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Review

Exploring the synergy of EMG and TENG in motion based hybrid energy harvesting

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ABSTRACT

This review paper explores the integration of electromagnetic generation (EMG) and triboelectric nanogeneration (TENG) technologies, emphasizing their classification based on motion types: linear, rotational, and vibration-based. By examining each motion type, we highlight the unique characteristics, advantages, and challenges associated with hybrid EMG-TENG systems. Linear motion devices are particularly effective in harnessing energy from predictable sources, such as ocean waves, demonstrating moderate power outputs suitable for marine applications. Rotational motion devices excel in environments with continuous high-speed motions, achieving higher energy outputs, especially in wind energy systems. In contrast, vibration-based devices capture energy from irregular and low-frequency movements, offering versatility for applications in vehicles and wearable electronics. The review also discusses recent developments in hybrid systems, showcasing advancements in materials and designs that enhance energy capture and efficiency. Despite the progress, challenges remain, including mechanical wear, environmental influences, and the need for precise alignment. By understanding the complementary nature of EMG and TENG technologies, this review highlights how their integration can address the limitations of each technology. EMG excels in capturing high-speed, continuous motion, while TENG is more effective for low-frequency and irregular motion, allowing hybrid systems to efficiently harvest energy in diverse environments. Ultimately, the findings suggest that the strategic integration of EMG and TENG technologies can contribute significantly to sustainable energy solutions, paving the way for innovative developments in energy harvesting.

1. Introduction

The escalating demand for sustainable and renewable energy solutions has become a global priority in light of the increasing impacts of climate change and the finite nature of fossil fuel reserves. Among the technologies emerging at the forefront of this energy revolution, electromagnetic generation (EMG) [1–7] and triboelectric nanogeneration (TENG) [8–11] are distinguished by their innovative approach to converting mechanical energy into electrical energy. EMG, based on the principles of electromagnetic induction [12–16], exploits the movement of a conductor within a magnetic field to induce electrical current. This method is crucial in traditional power generation as well as in modern applications such as wind turbines and kinetic energy recovery systems in vehicles, offering high power efficiency and adaptability to various scales of operation.

TENG technology, on the other hand, capitalizes on contact electrification [17–26] and subsequent electrostatic induction [27–30], a process where materials exchange charges upon contact and separation. This phenomenon is particularly adept at harvesting energy from ambient mechanical sources including human movement, machine vibrations, and wind flows. TENGs are celebrated for their versatility, cost-effectiveness, and exceptional capability to operate effectively across a spectrum of frequencies, including those typically overlooked by conventional energy harvesting methods [31].

The integration of EMG and TENG into hybrid systems harnesses the strengths of both technologies, facilitating a comprehensive approach to energy harvesting [32–41]. This synergy allows for the efficient capture of a wider range of kinetic energies available in varying environments, thereby enhancing overall system performance and energy yield [42–44]. Hybrid EMG-TENG systems are particularly effective in scenarios where energy availability is variable and sporadic, as they can continuously generate power under diverse conditions [45–55].

Despite the advances in technology, challenges persist, particularly in optimizing energy output and operational efficiencies across various

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motion types [56]. Addressing these challenges involves a detailed understanding of how different motion dynamics—linear, rotational, and vibrational—affect the performance of hybrid generators [57]. Classifying hybrid devices according to their primary motion type not only aids in tailoring technologies to specific applications but also enhances the predictability and reliability of energy outputs.

This review aims to delve into the intricate dynamics of hybrid EMG-TENG systems by categorizing them based on motion types [51,54,58,59], elucidating recent advancements, and outlining the applications and challenges associated with each type. Through a comprehensive examination of these elements, this paper seeks to clarify the current landscape and future trajectory of hybrid energy harvesting technologies, providing valuable insights into their potential to meet the burgeoning global demand for renewable energy.

EMG and TENG exhibit complementary strengths that make their integration highly advantageous in hybrid systems. EMG leverages electromagnetic induction to efficiently harvest energy from high-speed, continuous sources like wind turbines or mechanical rotation. In contrast, TENG effectively captures energy from low-frequency or irregular motion such as human activities or machine vibrations through the triboelectric effect. When combined, EMG ensures stable power output during continuous motion, while TENG compensates for energy losses in non-continuous scenarios. This synergistic integration significantly enhances the versatility and efficiency of hybrid energy harvesting devices. By exploring the fundamental principles, applications, and the complementary nature of EMG and TENG within hybrid systems, this review also highlights the innovative strategies that are shaping the future of energy harvesting [60]. As the world gravitates towards more sustainable energy solutions, understanding and advancing these technologies will be pivotal in harnessing the full spectrum of available mechanical energies for electrical power generation. Various types of hybrid generators is in Fig. 1.

2. Hybrid generators based on linear motion

2.1. Kinematic structure and energy absorption methods for linear motion

Linear motion devices are designed to harvest energy from straight-line movement. In the context of hybrid EMG-TENG systems, these devices typically feature a linear generator mechanism that moves along a fixed path, such as a rail or guide [68,69]. Linear motion kinematic illustration is in Fig. 2. The electromagnetic component generates energy through relative motion between magnets and coils [70], while the triboelectric component captures energy by creating friction between surfaces during the motion [71]. This dual mechanism allows for

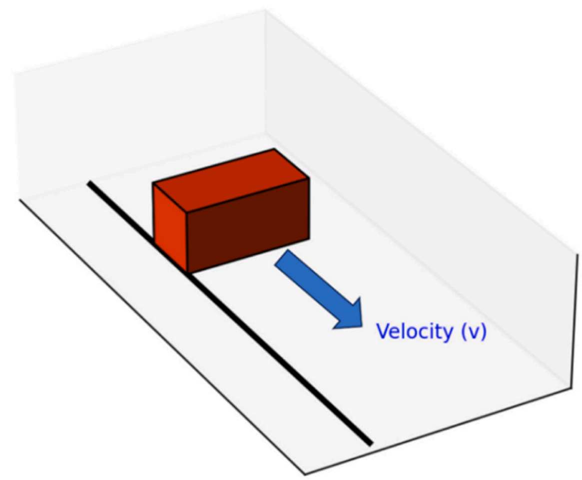

Fig. 2. Linear motion kinematic illustration.

