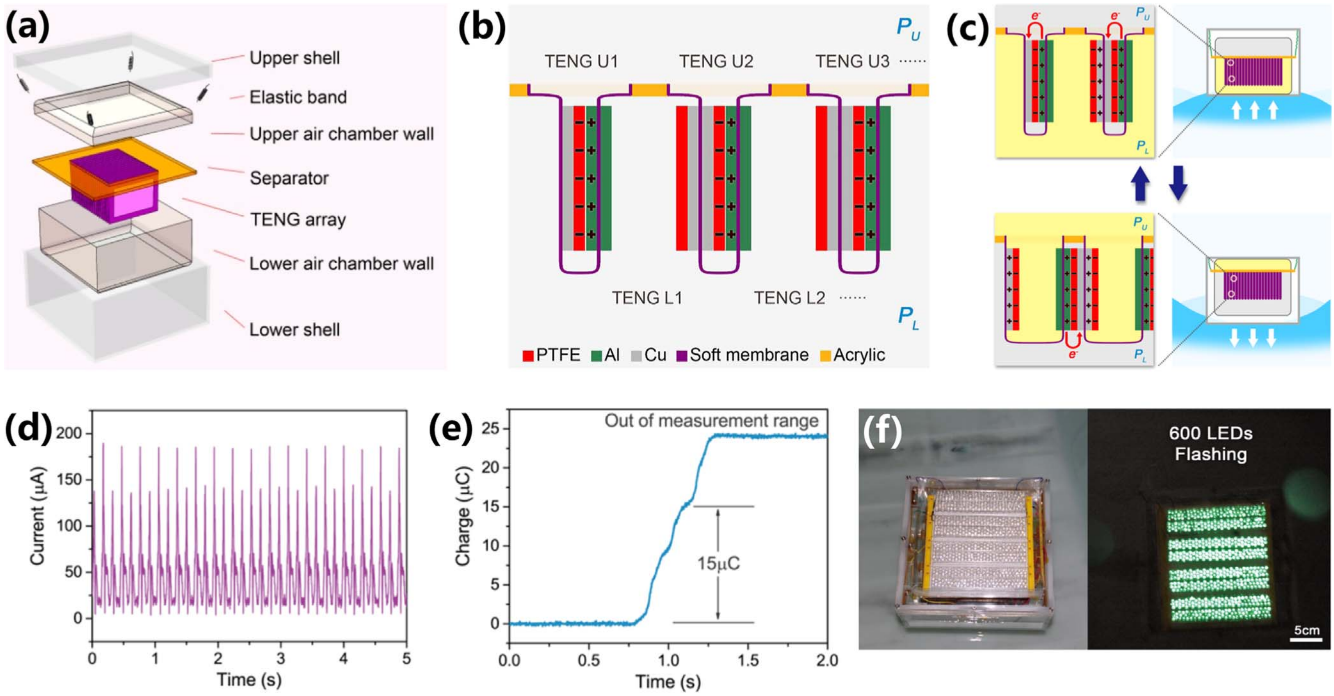

Fig. 12. (a) Schematic of the integrated TENG array device based on air-driven membrane structures. (b) Detailed structure of the TENG array. (c) Working principle of the TENG array device on water waves. (d) Rectified short-circuit current and (e) short-circuit accumulative charges of the integrated device. (f) Photographs of the device floating on water before and after 600 LEDs being lighten up.
Reproduced with permission from Elsevier [62].

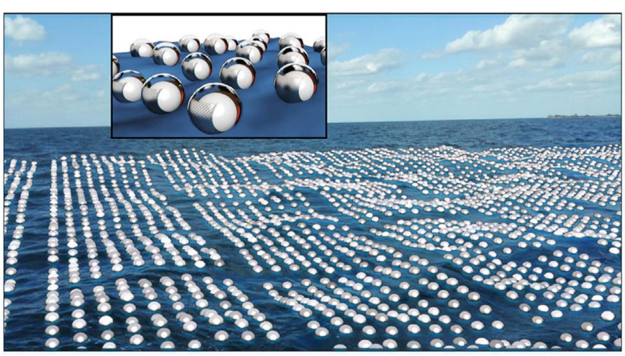

Fig. 13. A proposed TENG network composed of millions of spherical ball based TENG units for harvesting large-scale blue energy. The inset shows the structures of spherical TENGs.

the resonant frequency of about 2.9 Hz (Fig. 12d-e). An optimized peak power density of 13.23 W m^{-3} can be delivered, which is so high that the device can light up 600 LEDs simultaneously in real water waves (Fig. 12f). The device based on the air-driven mechanism can easily integrate large-scale high-density TENG arrays in one package and provides a promising route to effective water wave energy harvesting for various practical applications.

