Nanogenerators: A foundation for high-entropy energy and sensing systems

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Nanogenerators, since their invention in 2006, have experienced rapid growth in global research. The invention of the triboelectric nanogenerator (TENG) in 2012 further accelerated the expansion of this new scientific and technology discovery, which has now become an interdisciplinary field of research and applications, encompassing materials science, physics, chemistry, and electrical engineering. Nanogenerators are uniquely positioned to harness high-entropy energy that is low-intensity, abundant, and widely distributed in the environment. It has led to emerging concepts such as "Blue Energy," which provides grid-scale renewable energy from ocean waves, and human-powered electronics, which leverage biomechanical energy as the sole source of electricity. Additionally, nanogenerators have introduced new principles in chemistry and catalysis, using mechanical energy to drive charge transfer at interfaces. To support the rapidly growing nanogenerator community, this issue of *MRS Bulletin* curates feature articles that explore the core aspects of nanogenerator-related studies, from fundamental science and performance improvements to a wide range of representative applications. This article provides a historical overview of nanogenerators in both scientific and technological impacts in a wide range of fields such as medical science, robotics, environmental protection, human–machine interfacing, security, and even marine science.

Introduction about nanogenerators

Today's power generation primarily relies on fossil fuels, which are eventually converted into mechanical and thermal energy in our environment. This widely distributed, readily available, low-density, yet abundant energy is referred to as high-entropy energy.[1] Various methods have been developed to harness and utilize this high-entropy energy. The first piezoelectric nanogenerators (PENGs) were invented by Wang's group in 2006,[2] which utilizes the piezoelectric effect to convert mechanical energy into electrical power through piezoelectric semiconductor nanowires. Because the energy conversion was achieved using a single nanowire and an atomic force microscopy tip, with output in the nanowatt range, it was named "nanogenerators." By 2011, the output of PENGs was high enough to power a single light bulb, marking a milestone in the field.[3] A major breakthrough was made in 2012,[4] when Wang's group discovered that the triboelectric effect could also be used for energy conversion, with much higher output than PENGs. This led to the emerging of a new field of triboelectric nanogenerators (TENGs). Shortly after, nanogenerators based on the pyroelectric effect were demonstrated,[5] harnessing electric power from temperature variations. As of now, more than 16,000 scientists across 90 countries and regions have published scientific papers in the field of nanogenerators.[6]

Although nanogenerators were originally designed to generate nano- to microscale energy, their output has reached the tens-of-watts range by scaling up. Nanogenerators are no longer confined to the nanoscale; instead, they utilize Maxwell's displacement current, generated by the piezoelectric, triboelectric, or pyroelectric effects, as the driving force to convert ambient mechanical energy into electrical power or signals.[7] Due to the high output voltage of TENGs, they are particularly effective

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at harvesting low amplitude, low frequency, and low-density energy that is widely distributed in the ambient environment,[8] known as "high-entropy energy."[1] High-entropy energy serves as a complement to conventional fossil energy sources (e.g., coal, oil, and gas), which are most efficient for electricity generation using steam engines and electromagnetic generators (EMGs). As fossil energy resources become depleted in the future, harvesting high-entropy energy will be indispensable for the sustainability of humankind, and TENGs are poised to play a key role in achieving this goal.

Figure 1 shows the fourth version of our scientific "tree," summarizing the major applications as a result of inventions of PENG and TENG.[6] At the left-hand side, the major fields impacted by nanogenerators are presented, and this issue of *MRS Bulletin* covers only the recent advances made in nanogenerators. At the right-hand side, the major fields related to piezotronics and piezo-phototronics are presented, and the associated advances in the fields were covered in previous *MRS Bulletin* issues. This tree represents the key contributions and applications stemming from the discovery of nanogenerators 20 years ago.

Milestone advances made in developing nanogenerators

PENGs

To develop a physics concept into a significant scientific and technological field, many fundamental breakthroughs are needed. **Figure 2** highlights key advances in the development of nanogenerators, featuring selected milestone contributions that have shaped the field. The starting point of the entire field was the invention of the PENG in 2006.[2] Shortly thereafter, in 2007, the ultrasonic wave-driven PENG was demonstrated,[9] showing that power generation through arrays of nanowires was possible. In the same year, the concept of "piezotronics" was coined.[10] The mechanism and output characteristics of the PENG were further illustrated by a single-wire PENG in 2009,[11] further consolidating the science behind it. To enhance output, a PENG based on vertically integrated nanowire arrays was demonstrated in 2010.[12] In the same year, the concept of "piezo-phototronics" was first phrased.[13–15] After five years of research, the first light powered by PENG was lit in 2010,[3] showcasing the potential for practical applications. In 2012, PENG successfully powered portable microelectronic devices,[16] and the concept of "piezocatalysis" was first demonstrated.[17] In 2013, a fiber-based PENG was demonstrated with its output reaching 209 V, showing its potential for technological applications.[18] In addition to the well-known piezoelectric semiconductor nanomaterials, two-dimensional (2D) materials such as WS_2 were found to exhibit piezoelectric effects,[19,20] allowing PENG to be scaled down to the nanometer level. In 2020, the output current density reached a new record of 290 $\mu A\ cm^{-2}$ through a three-dimensional intercalated electrode design.[21] Furthermore, the development of wafer-scale amino acid-based flexible piezoelectric films[22] in 2021 opened the door to the design and application of PENGs using pure biomaterials for biomedical applications.

TENGs

The invention of the TENG in 2012 was a major breakthrough. It shows that triboelectrification is not only a means for generating charges, but also a driving force for power conversion and a new approach to mechanical sensing.[4,23] Driven by the electrostatic potential difference generated by triboelectric charges on opposite dielectric surfaces,[24] electrons are exchanged between the two electrodes on the top and bottom surfaces, respectively, due to the electrostatic induction effect, producing an AC output current. **Figure 3** summarizes the major milestones in the invention and development of TENGs and related advancements.