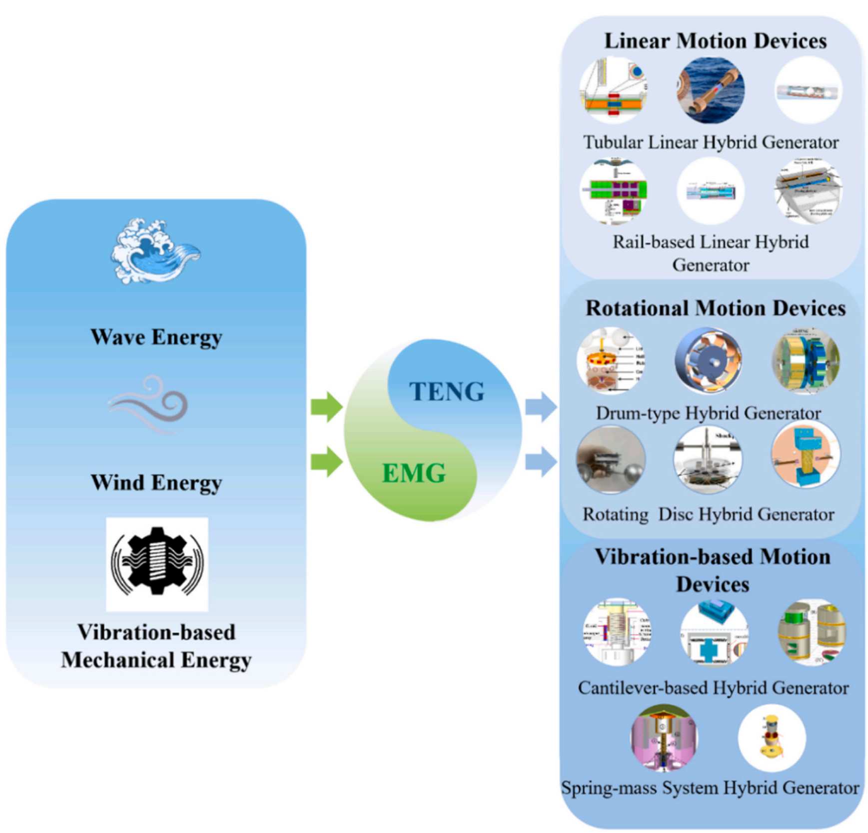

Fig. 1. Various types of hybrid generators [27,61–67].

efficient energy absorption from the linear motion, making it particularly suitable for applications where consistent, repetitive movements are present, such as in transportation systems or industrial machinery.

The energy absorption process in linear hybrid devices depends on the coordination between the electromagnetic and triboelectric elements. The EMG component generally relies on Faraday's law of electromagnetic induction, while the TENG component utilizes surface charge transfer. This combination enhances the overall energy output and widens the range of operating conditions where energy can be harvested.

2.2. Linear motion hybrid devices

2.2.1. Rail-based linear hybrid devices

Rail-based linear hybrid generators are innovative systems designed to capture energy from linear motion efficiently, particularly in environments characterized by smooth and continuous movements, such as marine and industrial applications [54]. These devices typically integrate a linear electromagnetic generator (EMG) and a triboelectric nanogenerator (TENG) along a guided rail system, enabling simultaneous energy harvesting through electromagnetic induction and triboelectric effects [69].

Prof. Clemente's team introduced an innovative hybrid wave energy harvesting system that combines TENGs with a wave energy converter called E-Motions, designed to convert ocean wave energy into electrical power. Fig. 3(a) presents the conceptual design of the E-Motions system, where the hull of the floating platform houses the energy conversion mechanisms, combining both TENG and power take-off (PTO) systems. Fig. 3(b) details the forces acting on the PTO, including gravitational forces, damping, and the dynamic energy conversion as the device oscillates with the waves. Fig. 3(c) illustrates the system's operation under wave action, highlighting how the platform's rolling oscillations move the PTO, generating energy through the mechanical sliding mechanism. This hybrid system significantly improves energy output efficiency by harnessing both the triboelectric effect and conventional wave energy conversion, making it adaptable to various offshore applications.

Similarly, Prof. Sun's team proposed a novel direct-driven triboelectric-electromagnetic hybrid wave energy converter (DTEWEC) for buoy power supply. This device integrates TENG and EMG units to capture ocean wave energy effectively. Fig. 3(d) details the EMG structure, featuring coils and magnets in an optimized configuration to enhance electromagnetic energy generation. Fig. 3(e) shows the overall structure of the DTEWEC, with the TENG and EMG units housed within the buoy system, and components such as the stator substrate and connecting rods facilitating energy conversion. This hybrid design enables the device to capture both high-frequency and low-frequency mechanical energy, significantly improving buoy power supply capabilities.

In another instance, Prof. Naguib's team developed a hybrid triboelectric-electromagnetic wave energy harvester, utilizing a heaving point absorber mechanism to capture ocean wave energy. Fig. 3(f) and (g) illustrate the device's schematic, which consists of a floating buoy connected to an energy harvester. As the buoy moves with the waves, it drives a slider inside the harvester, which is connected to both an EMG and a TENG. The slider moves within the device's stator, converting the wave's mechanical energy into electrical energy through both triboelectric and electromagnetic processes. This simple, direct-drive system, free of complex mechanical components, provides an efficient solution for ocean wave energy harvesting.

Rail-based linear hybrid generators are particularly effective for harvesting energy from wave and wind energy, as well as other forms of mechanical motion, due to their high efficiency in stable environments.