In addition to the above four structures, other prototypes were also reported for harvesting water wave energy, for example, spring-assisted TENG and hybrid electromagnetic-triboelectric nanogenerator with a cylindrical or rolling-rods-based structure [63–67]. Jiang et al. designed and fabricated a kind of spring-assisted TENG in which two Cu-PTFE-based contact-separation mode TENGs are connected by a spring [63]. The introducing of the spring is to store the potential energy built during mechanical triggering for multiple cycles of conversion into electricity afterwards, and to transform a low frequency motion into a high frequency oscillation for improving the energy conversion efficiency. They found that the efficiency can be improved by 150.3%, providing an approach to improving the output performance and efficiency of TENGs in harvesting low-frequency water wave energy. Guo and Wen et al. presented a waterproof hybrid electromagnetic-triboelectric nanogenerator for harvesting the water wave and water flow energies, using the noncontact attractive force between pairs of magnets to drive the moveable part of TENG [64]. Then they designed a concentric cylindrical device structure to harvest water wave energy at arbitrary time [65]. When the ocean wave frequency increases, the EMG not only provides a noncontact attractive force, but also generates electricity, enabling the device to work in a broad frequency range. The hybrid generator can also realize the harvesting of energy toward the applications of complicated scenes by taking advantages of different technologies.

3.3. TENG network for blue energy harvesting

Fundamental TENG units can serve as a small-scale power source for small electronics, and their assembly and integration can be the basis for large-scale energy harvesting. An idea of using TENG networks to harvest large-scale water motion energy was proposed by Wang in 2014 [35]. As shown in Fig. 13, the TENG network can be made of millions of spherical balls based TENG units connected as fishing net [68]. The spherical TENGs use lightweight organic and metal materials, and are partially filled up with air, so they can float at the vicinity of the water surface. They convert the water wave energy into electricity through the rolling of a dielectric ball inside a dielectric spherical shell, just as illustrated above. The total energy by gathering electric energy from all units will be huge.

Based on the proposed idea of TENG network, Chen et al. constructed a small array network of TENG units by using fully enclosed box-like device with self-restorable arch-shaped TENGs [69]. The water wave motion induces collisions between a metal ball and TENG internal walls in the packaged devices, realizing the conversion from mechanical energy to electric energy. They also proposed a configuration of the TENG network to improve the output power for practical applications, in which the TENG units in a lower layer are electrically connected in parallel to enhance the output current, while the TENGs are connected in series to enhance the output voltage. It was preliminarily estimated that an average power output of 1.15 MW can be generated in a water area of 1 km^2. Given the low cost and unique applicability resulting from distinctive mechanism and simple structure, the TENG network renders an innovative approach toward large-scale blue energy harvesting from the ocean.

4. Summary and perspective

In this review, the EMG and the TENG as two technologies for ocean energy harvesting were systematically compared from the viewpoints of operation principles, fundamental physics mechanisms, and output performances. The mechanism of EMG is resistive free electron conduction driven by Lorentz force, while that of TENG is capacitive displacement current from polarization of surface electrostatic charges, which are essentially different and distinct. The output advantages of TENG over EMG at a low frequency provide the killer application of TENG in harvesting low-frequency water wave energy. The recent developments of the TENG technology in water motion energy harvesting, including the liquid-solid contact electrification TENG, fully enclosed TENG and TENG network, are summarized. Various prototypes have been designed and optimized (Fig. 14), and the performance of TENG has also been gradually enhanced in water motion energy harvesting. We demonstrate that the energy provided via TENG, a technology discovered 180 years after the discovery of electromagnetic induction, is not only a new energy in parallel to wind and solar energy, but more importantly, it is an energy for the new era - the era of internet of things and sensor networks. TENG is invented not for replacing EMG, but complementary usage for solving our future energy need for micro-grid and macro-grid. We anticipated that the macro-grid is till driven by the well established EMG technology, whilte the micro-grid and small electronics can be driven by distributed energy harvested using TENG. The current power technology is based on EMG that requires a high operation frequency, which is a result that EMG has been the only available technology for harvesting mechanical energy in the last century. Now, with the newly developed TENG, the choice of technological approach could be different. In such a case, the energy for the era of internet of things can be TENG. This prediction remains to be verified in the near future.