Several major milestones were achieved in 2014. The four operation modes of TENG were first established,[25–27] covering most mechanical actions encountered in our daily life. Basic techniques and associated theoretical models have also been developed for each corresponding mode.[28] The freestanding mode TENG demonstrated an energy-conversion efficiency greater than 50 percent.[29,30] Additionally, 2014 saw the first discovery of the liquid–solid TENG,[31,32] which has since become an exciting field for many researchers. Sometimes referred to as a droplet TENG, hydrovoltaic generator, or vapor gradient power generator, its fundamental principle is about the variation in the dynamic electric double layer and its coverage area at the liquid–solid interface. An astonishing concept introduced in 2014 was the "blue energy," which involves utilizing networks of TENGs to harvest water wave energy.[33] This field has advanced rapidly and is now capable of powering a light tower. In the same year, fundamental studies were also initiated to investigate the role of electron transfer in contact electrification.[34]

In 2015, the figure of merit of TENG was first proposed,[35] establishing the standards for evaluating its performance. The rolling mode TENG,[29] as the fifth mode, was first demonstrated, which is most effective for extending the lifespan of TENGs. Analogous to piezotronics, field-effect transistors can be designed using the triboelectric field in contact or noncontact mode, a concept known as tribotronics.[36] In 2016, a killer application of TENG was discovered,[8] which was shown to be far more effective than electromagnetic generators when operating at low frequency and low triggering amplitude. This finding laid the foundation for TENG's superior performance over electromagnetic generators in various applications.

The formal theory of TENG began to take shape in 2017.[7] We first recognized that the output of TENG is governed by Maxwell's displacement current, which has to be expanded to include mechano-driven polarization. Experimentally, it was found that TENG output is limited by three factors:[37] triboelectrification charge density, air breakdown, and dielectric breakdown. A fourth major application of TENG as a high-voltage source has also been demonstrated.[38] Further enhancement of surface charge density was achieved through charge pumping technology.[39] In 2018, the first model for electron transfer in contact electrification was proposed,[40] which has

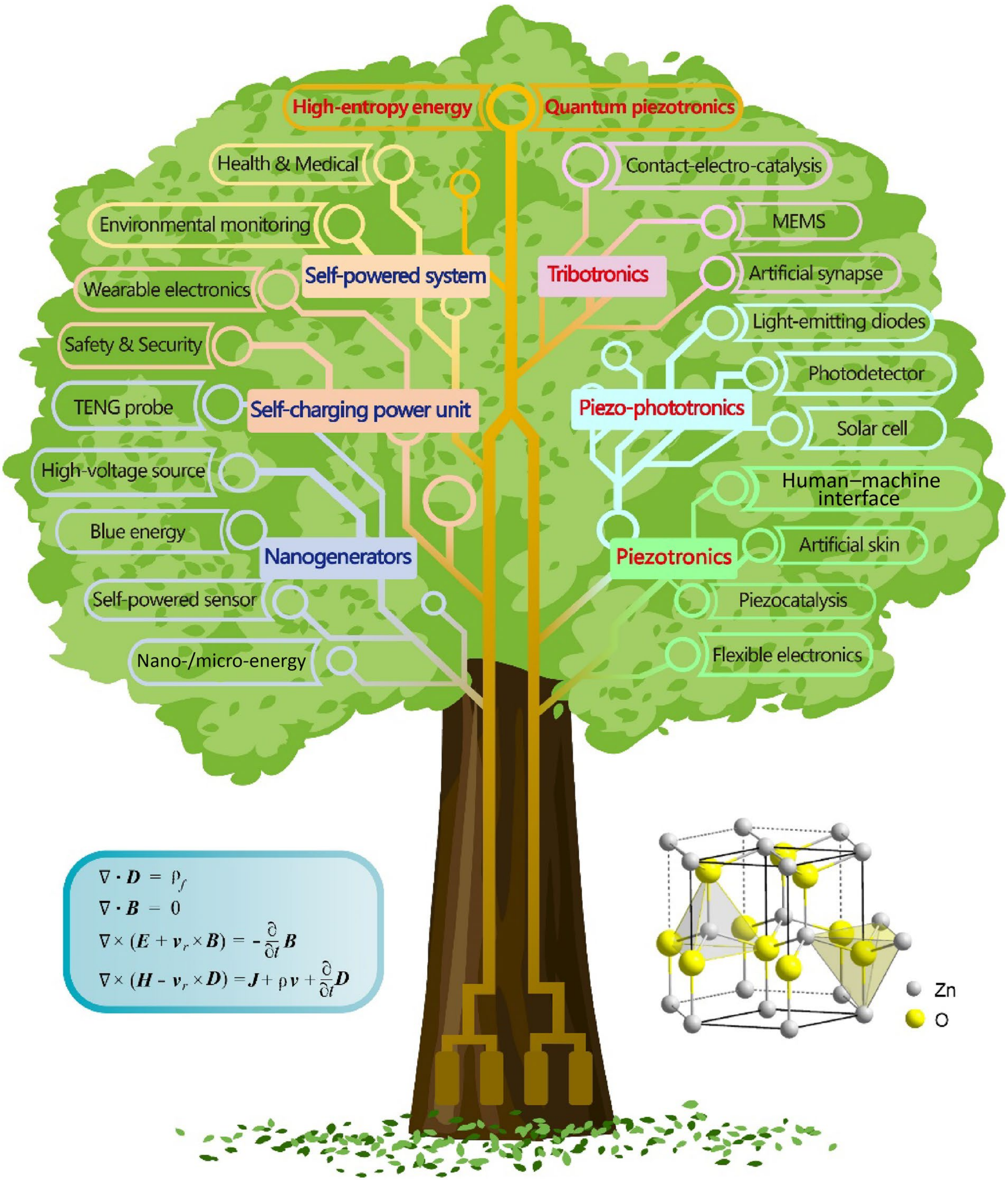

Figure 1. The scientific fields and technological application coined and developed as a result of the first invention of nanogenerators, which are represented by a "tree" design. The root represents the in-depth science based on which all of the original discoveries were made. The pole represents the core theme of the two fields: nanogenerators and piezotronics. The branches and leaves are the major applications of the two fields. TENG, triboelectric nanogenerator; MEMS, microelectromechanical systems.