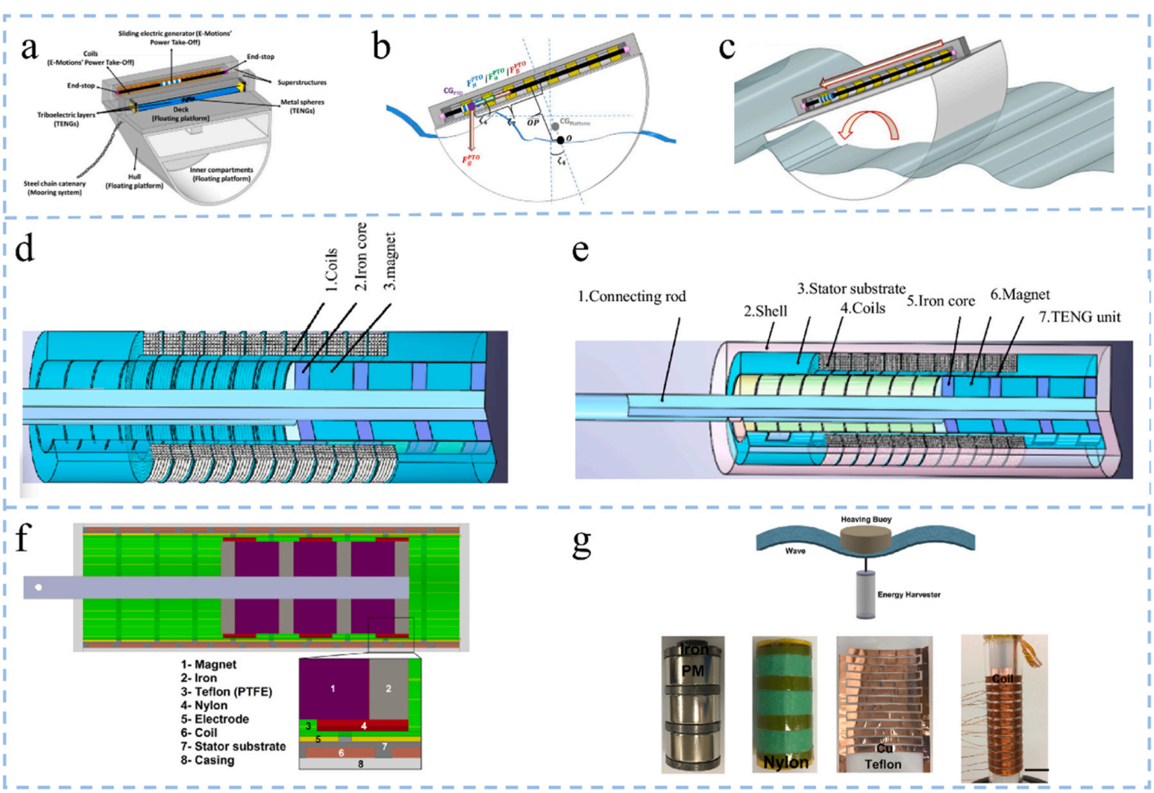

Fig. 3. (a) Conceptualization of E-Motions with integrated triboelectric nanogenerators. The inner compartments can also accommodate either the E-Motions' PTO or the TENGs. (b) Acting forces on the E-Motions'. (c) touring moment induced roll oscillations and PTO sliding towards the superstructure's end-stop at a lower height. Reproduced with permission Applied Nanoscience [72]. (d) EMG unit. (e) Layout plan of DTEWEC. Reproduced with permission Science and Engineering [73] (f) structural configuration of the device. Fabricated components of the device. (g) Schematic mechanism of the heaving point absorber and the various parts of EMG. Reproduced with permission Elsevier [62].

However, several factors can affect the energy output of these devices, including mechanical wear, environmental conditions, and the need for precise alignment of components. For example, wear on TENG surfaces caused by continuous friction can reduce performance over time, while temperature and humidity variations may influence the efficiency and reliability of the energy harvesting process. Future improvements will need to address these challenges by enhancing material durability and optimizing designs for consistent performance in diverse operational conditions.

2.2.2. Tubular linear hybrid devices

The tubular linear hybrid generator is a novel device designed to capture ocean wave energy efficiently. It typically integrates an EMG and a TENG within a sealed tubular structure, converting mechanical energy into electrical energy [53]. The tubular design not only shields internal components from environmental effects but also maximizes energy capture efficiency [74], making it ideal for marine and fluctuating environments.

One example is Prof. Xue's tube-shaped solid–liquid interfaced triboelectric–electromagnetic hybrid nanogenerator (TTEHG), designed for efficient ocean wave energy harvesting. Fig. 4(a) and (b) show the 3D structural schematic of the TTEHG, featuring a sealed FEP tube, deionized water, copper foil electrodes, coils, and a magnet. As the DI water and magnet move inside the tube, they generate triboelectric and electromagnetic energy. Fig. 4(c) details the working mechanism, where wave-induced motion causes the DI water and magnet to oscillate within the tube, generating triboelectric energy through water contact with the FEP film and electromagnetic current through coil-magnet interactions. This design ensures high sensitivity to ultra-low-frequency waves, maximizing energy harvesting efficiency.

Another example is Prof. Lee's non-resonant piezoelectric–electromagnetic–triboelectric hybrid energy harvester (PETHEH) for capturing low-frequency human motion energy. Fig. 4(d) shows the 3D schematic of the device, featuring a symmetrical cylindrical structure with an EMG at the center, piezoelectric generators (PEGs) at both ends, and a TENG on the inner surface. A cylindrical NdFeB magnet serves as the proof mass, driving all three energy conversion units. Fig. 4(e) and (f) provide a detailed view of the hybrid system, illustrating how the moving magnet triggers piezoelectric and triboelectric components. This synergistic design efficiently converts low-frequency vibrations into electrical energy, making it ideal for wearable applications.

Additionally, Prof. Xu's team developed a highly integrated triboelectric-electromagnetic wave energy harvester (TEWEH) for marine energy harvesting and self-powered marine buoys. Fig. 4(g) and (h) show the TEWEH integrated within a buoy, with key components like aluminum electrodes and copper coils facilitating the triboelectric and electromagnetic generation processes. Fig. 4(i) details the triboelectric mechanism, where a PTFE ball repeatedly contacts and separates from aluminum electrodes inside the tube, generating alternating current. This design allows the TEWEH to harvest wave energy across a wide range of frequencies, enabling continuous power generation even in low-frequency conditions.

In summary, tubular linear hybrid generators are particularly well-suited for harvesting energy from wave and wind energy, as they efficiently capture stable and repetitive fluctuating motion. However, several factors, such as mechanical wear, environmental conditions, and component alignment, influence energy output. Friction between TENG components can degrade performance over time, while environmental factors like temperature and humidity can impact efficiency and reliability. Future research should focus on enhancing material durability and optimizing designs for consistent performance in varying conditions.