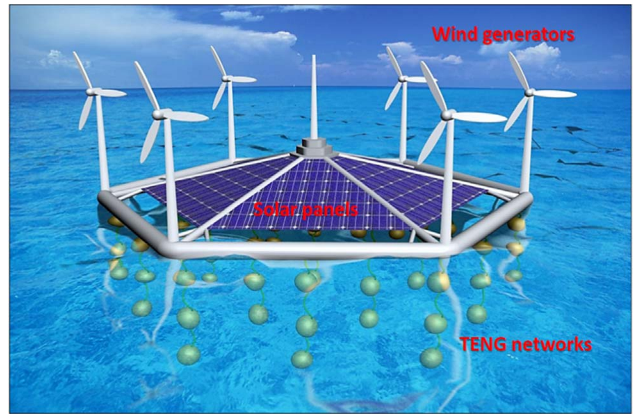

Fig. 15. A blue energy dream through three dimensional networks of TENGs, and wind generators and solar panels can be installed above water surface to add power and maximize the space utilization efficiency.

For future applications of TENGs in large-scale blue energy harvesting from the ocean, the networks of TENGs are expected to be a feasible approach to realizing this blue energy dream. The networks of TENGs constructed by linking millions of spherical TENG units using cables can float on the water surface or locate beneath the surface with certain depth, forming a three dimensional network structure. If agitated two or three times per second and each unit produces a power of around 1–10 mW, a TENG network covering an ocean area as equal to the size of Georgia and a depth of 10 m at a unit space of 10 cm can meet the world's energy needs today in theory [68]. Meanwhile, an energy harvesting panel floating on the ocean surface is proposed to simultaneously harvest wave, wind and solar energy (Fig. 15). The wind turbines and solar panels can be installed alongside the TENG networks to add power supply. The electricity produced by wind-driven generators, solar cell panels, and TENG networks could be used locally on a floating platform or transferred to power plants or the electric grid on land. This blue energy dream will offer a new energy path for human kind, and we hope that the dream can be realized in the near future.

Toward the blue energy dream, many technical hurdles need to be addressed, such as improving the efficiency and durability of nanogen-

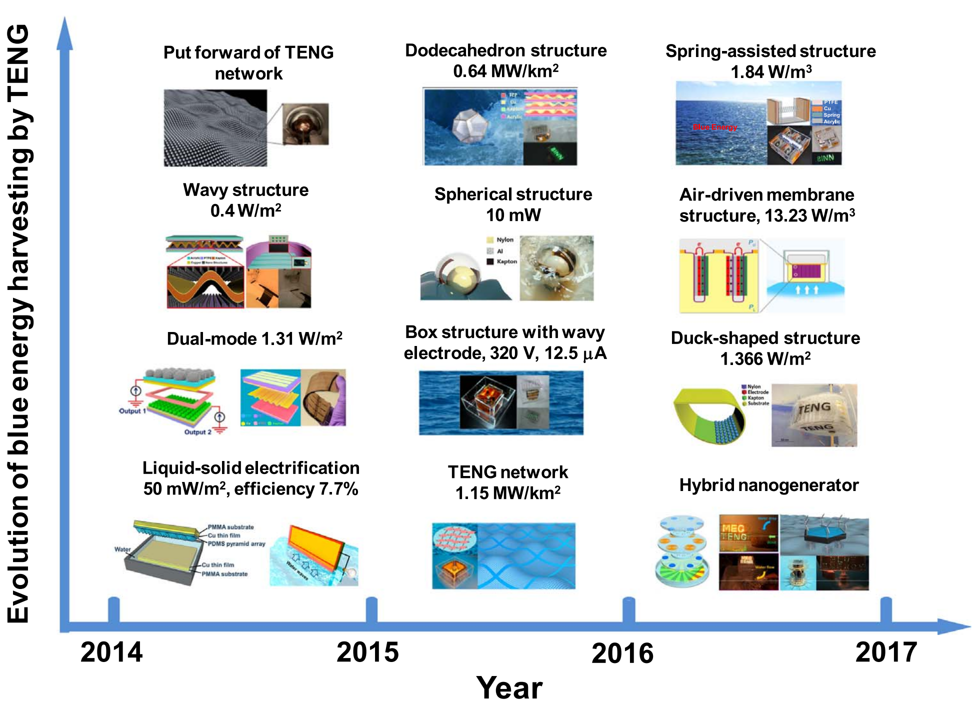

Fig. 14. Evolution in the structure and performance of TENG prototypes designed for blue energy harvesting.

erator materials and designs; connecting them into large networks that work in the open ocean; managing, storing the electricity and transporting it to land. Future researches on the hydrodynamics theory, model tests, structural design of nanogenerators, and so on should be carried out. The location and size of blue energy networks would need to be carefully considered to minimize disruption to the public, marine life and shipping. The ocean energy conversion is a systematic engineering, which can be speeded up by establishing a research institute dedicated to blue energy. Under the collective supports of the government, policy, private investors and major energy companies, the blue energy dream will eventually come true.

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