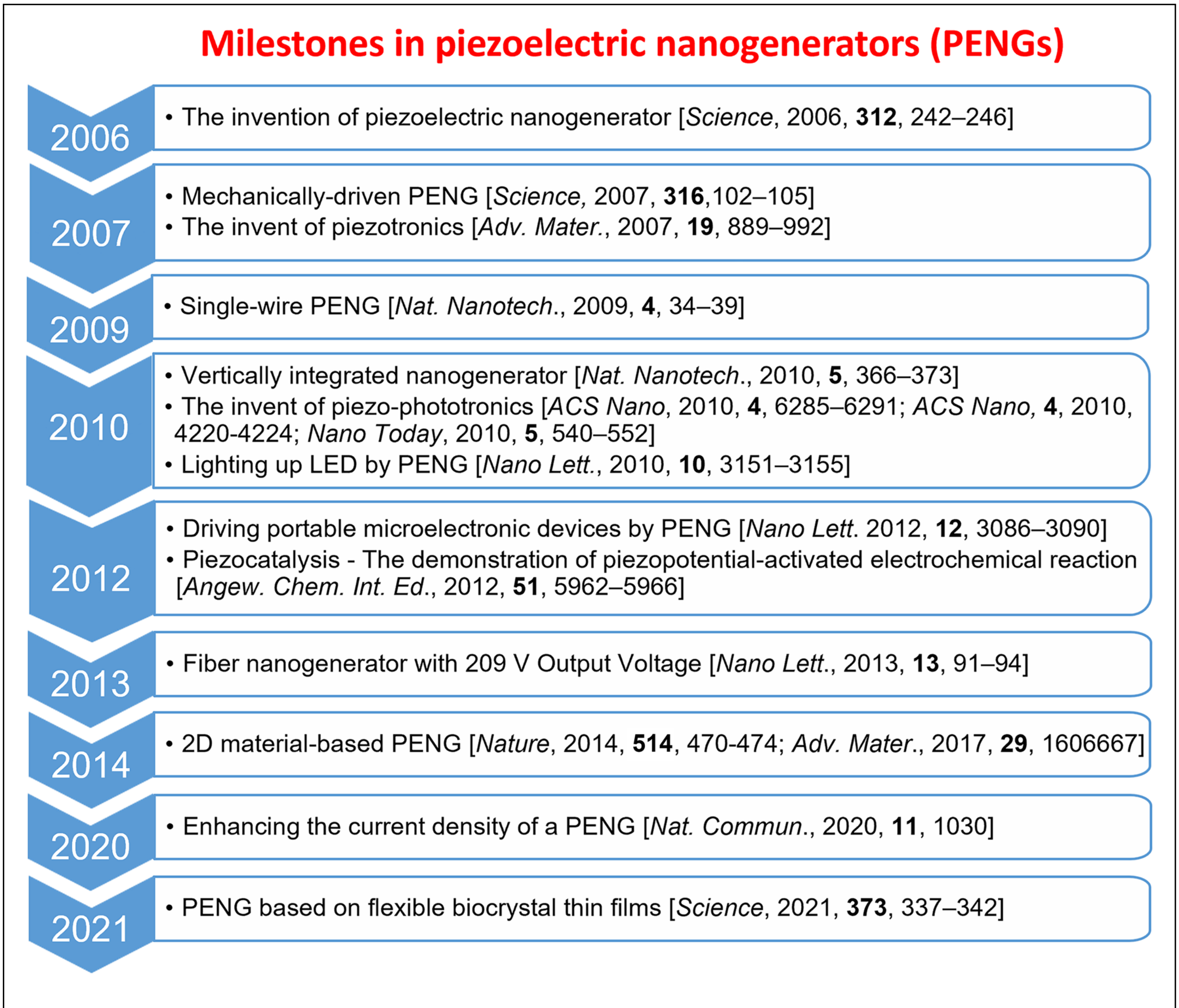

Figure 2. Major milestones in the development of piezoelectric nanogenerators (PENGs).

since become widely accepted as the standard model for triboelectrification between solid materials. More importantly, electromagnetic radiation generated by a rotating TENG was observed for the first time,[41] providing the first experimental proof that supports the expansion of Maxwell's equations.

In 2019, Wang published a comprehensive review regarding the mechanism of contact electrification,[42] where three new effects were proposed: interatomic electron transition-induced photon emission at the interface, the tribovoltaic effect, and the formation process of the electric double layer at a liquid–solid interface, all of which were later observed experimentally. The concept of high-entropy energy was also phrased in 2019.[1] The first quantitatively measurement of triboelectric series was demonstrated in that year as well.[43] Additionally, the direct-current TENG was invented by using electrostatic breakdown between electrodes,[44] allowing for the complete harvesting of energy from contact electrification.[45]

In 2020, three major advances were made. First, a method for quantifying electron and ion transfer at liquid–solid interfaces was introduced,[46] which unambiguously proved that water can donate an electron and it can directly participate in chemical reactions over a short time period. More importantly, this confirmed the two-step model for the formation of the electric double layer at liquid–solid interfaces: an initial rapid electron transfer, followed by a slower ion adsorption process. Second, the tribovoltaic effect was experimentally observed at both solid–solid and liquid–solid interfaces in semiconductor materials.[47,48] Finally, the single-electrode TENG was validated as a probe for studying charge transfer at liquid–solid interfaces,[49] establishing the fifth major application of TENG. In 2021, the interatomic electron transition was observed experimentally.[50]

From 2022 to 2024, two major advances occurred. First, Maxwell's equations for a mechano-driven medium system

Milestones in triboelectric nanogenerators (TENGs)

2012

- The invention of TENG [*Nano Energy*, 2012, **1**, 328–334]
- Self-powered sensor application of TENG [*Nano Lett*., 2012, **12**, 3109–3114]