Linear motion devices are particularly effective in environments with

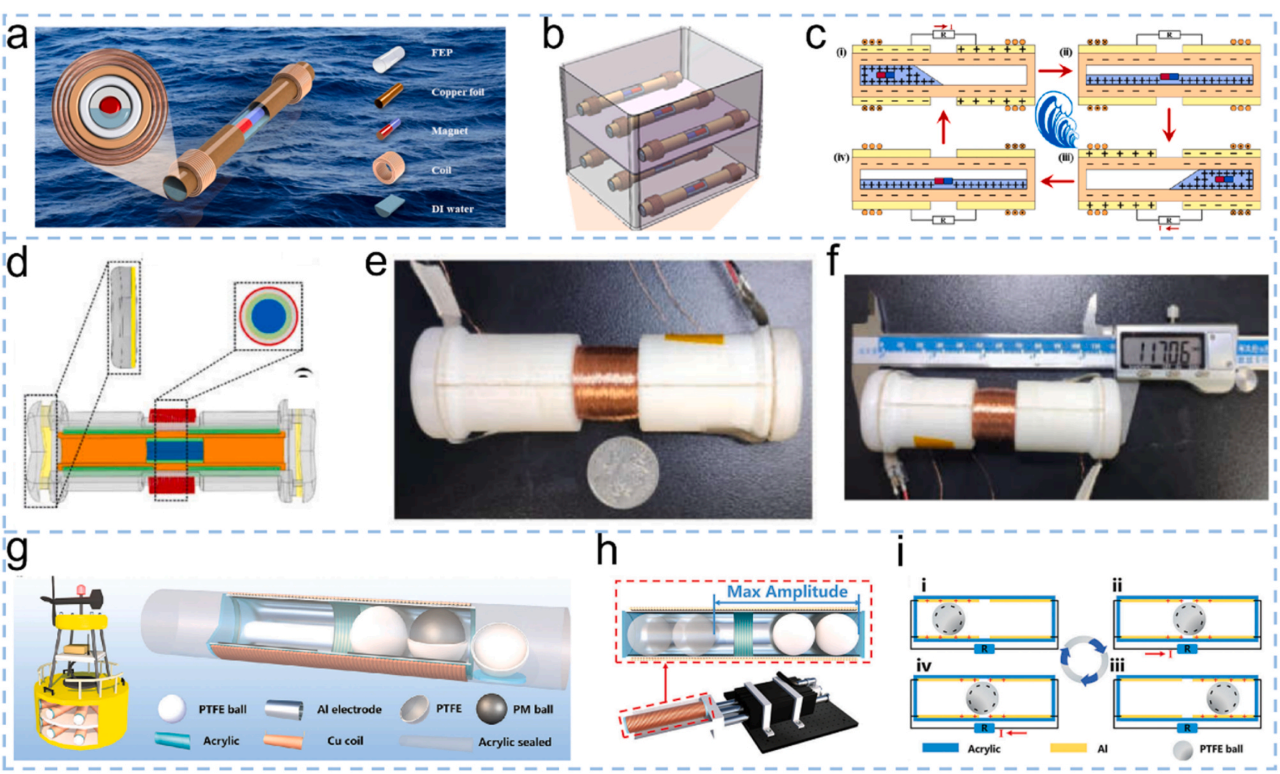

Fig. 4. (a) 3D structural schematic of the TTEHG. (b) Schematic diagram of experimental apparatus (c) Schematic of the working mechanism of the TTEHG. Reproduced with permission Wiley [75]. (d) TENG-EMG unit. (e) Photograph of the hybrid energy harvester. (f) The length of the hybrid energy harvester. Reproduced with permission Nanomaterials [76]. (g) A schematic showing the TEWEH integrated inside a buoy as the power supply, along with an internal view of the TEWEH's structure. (h) Schematic of the horizontal excitation experiment system.(i) Schematic of the TENG component's working principle. Reproduced with permission Elsevier [77].

consistent, repetitive motion, such as ocean wave energy harvesting. Their simple kinematic structures make them suitable for stable applications. However, their performance is often limited by mechanical wear and alignment issues, which can significantly impact long-term efficiency. For instance, continuous friction between components may degrade triboelectric surfaces over time, reducing energy output. Additionally, environmental factors like corrosion in marine environments pose further challenges to maintaining system performance.

2.3. Recent developments of linear motion devices

Linear motion devices within hybrid EMG-TENG systems have seen transformative advancements, particularly in the integration of mechanical and electrical systems to enhance energy harvesting efficiency. A key development is the refinement of device designs, making them more compact and reducing mechanical friction and wear, which in turn boosts electrical output. Recent advancements in material technology, such as the use of nanocomposites and high-density polyurethane, have significantly enhanced the durability of linear motion devices in harsh marine environments. For example, reinforced fiberglass has been employed to resist saltwater corrosion, extending the lifespan of these devices. Additionally, modular designs have been introduced, allowing for easier maintenance and reducing operational downtime by enabling quick component replacement [70]. Additionally, the emergence of modular linear motion devices marks a significant stride in adaptability. These devices can be tailored for various settings, from marine to industrial, through easily interchangeable modular components. This not only facilitates seamless integration into different systems but also minimizes maintenance costs and operational downtime.

Technological and Precision Enhancements: The field has also witnessed the advent of precision engineering techniques that heighten the accuracy of component alignment and movement in linear generators. Technologies like laser-guided assembly and computer-aided design (CAD) ensure that these devices are assembled with exact precision, maximizing energy transfer and minimizing losses due to misalignment. Moreover, the electrical aspects have been enhanced through the integration of smart electronics that enable adaptive control of EMG and TENG components [52,78]. These systems adjust in real-time to varying energy needs and environmental conditions, optimizing power output and efficiency. Such advancements not only improve the operational efficiency but also support sustainable energy management practices within these devices.

Integration of IoT and Future Prospects: Furthermore, incorporating Internet of Things (IoT) technology into linear motion devices opens new avenues for remote monitoring and control, which enhances both the operational efficiency and maintenance processes [79]. IoT capabilities allow for real-time data collection and analysis concerning device performance and environmental conditions, which aids in making informed decisions regarding system adjustments and enhancements. These cumulative developments in material technology, design innovation, precision engineering, and IoT integration significantly boost the robustness, efficiency, and versatility of linear motion devices, setting a new standard for energy harvesting solutions in marine and industrial applications. These advancements are expected to continue shaping the future landscape of energy solutions, driving towards more sustainable and efficient practices.

2.4. Applications of linear motion devices

Linear motion devices in hybrid EMG-TENG systems find their use in a wide range of applications, demonstrating significant versatility and effectiveness in energy harvesting [74]. Notably, they are integral to marine energy systems, industrial automation, and infrastructure monitoring, capitalizing on their capability to efficiently convert linear kinetic energy [80]. For instance, in marine settings, these devices excel in ocean wave energy harvesting. They are typically deployed in configurations such as rail-based linear hybrid generators on maritime buoys [75], offshore platforms, and coastal barriers, where they convert the rhythmic motion of waves into electrical power [77]. This continuous energy supply is vital for operations like navigation, environmental monitoring, and data transmission to shore facilities, enhancing the sustainability of marine infrastructure.

Environmental factors play a significant role in the performance of linear motion devices. In marine environments, saltwater corrosion and temperature fluctuations pose serious challenges to material durability and energy efficiency. To address these issues, multi-layer protective coatings and self-healing materials have been developed to resist corrosion and maintain stable performance under varying conditions. Additionally, the buildup of biofouling, such as algae and barnacles, on exposed surfaces can hinder motion and reduce energy output in long-term deployments. Antifouling coatings or active cleaning mechanisms are essential to mitigate these effects. Humidity can also impact the triboelectric performance of TENG components, necessitating the development of materials with enhanced moisture resistance. Finally, debris and particulate matter in industrial settings can obstruct linear motion, highlighting the need for robust protective housings to ensure uninterrupted operation.