2013

- Sliding mode of TENG [*Nano Lett*., 2013, **13**, 2226–2233]
- Single-electrode mode of TENG [*ACS Nano*, 2013, **7**, 7342–7351]

2014

- Freestanding triboelectric-layer mode of TENG [*Adv. Mater*., 2014, **26**, 2818–2824]
- Liquid-Solid TENG [*Adv Mater*., 2014, **26**, 4690–4696; *ACS Nano*, 2014, **8**, 6031–6037]
- Proposal of TENG for blue energy [*Faraday Discuss*., 2014, **176**, 447–458]
- Electron transfer in contact electrification [*Nano Lett*., 2014, **14**, 1567–1572]
- TENG with >50% energy-conversion efficiency [*Adv. Mater*. 2014, **26**, 3788–3796]

2015

- Standards and figure of merits of TENG [*Nat. Commun*., 2015, **6**, 8376]
- Tribotronics [*Adv. Electron. Mater*. 2015, **1**, 1500124; *Adv. Mater*., 2015, **27**, 3533–3540]
- Contact-sliding mode of TENG [*ACS Nano*, 2015, **9**, 922–930]
- Rolling mode TENG with efficiency ~55% [*ACS Nano*, 2015, **9**, 922–930]

2016

- A killer application of TENG for blue energy [*ACS Nano*, 2016, **10**, 4797–4805]

2017

- Maxwell displacement current theory for TENG [*Mater. Today*, 2017, **20**, 74–82]
- Three limitation factors about the outputs of TENG [*Nat. Commun*., 2017, **8**, 88]
- High-voltage application of TENG [*Nat. Nanotech*., 2017, **12**, 481–487]

2018

- Charge pumping technology [*Nano Energy*, 2018, **49**, 625–633]
- Electron-transfer model in contact-electrification [*Adv. Mater*., 2018, **30**,1803968]
- Medium motion induced electromagnetic radiation [*Adv. Mater*., 2018, **30**, 1704077]

2019

- Origin of contact electrification [*Mater. Today,* 2019, **30**, 34–51]
- High-entropy energy [*Nano Energy,* 2019, **58**, 669–672]
- Self-charge excitation for high-performance TENG [*Nat. Commun*., 2019, **10**, 1426]
- Method for quantifying the triboelectric series [*Nat. Commun*., 2019, **10**, 1427]
- The invent of direct-current TENG [*Sci. Adv.,* 2019, **5**, eaav6437]

2020

- Quantifying electron-transfer in liquid-solid CE [*Nat Commun*., 2020, **11**, 399]
- Tribovoltaic effect and tribovoltaic nanogenerator [*Adv. Mater*., 2020, **32**, 2000928; *Adv. Energy Mater*. 2020, **10**, 1903713]
- TENG as a probe about solid–liquid interface [*ACS Nano*, 2020, **14**, 17565–17573]

2021

- CE induced interatomic electron transition [*Sci. Adv*., 2021, **7**, eabj0349]

2022

- Expand Maxwell's equation for moving objects [*Mater. Today*, 2022, **52**, 348–363; *Int. J. Mod. Phys. B*, 2023, **37**, 2350159; *Adv. Phys. X*, 2024, **9**, 1–55]
- Contact-eletro-catalysis [*Nat. Commun*., 2022, **13**, 130; 2024, **15**, 757]

Figure 3. Major milestones in the development of triboelectric nanogenerators (TENGs).

were systematically established,[51–53] allowing for the quantification of both TENG output and electromagnetic radiation from accelerated moving objects. Second, contact-electrocatalysis (CEC) was discovered experimentally, showing that catalysis can occur at liquid–solid interfaces due to contact electrification when excited by ultrasonic waves or mechanical ball milling.[54,55]

Impact of nanogenerators to fundamental physics

Mechanism of contact electrification at solid–solid interface

The surface charge density due to triboelectrification is a key factor in determining the output power of TENG. However, the mechanism for charge transfer in triboelectrification has been debated for decades, particularly whether it is due to electron transfer, ion transfer, and/or material species transfer.[56] In the last decade, for solid–solid contact electrification, Kevin probe study showed that electron transfer plays a dominant role. A general model has been proposed to explain electron transfer in contact electrification, by assuming the interatomic electron transfer and transition are due to the large overlap of electron wave functions at the interface under mechanical stress, which has been observed experimentally. This model is called Wang's model, which can also be extended to cases involving liquids and gases.[57]

Mechanism of contact electrification at semiconductor interface: The tribovoltaic effect

The tribovoltaic effect was first proposed in 2019, and was experimentally observed in 2020 by studying charge transfer at metal–semiconductor or semiconductor–semiconductor interfaces.[47] In the case of an *n*-type and *p*-type semiconductor, relative sliding between the two generates a DC output.[47] This is a result of the electron–hole pairs generated at the *p–n* junction due to the excitation by the energy released during the formation of interatomic bonds. The built-in electric field at the interface separates the electrons from the holes, resulting in a DC output. Similarly, a DC nanogenerator can also be fabricated using the tribovoltaic effect.

Theory for nanogenerators and the expansion of Maxwell's equations

In general, the theory for nanogenerators is based on an equivalent circuit model. The first work for quantifying the output power was conducted in 2017, which relied on the calculation of the displacement current.[7] However, traditional Maxwell's equations describe media at rest. To apply Maxwell's equations to calculate the TENG output, the displacement vector **D** was expanded to include a media motion-produced polarization term $\mathbf{P}_s$. Further experiments showed that this adjustment was insufficient, as electromagnetic radiation was observed when a TENG was triggered by sonic waves or hand tapping.[58] This indicates that Maxwell's equations need to be expanded to systematically account for medium motion.

From 2021 to 2024, the theory describing the electromagnetic phenomena in electromagnetic-mechano systems was developed. Wang derived the Maxwell's equations for a mechano-driven media system (MEs-f-MDMS) under low-speed approximation ($v << c$). The MEs-f-MDMS are essential for describing the electrodynamics of a moving object that undergoes not only accelerated translational motion but also rotational motion. In a system composed of moving media or objects, the electromagnetic behavior is described in the Lab frame (S frame), while the moving object is present in the space that is traveling with its reference center S' at v(t). The electromagnetic behavior inside the moving medium is described by the MEs-f-MDMS equations, which are given by[52]

$$\nabla \cdot \boldsymbol{D} = \rho \qquad \text{1a}$$

$$\nabla \cdot \boldsymbol{B} = 0 \qquad \text{1b}$$

$$\nabla \times (\boldsymbol{E} + \boldsymbol{v}_r \times \boldsymbol{B}) = -\frac{\partial}{\partial \mathrm{t}}\boldsymbol{B} \qquad \text{1c}$$

$$\nabla \times (\boldsymbol{H} - \boldsymbol{v}_r \times \boldsymbol{D}) = \boldsymbol{J} + \rho \boldsymbol{v} + \frac{\partial}{\partial \mathrm{t}}\boldsymbol{D} \qquad \text{1d}$$

where $\boldsymbol{v}(t)$ is the translation moving velocity of the origin of the reference frame S', which is only time-dependent, and $\boldsymbol{v}_r(\boldsymbol{r}, t)$ is the relative velocity of the point charge with respect to the reference frame S', which is space- and time-dependent, and can be simply referred as "rotation speed." The classic Maxwell's equations are to describe the electrodynamics in the region where there is no local medium movement. The full solutions of the two regions satisfy the boundary conditions, so that the rotation of the object affects the electromagnetic field at vicinity.

In practical engineering, there are many cases that has no translation motion but rotation motion of the object, as presented in the section "Milestone advances made in developing nanogenerators." In this case, we have $\boldsymbol{v} = 0$, so that $\boldsymbol{v}_t(\boldsymbol{r}_t) = \boldsymbol{v}_r(\boldsymbol{r}_t)$. This for the case that the system can rotate around the origin, and its boundaries, surface, and volume can expand and/or contract. Using constitutive relationship, Equations 1a–b reduce to[53]

$$\varepsilon \nabla \cdot \boldsymbol{E}_{\text{eff}} = \rho \qquad \text{2a}$$

$$\mu \nabla \cdot \boldsymbol{H}_{\text{eff}} = 0 \qquad \text{2b}$$

$$\nabla \times \boldsymbol{E}_{\text{eff}} \approx -\mu \frac{\partial}{\partial \mathrm{t}}\boldsymbol{H}_{\text{eff}} \qquad \text{2c}$$

$$\nabla \times \boldsymbol{H}_{\text{eff}} \approx \boldsymbol{J} + \varepsilon \frac{\partial}{\partial \mathrm{t}}\boldsymbol{E}_{\text{eff}} \qquad \text{2d}$$

where the effective fields are defined by

$$\boldsymbol{E}_{\text{eff}} = \boldsymbol{E} + \mu \boldsymbol{v}_r \times \boldsymbol{H}, \qquad \text{3a}$$

$$\boldsymbol{H}_{\text{eff}} = \boldsymbol{H} - \varepsilon \boldsymbol{v}_r \times \boldsymbol{E}. \tag{3b}$$

Equations 2a–d are identical to the classical Maxwell equations except that the electric field $\boldsymbol{E}$ and magnetic field $\boldsymbol{H}$ are replaced by the effective fields $\boldsymbol{E}_{\text{eff}}$ and $\boldsymbol{H}_{\text{eff}}$, respectively. In Equation 3a, the second term at the right-hand side is the Lorentz force. Similarly, in Equation 3b, the second term is the contribution of the local electric field to the local magnetic field due to medium movement. Therefore, the medium motion is a source for generating electromagnetic fields; the motion of a medium in the presence of a magnetic field generates an additional component to the electric field; and the medium motion in the presence of an electric field would generate an additional term to the magnetic field. The propagation, scattering, and reflection of the effective fields satisfy the classical Maxwell equations as for the case there would be no medium motion. Such equations are believed as the first principle theory for quantifying the output of TENG and related systems.

Impact of nanogenerators to fundamental chemistry

Mechanism of contact electrification at liquid–solid interface and the two-step model about the formation of the electric double layer

The first liquid–solid TENG was demonstrated in 2014.[31,32] The fundamental principle for liquid–solid TENG is likely due to the dynamic electric double layer (EDL). The term dynamic EDL has twofold meanings. First, the charge-carrier composition of electrons versus ions at the liquid–solid interface varies at initial contact due to the movement of the liquid level or coverage. Second, the area of the liquid covering the solid varies with temperature. In this scenario, the unbalanced charges in the EDL lead to a flow of electrons between the electrodes to balance the potential difference produced by the dynamic EDL, which is the principle behind the generation of current output. This also explains the mechanism of the hydrovoltaic effect.

By using the thermionic emission characteristics of electrons from a solid surface, Wang's group was the first to demonstrate that electron transfer is possible from water to a polymer surface, and a method for quantifying the ion transfer versus electron transfer.[46] As a result, a two-step model has been proposed to explain the formation of EDL, which is suggested to occur due to charge transfer at a liquid–solid interface resulting from contact electrification. In this model, electron transfer occurs first, forming the initial layer of charges, followed by ion adsorption due to surface electronic interactions. Later, the transferred electrons can be partially replaced by ions if there is temperature fluctuation. This is called the Wang's Hybrid EDL.