In industrial automation, linear motion devices are strategically utilized to extract energy from machinery movements to power sensors and actuators within systems, especially in environments where wiring poses challenges or frequent battery replacements are impractical. For example, in manufacturing settings, energy is harnessed from assembly line movements to fuel real-time monitoring systems. These systems are crucial for tracking production quality and maintaining equipment health, thereby boosting both safety and operational efficiency. Additionally, in infrastructure monitoring, these devices are embedded within structures like bridges and skyscrapers to collect energy from natural expansions, contractions, and stresses induced by traffic, weather, and temperature variations. The harvested energy powers sensors that monitor structural health, providing early warnings for potential issues, thus safeguarding against structural failures.

Expanding further into smart grid and emergency applications, linear motion devices are increasingly integrated into urban infrastructure. In smart grids, they enhance power distribution efficiency by harvesting energy from linear movements in subways and elevators, contributing power back into the building's system or the city grid, reducing costs and bolstering urban energy efficiency. In emergencies, such as natural disasters leading to power outages, these devices offer crucial backup power to essential systems like emergency lights, communication networks, and medical apparatus, ensuring uninterrupted operation. The broad adaptability and potential of linear motion devices across various sectors underscore their role in not only augmenting energy efficiency but also in fostering more resilient and sustainable energy ecosystems. Linear motion devices in hybrid EMG-TENG systems is in Fig. 5.

3. Hybrid generators based on rotational motion

3.1. Kinematic structure and energy absorption methods for linear motion

Rotational motion devices are designed to capture energy from rotational movements, such as spinning or turning motions. Rotational motion kinematic illustration is in Fig. 6. In hybrid EMG-TENG devices [81], these systems typically integrate a rotating disc or drum [82], embedding electromagnetic coils and triboelectric materials. The electromagnetic generator (EMG) component works by inducing current through the relative motion of magnets and coils as the disc or drum rotates, while the triboelectric nanogenerator (TENG) captures energy through contact electrification and electrostatic induction when surfaces come into contact and separate during rotation [83].

This dual energy absorption mechanism allows rotational motion hybrid devices to harness energy from a wide range of rotational

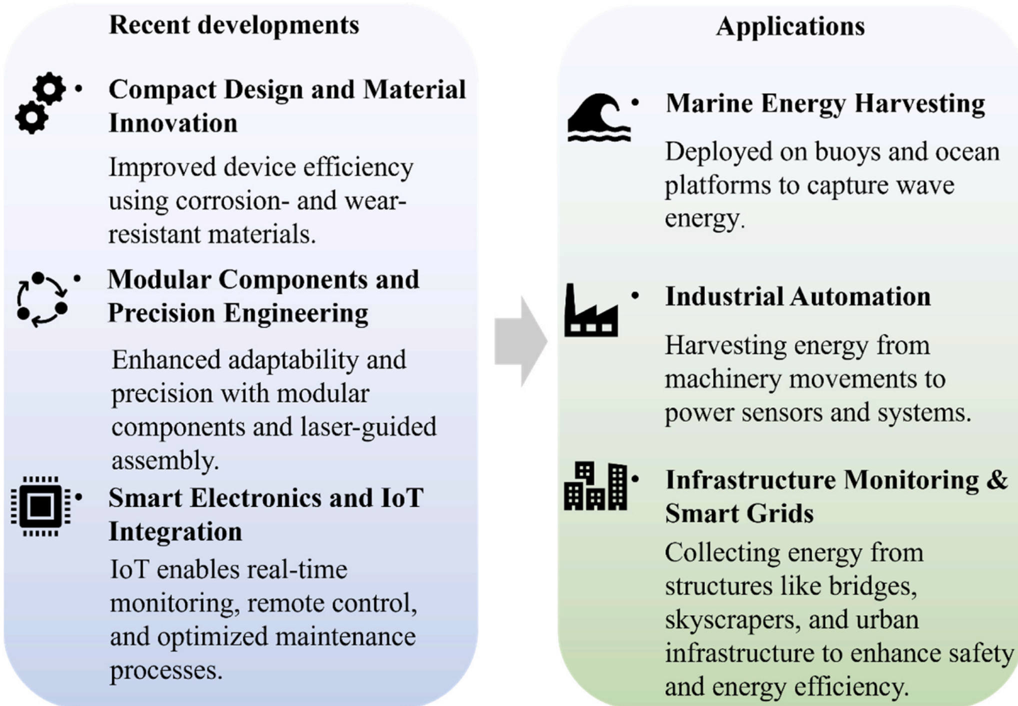

Fig. 5. Linear motion devices in hybrid EMG-TENG systems.

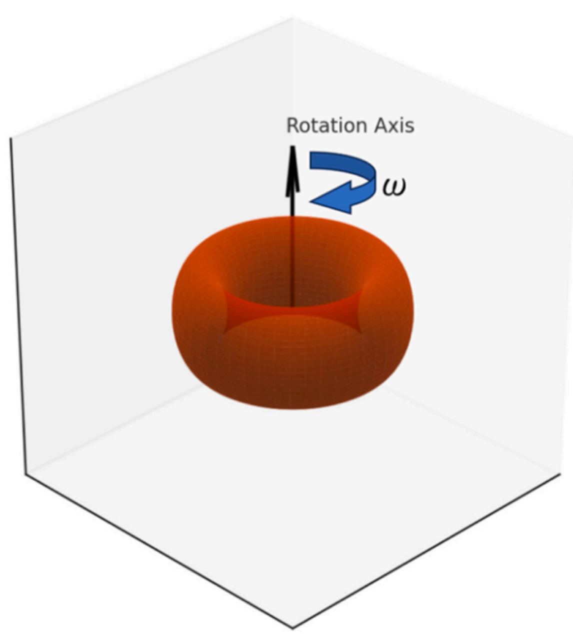

Fig. 6. Rotational motion kinematic illustration.

movements [84]. Applications include wind turbines, rotational machinery, and even wearable devices that experience twisting or turning forces [85,86]. The integration of both EMG and TENG components enables efficient energy harvesting, as the rotational speed and the frequency of contact events between surfaces directly influence the energy output of these devices. Rotational motion devices, therefore, offer a versatile solution for energy harvesting in dynamic environments, where rotational movements are prevalent.

3.2. Rotational motion hybrid devices

3.2.1. Rotating disc hybrid devices

Rotating disc hybrid generators are engineered to efficiently harvest energy from rotational movements, making them ideal for applications where continuous spinning or turning occurs, such as wind energy and machinery [87]. These devices typically integrate an electromagnetic generator (EMG) with a triboelectric nanogenerator (TENG) in a disc-like structure, enabling dual-mode energy harvesting to enhance overall power output [88].

One notable example is the self-powered wireless flexible sensing system for food storage proposed by Prof. Wang's team. This system is based on a triboelectric-electromagnetic generator (TEG-EMG) designed to monitor gas flow velocity and food surface conditions in Controlled Atmosphere (CA) storage. Fig. 7(a) shows a physical image of the EMG, which consists of a rotor with magnets and a stator with copper coils. This setup captures wind energy within the CA storage warehouse and converts it into electrical power. Fig. 7(b) provides an exploded view of the EMG, detailing the rotor-stator structure. The rotor, driven by wind via turbine blades, induces an alternating current in the stator's copper coils, ensuring continuous energy generation. Fig. 7(c) presents the triboelectric nanogenerator (FV-TENG), which captures wind energy from gas flow in the CA pipeline and converts it into electrical signals for real-time gas flow velocity monitoring. The flexible copper foil blades interact with a PTFE dielectric layer to generate charges during the contact-separation cycle, optimizing the energy harvesting process.

Similarly, Prof. Zhang's team developed a piezoelectric-triboelectric-electromagnetic tri-hybrid energy harvester (THEH) designed for ultralow-frequency rotational motion with a dual-frequency-up-conversion mechanism. Fig. 7(d) illustrates the schematic structure of the THEH, integrating one EMG module, two TENG modules, and two piezoelectric nanogenerator (PENG) modules. These components work in concert through the movement of a central magnet, which slides within the shell, activating the TENG, PENG, and EMG modules to capture rotational motion energy. Fig. 7(e) and (f) depict the fabricated prototype, showcasing its compact design, where the central magnet, coils, piezoelectric beams, and triboelectric layers are all integrated to

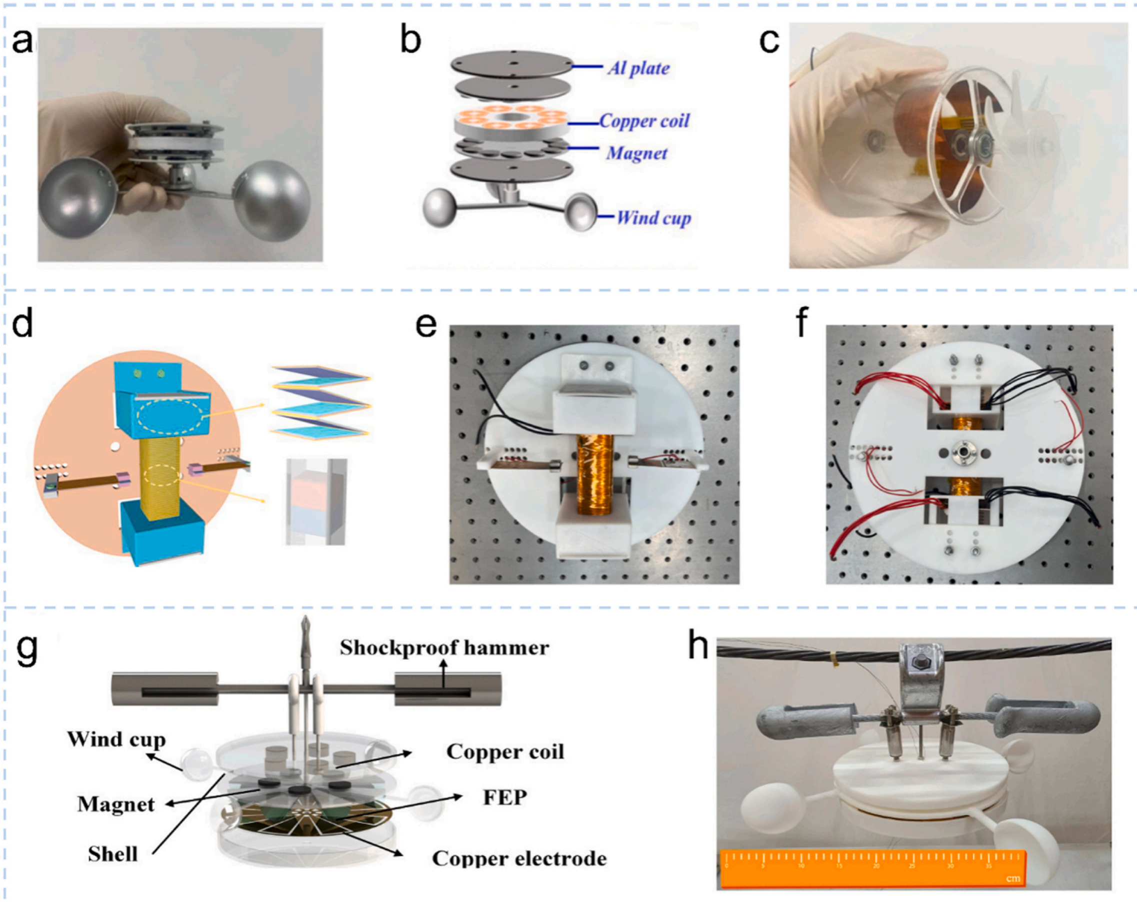

Fig. 7. (a) The real shots of the EMG. (b) Exploded view of the EMG. (c) The real shots of the FV-TENG. Reproduced with permission Elsevier [64]. (d) Schematic illustration of the THEH. (e) Front view of the prototype. (f) Back view of the prototype. Reproduced with permission Elsevier [65]. (g) Structure schematic of the WS-TEHG. (h) Physical photograph of the WS-TEHG integration. Reproduced with permission Elsevier [63].

maximize energy output from low-frequency movements. This hybrid design enables efficient energy harvesting, especially for low-speed rotational applications such as wind turbines.

Prof. Gao's team introduced a wind-driven suspended triboelectric-electromagnetic hybrid generator (WS-TEHG) designed for environmental monitoring in high-voltage power transmission lines. Fig. 7(g) outlines the WS-TEHG's three-layer integrated design, where the middle rotor disc, equipped with four wind cups, is sandwiched between the upper and lower stator discs. The rotor's wind-driven motion generates energy through both triboelectric and electromagnetic mechanisms. Fig. 7(h) presents a physical image of the WS-TEHG, highlighting the integration of the rotor, stator, and wind cups connected via a central shaft to ensure smooth rotation and stable operation in suspended environments. This innovative design simultaneously harvests wind energy and mitigates vibrations in power transmission lines.

Rotating disc hybrid generators are particularly effective at harvesting energy from wind and other rotational sources due to their ability to maximize energy conversion from continuous motion. However, several factors can impact their energy output, including mechanical wear, environmental conditions, and the alignment of moving components. Mechanical abrasion between TENG surfaces can degrade performance over time, while external factors like wind variability can affect energy generation consistency. Future research should focus on improving material durability and optimizing designs to ensure reliable performance across diverse operational contexts.