As a probe for studying liquid–solid interface charge transfer

TENG was proposed as a probe for measuring the charge transfer at a liquid–solid interface.[49,59] Using an array of single-electrode TENGs, the charge transfer between a sliding water droplet and a solid surface was mapped.[60] This provides a new tool for studying charge transfer at surface chemistry. Recently, a triboelectric spectrum has also been demonstrated for analytical chemistry.[61]

New catalysis mechanisms: Contact-electro-catalysis

Under external mechanical strain, piezoelectric polarization is generated on the two opposite surfaces of a piezoelectric material. The positively charged surface attracts electrons from catalytic nanoparticles, whereas the negatively charged surface attracts holes, resulting in oxidation and reduction reactions at the respective surfaces. This phenomenon is known as piezocatalysis. By using the electron exchange process in contact electrification, Wang's group has demonstrated the first contact-electro-catalysis (CEC).[55] In the initial step, a water molecule loses an electron to a solid surface upon contact and becomes a short-lived water ion H_2O^+, which quickly combines with another water molecule to form H_3O^+ and $^{\cdot -}OH$. In the second step, the electron transferred to the solid surface can be released due to phonon excitation and captured by dissolved oxygen, forming a negatively charged oxygen molecule, $^{\cdot}O_2^-$. This ion then combines with $H_2O^{\cdot +}$ from the first step, resulting in the recovery of H_2O and $HO_2^{\cdot}$. The formed radicals degrade other chemical species in the solution, rendering them environmentally benign. This process may represent how catalysis occurs naturally. Importantly, this study suggests that water is not only a solvent but also directly participates in chemical reactions, which adds to classical chemistry understanding.

Major technological applications of nanogenerators

The broad and significant impacts of nanogenerator technology have led to revolutionary application potentials particularly for high-entropy energy and sensing. Covered under these two overarching application directions, the application of NG technology can be categorized into five important directions: blue energy, nano- and micro-energy source, self-powered sensors, high-voltage sources, and probing electron transfer at liquid–solid interfaces (**Figure** 4).

Blue energy

Wang first proposed the idea of using TENG networks for harvesting water wave energy and coined the concept of blue energy in 2014.[33] This opened up research into TENGs for marine science and lately hybrid energy solutions for human sustainability. The uniqueness of TENGs for blue energy compared to electromagnetic generators (EMGs) is attributed to their outstanding energy-conversion efficiency at low frequencies and low amplitude.[8] Blue energy has garnered broad interest from the energy community as a new approach to sustainable energy derived from the environment.[62,63] More broadly, blue energy also includes general mechanical vibrations in the environment, such as those produced by vehicles on roads or machinery in factories, which

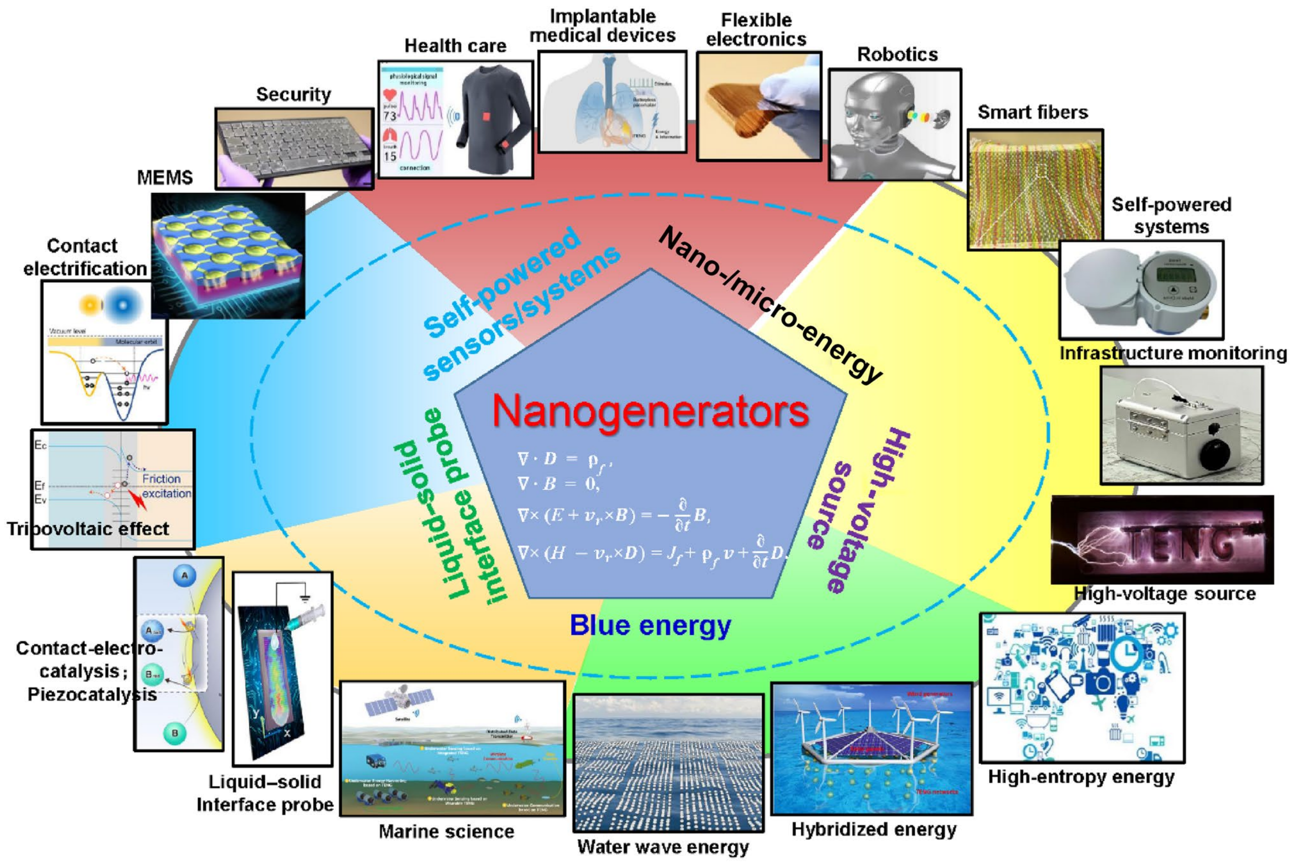

Figure 4. Major applications and impacts of nanogenerators. MEMS, microelectromechanical systems.