3.2.2. Drum-type hybrid devices

Drum-type hybrid generators are designed to capture energy from rotational movements, using a cylindrical structure that incorporates both electromagnetic generation (EMG) and triboelectric nanogeneration (TENG) mechanisms. This hybrid design efficiently converts mechanical motion into electrical energy, making it advantageous for applications such as wind energy harvesting and ocean wave energy capture. The cylindrical form allows for continuous rotation and maximizes the contact area for triboelectric effects, enhancing overall energy output.

One prominent example is the flexible-contact electromagnetic-triboelectric hybrid nanogenerator (EMG-TENG) developed by Prof. Zhao's team for rotational energy harvesting and speed monitoring of downhole motors. This innovative device integrates an EMG with a rotating triboelectric nanogenerator (R-TENG) to maximize energy collection efficiency. The EMG and R-TENG were structurally optimized, achieving maximum voltages of 14.8 V and 230 V, respectively, demonstrating strong charging performance, capable of powering small electronic devices like a Bluetooth thermo-hygrometer. Fig. 8(a) shows the side structure, with the rotor and stator connected via bearings to ensure stable rotation. Fig. 8(b) presents the internal structure, featuring coils within the stator and magnets attached to the rotor for EMG, alongside PVDF blades and copper electrodes for R-TENG. Fig. 8(c) provides a physical view of the hybrid nanogenerator, where sponge blocks minimize the distance between magnets and coils, improving energy conversion. This system efficiently collects rotational energy and serves as a self-powered sensor for downhole motor speed monitoring, with an error rate below 2 %, offering a promising solution for sustainable energy harvesting in complex environments.

Another example is the triple-mode hybrid generator (TMHG)

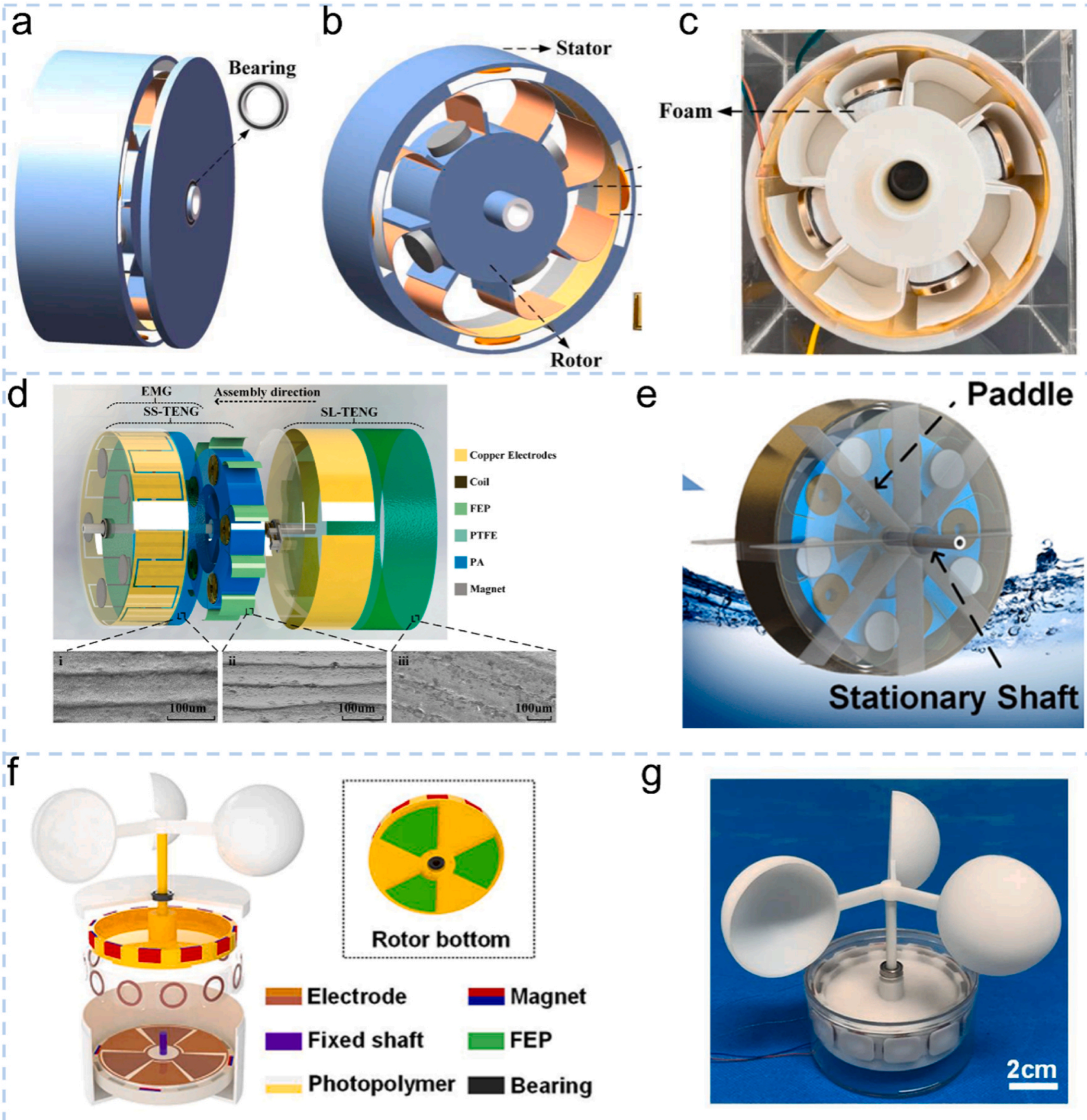

Fig. 8. (a) Hybrid nanogenerator side structure. (b) Hybrid nanogenerator internal structure. (c) The physical structure of the hybrid nanogenerator. Reproduced with permission Elsevier [89]. (d) Detailed structure schematic of the TMHG, including SS-TENG, SL-TENG and EMG. (e) The TMHG structure. Reproduced with permission Elsevier [90]. (f) Exploded view of the AMT-TEHG (The inset shows the arrangement of the FEP films). (g) A picture of the AMT-TEHG prototype. Reproduced with permission Elsevier [61].

proposed by Prof. Gao's team. It integrates solid-solid TENG (SS-TENG), solid-liquid TENG (SL-TENG), and EMG for efficient water flow energy harvesting and water quality monitoring. This hybrid system leverages the strengths of each mode to enhance overall energy conversion efficiency. Fig. 8(d) illustrates the TMHG's waterwheel-based design, which integrates SS-TENG, SL-TENG, and EMG in a compact space to maximize energy capture from water flow. The waterwheel rotates as water flows, driving energy conversion through the various generator modules. Fig. 8(e) provides an overview of the TMHG's setup in a water flow environment, showing its integration with floating platforms and stabilizing anchors to ensure continuous operation on the river surface, improving space utilization and ensuring stable energy collection in natural water conditions.