were the initial targets of nanogenerator technology. Various designs and a wide range of functional materials have been investigated for environmental mechanical energy harvesting, demonstrating significant potential for applications in environmental sensing and monitoring, as well as serving as an emergency power source in post-disaster conditions such as earthquakes or floods, or even being integrated into the power grid. TENGs have also been designed to capture energy from wind by converting the kinetic energy from wind-induced vibrations or airflow into electrical power, providing low-cost energy in remote or off-grid areas.[64]

Nano- and micro-energy source

The unique structural and material features of NGs enable energy sources at the nano- and microscale, both in terms of dimensions and energy output. This allows for excellent flexibility, integrability, and adaptability with nano- and microsystems. Therefore, NG devices are particularly suitable for interfacing with the human body. By directly harvesting energy from various biomechanical sources, such as heartbeats, breathing, muscle stretching, and cell-generated forces, NGs can provide sufficient energy for biomedical devices such as pacemakers, glucose monitors, and neural stimulators.[65,66] This capability highlights the potential to power implantable electronic devices using everyday movements, eliminating the need for batteries or other power supplies. The high electromechanical coupling efficiency of NGs also enables the recognition and differentiation of vital signs (e.g., pulse, body temperature, respiration) and various gait patterns (e.g., walking, running, jumping, falling), showcasing significant potential for the development of wearable biomedical sensors and healthcare monitoring systems.[67] The feasibility of developing NGs using textiles further allows for the creation of smart fabrics and clothing that harvest energy from human movement to power small electronics or sensors, with applications in sports, rehabilitation, security, and personal health care. Recently, NG technology has led to the concept of closed-loop electrostimulation,[65] which uses biomechanical energy to generate electrostimulation signals locally. This strategy eliminates the need for electronics or batteries and enables self-powered and self-regulated electrostimulation therapeutics. The weak electric fields produced by NGs have been demonstrated to accelerate wound healing, nerve repair, bone healing, hair regeneration, and to stimulate the vagus nerve to influence physiological functions such as food intake for weight control.[68,69] In general, NG technology offers a versatile strategy for utilizing biomechanical forces as nano- and micro-energy sources, introducing a paradigm shift in NG applications for powering small electronics and developing various biomedical technologies.[70,71]

Self-powered sensors and Internet of Things

In addition to electrical energy generation, NGs couple different forms of energy and are naturally suited for various sensing applications. NG-based sensors can detect signals across a wide range of domains, including the human body, natural and industrial environments, transportation systems, and public spaces.[72] This broad sensing capability aligns with the needs of the Internet of Things (IoT), which integrates numerous sensors and software to gather and communicate data. The self-powering capability of NG-based sensors could also substantially simplify design, reduce maintenance needs, and improve integration.

The various electromechanical coupling principles of NGs offer a broad spectrum for sensing applications, with a wide range of operational modes and material choices, including polymers, metals, fabrics, and natural materials.[73] The electricity generation performance of NGs can be influenced by numerous factors, which allows NGs to detect changes not only in mechanical motions but also in environmental parameters. As a result, NGs have been utilized as self-powered sensors for environmental monitoring, including air quality, temperature, humidity, and pollution. These applications are particularly ideal for remote or difficult-to-access areas where replacing batteries is impractical.[74] NG-based sensors can enable self-sustaining IoT systems in smart homes and cities, supporting functionalities such as motion-activated lighting, door/window sensors,[75] and traffic monitoring systems by harvesting mechanical energy from vibrations, wind, or human activities.[76] Additionally, by capturing energy from passing vehicles or wind, NGs facilitate self-powered sensors for real-time monitoring of structural health in bridges, buildings, and transportation networks.[77] Furthermore, NGs are particularly well suited for integration into flexible and wearable electronics, where their ability to generate power from body movements can be harnessed to monitor health metrics or interact with electronic devices.[78–80] They can provide power for wearable human–machine interfaces that respond to body movements or gestures, with applications in virtual reality (VR) controllers, haptic feedback systems, and prosthetic devices.[81,82]

High-voltage sources

A unique application of triboelectrification is its ability to generate high output voltages, which can serve as a small-sized high-voltage source for specific applications. These include acting as a charge source for mass spectrometry with precisely controlled amounts of charge, as well as providing a compact source for exciting plasmons.[38,83]

As a probe for studying liquid–solid interface charge transfer

Charge transfer at the liquid–solid interface could also result from the contact-electrification (CE) effect, which plays a significant role in electrochemistry and catalysis. Additionally, charge transfer can occur in many solid–liquid systems, such as electrowetting, photosynthesis, biochemical sensing, and nerve stimulation.[84–86] TENG technology and the associated CE studies provide a versatile approach to understanding charge-transfer phenomena at liquid–solid interfaces. Using TENGs as a model system, recent research has demonstrated that electron transfer plays an important role alongside ion transfer in many liquid–solid systems. Studies have revealed that electron transfer at the liquid–solid interface could be governed by temperature-induced thermionic emission[87] and UV light-induced electron emission.[88] The electron transfer from liquid–solid CE is believed to contribute to the formation of the electric double layer (EDL), which leads to Wang's hybrid EDL model.[57]

Understanding liquid–solid CE could have a substantial impact on mechanical energy harvesting from liquid movements, as well as on classic electrochemical systems for energy storage, energy conversion, chemical reactions, and sensing. Based on the principle of liquid–solid CE, TENGs have been developed for large surfaces such as umbrellas, raincoats, windows, and walls to harvest energy from water waves or raindrops.[89] The principle of water energy harvesting can be readily integrated with other forms of energy harvesting from the environment, such as solar or wind energy, enabling hybrid NGs with higher power output and more consistent energy production.[90] In addition to energy harvesting, liquid–solid CE also shows promising potential for sensing applications, particularly in microfluidic systems for movement, displacement, or pressure detection.[91] TENG-based microfluidic sensors can be designed to be flexible and work with the human body as wearable devices. By integrating the electrowetting effect, liquid–solid TENGs also enable self-powered actuation in microfluidic systems.[92] Furthermore, the CE effect in liquid–solid TENGs can be utilized for corrosion protection or antifouling in marine systems by directly leveraging the kinetic energy from ocean waves.[93] Given the wide variety of liquid–solid systems in energy and environmental applications, liquid–solid TENG technology will significantly contribute to the development of fundamental concepts and practical devices for global sustainability today.

In this issue

As we elaborated in previous sections, the impacts of NG technology are marked by the rapid involvement of research in the field, encompassing a broad spectrum from fundamental principle investigations to diverse multidisciplinary applications. This issue curates feature articles to provide the latest updates on the core aspects of nanogenerator-related studies.

To achieve this goal, we arranged 16 articles from leading researchers in the field and distributed them across two consecutive issues.

There are articles focused on the fundamental principles of NGs, including design, materials, operation, and output control. Wang et al. provide a comprehensive overview of NG technology, detailing operational modes and theories based on piezoelectric, triboelectric, pyroelectric, and tribovoltaic effects.[94] Shao et al. discuss the expanded Maxwell's equations for understanding dynamic charge induction and transport in NG operation, highlighting their application for quantifying TENG output.[95] The power output of NGs, a key figure of merit, is addressed in three articles. Zou et al. explore material selection principles for maximizing output based on electromechanical coupling efficiency, mechanical properties, and biocompatibility.[96] Du et al. review advancements in TENG systems and strategies to enhance output power through innovative design inspired by other energy-harvesting techniques.[97] Baik et al. further analyze methods for boosting TENG outputs, including surface and bulk modifications, structural designs, and tailored mechanical systems.[98] Emerging concepts also present new opportunities for NG applications. Zhang et al. discuss charge generation and transfer at liquid–solid interfaces through contact electrification, along with related sensing and energy-conversion applications.[99] Zhang et al. examine the tribovoltaic effect at semiconductor interfaces, covering fundamental principles and material relationships, as well as representative applications.[100] Finally, Yang et al. introduce design principles for integrating energy harvesting from multiple sources or mechanisms, including energy-storage components.[101]

Other articles explore diverse applications of NG technology, including blue energy, micro-nano power sources, high-voltage sources, self-powered sensors, liquid–solid interface probes, and electrochemical catalysis. Lee et al. discuss material selection and design principles for NGs as nano- or micro-power sources and as coupling elements for self-powered sensors across various applications, including energy, electronics, environmental, and biomedical fields.[102] Choi et al. provide a general overview of nano- and micropower sources, highlighting principles and examples of NGs developed from functional materials such as fibers and cellulose for effective electrical power generation at the nano- to micro-watt level.[103] Jiang et al. focus on blue energy, discussing materials, device design, and scaling strategies for harvesting energy from ocean waves.[104] Xu et al. further analyze NG applications in underwater sensing and monitoring.[105] In the medical field, Li et al. provide an overview of advancements in NGs for implantable biomedical devices, serving as sustainable power sources or power-free electrical therapies.[106] Zi et al. discuss applications in flexible and wearable devices within health care, emphasizing sensing, monitoring, diagnosis, treatment, and data communication.[107] The last two articles examine liquid interfacing. Lin et al. analyze the principles governing electricity generation from liquid movement on solid surfaces, including device design and performance strategies.[108] Berbille et al. introduce a new catalysis strategy utilizing the contact-electrification effect to drive electrochemical reactions at liquid–solid interfaces, providing insights into fundamental electronic and electrochemical principles and their practical applications in catalysis.[109]

Perspectives and conclusions

It has been almost two decades since the invention of NGs. We are witnessing that NG-related research rapidly evolves into a global multidisciplinary field encompassing materials science, physics, chemistry, biology, and engineering. Intriguing application potentials have been consistently demonstrated, supported by exciting discoveries that deepen our fundamental understanding. Although this issue aims to provide a broad range of fundamental knowledge and practical applications in the growing field of NGs, it may not completely cover all renowned researchers and state-of-the-art discoveries. Given the vast potential of NG technology, we hope this series of featured articles inspires new ideas and research directions to advance NG technology to new horizons. Before concluding, we would like to highlight a few critical points in NG development that could help readers better understand and envision the current and future landscape of NG technology. These issues should be urgently addressed through the joint efforts of the NG community.

Efficiency improvement: Efficiency has always been a technical goal in the development of NGs. It is exciting and encouraging to see numerous fundamental discoveries and engineering designs that continually elevate the energy-conversion efficiency of NGs. Nevertheless, for many applications, although the mechanical energy sources are considered sufficient, the energy output from NGs still falls short of sustaining regular operations. We envision that innovations in new materials or composites, along with a better understanding and engineering of heterogeneous interfaces, are two research directions that offer the greatest potential to enhance the energy-conversion efficiency of NGs to new heights.

Durability and longevity require constant movement of their functional components. Therefore, the durability of the materials and devices is a major concern for the application of NGs. Improvements in the longevity of NGs focus on enhancing the materials' resistance to wear and tear caused by repeated bending, movement, touching, or pressing. Typical strategies include the development of new materials with exceptional strength or flexibility, combining various NG modes to reduce dependence on movements, and interface engineering to minimize friction and wear.

Standardization: The critical requirements for NG materials and engineering necessitate a standard matrix for evaluation, especially as we transition NG technology from the laboratory to the market. This standardization is urgently needed, given the exponentially increasing number of research results reported daily. The development of international industry standards for NGs should encompass performance metrics, material specifications, and durability.

Scalability and Mass Production: As NG technology advances toward industrial application, scalability and mass production become essential. This transition may require completely different device architectures or material selections to meet industry manufacturing requirements. It is encouraging to note that many current NGs are fabricated using industry-compatible techniques, such as 3D printing. Given that one of the major advantages of NGs is their low cost and simple structure, it is wise to consider scalability and compatibility with existing manufacturing techniques when developing new NG devices, particularly in terms of material selection and structural design.

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Authors contributions

Z.L.W. conceived, organized, and composed the manuscript; X.D.W. conceived, organized, and composed the manuscript; S.W.K. edited the writing; and R.Y.Z. contributed and edited the writing.

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