Additionally, Prof. Wang's team developed a robust triboelectric-electromagnetic hybrid nanogenerator (TEHG) with maglev-enabled automatic mode transition (AMT) to efficiently harvest breeze energy. The design uses a maglev mechanism to automatically switch between intermittent-contact (IC) and non-contact (NC) working modes, significantly reducing material wear and improving durability. Fig. 8(f) shows the AMT-TEHG's basic structure, where the rotor, comprising magnets and FEP films, is mounted within a stator housing pick-up coils and magnets. This structure allows the rotor to oscillate vertically under magnetic levitation, facilitating energy conversion. Fig. 8(g) presents the fabricated TEHG prototype, which is compact, making it portable and easy to integrate with other electronics. This hybrid nanogenerator efficiently harvests energy from breezes as low as 2.4 m/s and serves as a self-sufficient wind speed sensor, demonstrating excellent performance in both energy harvesting and environmental monitoring.

In summary, drum-type hybrid generators are well-suited for harvesting energy from wind and ocean waves due to their ability to efficiently convert rotational motion into electrical energy. These devices excel in capturing predictable, continuous motion, making them advantageous for renewable energy applications. However, several factors, such as mechanical wear, environmental conditions, and component alignment, influence energy output. Wear on TENG surfaces due to constant contact can degrade performance, while external factors like humidity and temperature can affect energy generation consistency. Future research should focus on improving material durability, optimizing designs, and ensuring reliable performance across various operational conditions.

Rotational motion devices excel in high-speed, continuous motion environments, such as wind turbines and industrial machinery. Their consistent motion allows for higher energy output compared to other modes. However, these devices face challenges such as wear on triboelectric surfaces due to continuous rotation and the need to operate within an optimal speed range. Performance may drop significantly at low speeds, and excessive wear at high speeds can shorten device lifespan.

3.3. Recent developments of rotational motion devices

Advancements in hybrid EMG-TENG systems for rotational motion devices have significantly improved both their performance and efficiency. Technological innovations have focused on enhancing the ability of these devices to convert rotational kinetic energy into electrical energy for various applications, ranging from industrial machinery to consumer electronics. Notable improvements include the development of high-efficiency generators through the use of novel magnetic materials, which provide higher flux densities and reduce eddy current losses. Recent developments in rotational motion devices have focused on both material and design innovations to enhance energy harvesting performance. For example, advanced rare-earth magnetic materials such as NdFeB have been employed in EMGs, providing higher magnetic flux densities and reducing eddy current losses. These improvements significantly enhance energy conversion efficiency, especially in low-speed environments. Meanwhile, micro-structured triboelectric materials, such as patterned polytetrafluoroethylene (PTFE) films, have been integrated into TENGs, increasing surface contact area and improving charge transfer efficiency. In terms of design, dual-layered rotating discs have been introduced to minimize mechanical wear and distribute rotational forces evenly, extending device lifespan and reliability. Additionally, the structuring of these materials at the micro and nanoscale has expanded the contact area, enhancing triboelectric effects. Hybrid system integration has also progressed, with EMG and TENG technologies being seamlessly combined into compact units that capture more energy from rotational motion while allowing for modular, scalable designs. Notably, devices have been developed to harvest energy from low-speed rotational movements, a critical advancement for renewable energy applications like wind and hydro turbines.

The incorporation of smart and autonomous systems has further transformed rotational motion devices, enabling real-time data processing and IoT connectivity. Modern devices are equipped with sensors that allow for real-time monitoring and control, autonomously adjusting parameters to optimize energy harvesting. Machine learning and predictive analytics have improved predictive maintenance capabilities, allowing these devices to predict maintenance needs and potential failures before they occur, thus reducing downtime and extending device lifespan. Integrated energy management systems help store and distribute harvested energy, which is essential for grid integration, especially in managing intermittent renewable energy sources. These technological innovations not only increase the energy harvesting capabilities of rotational devices but also enhance their overall functionality and efficiency, expanding their potential applications and supporting the global transition to sustainable energy solutions.

3.4. Applications of rotational motion devices

Rotational Motion Devices are integral to numerous industries due to their ability to efficiently convert kinetic energy from rotational movements into electrical energy. Their applications span sectors such as renewable energy, automotive, industrial automation, consumer electronics, and smart cities. In renewable energy, these devices are essential in wind turbines, where they capture kinetic energy from wind to generate electricity, and in hydroelectric plants, where they convert the motion of water turbines into electrical power. Technological advancements in turbine and blade design have maximized energy capture even at varying wind speeds. Similarly, in the automotive industry, rotational motion devices are used in regenerative braking systems, converting kinetic energy from braking into electrical energy, thus improving energy efficiency and extending electric vehicle range. Automotive alternators, another application, charge the vehicle's battery and power the electrical system, contributing to better fuel efficiency and lower emissions through more compact and efficient designs.

Environmental conditions critically influence the performance and lifespan of rotational motion devices. For instance, temperature fluctuations can cause thermal expansion or contraction of rotating components, leading to misalignment or increased mechanical wear over time. High humidity levels, often present in outdoor applications, can degrade triboelectric materials, reducing their ability to generate charges effectively. To mitigate these challenges, advanced polymer coatings with hydrophobic properties have been developed to prevent moisture infiltration, while heat-resistant composites are employed to maintain structural stability under fluctuating temperatures. Furthermore, dust and particulate accumulation on rotating parts in industrial settings can obstruct motion and reduce efficiency, necessitating the inclusion of self-cleaning surface designs or protective enclosures.

In industrial automation, these devices are employed in conveyor belt systems to generate energy from belt movements, which powers integrated sensors and controls, enhancing overall automation and efficiency. They are also used in rotating machinery to harvest energy for powering monitoring devices that track performance and predict maintenance needs. Consumer electronics benefit from the miniaturization of rotational motion devices, particularly in wearable technology like smartwatches, where they harvest energy from human motion, reducing the need for frequent recharging. Portable electronics also utilize these devices for sustainable power through user interaction, such as shaking or spinning the device. In the context of smart cities and infrastructure, rotational motion devices are incorporated into energy-harvesting tiles in urban environments, converting pedestrian foot traffic into electricity to power street lights and signage. They are also used in public transport systems, where they capture energy from wheel rotations to power internal systems, contributing to more sustainable urban transportation. The growing applications of these devices highlight their versatility and increasing importance in energy-efficient technologies as they continue to evolve and integrate into more complex systems. Rotational motion devices in hybrid EMG-TENG systems is in Fig. 9.

4. Hybrid generators based on vibration motion

4.1. Kinematic structure and energy absorption methods for Vibration Motion

Vibration-based energy harvesting devices are specifically designed to capture energy from irregular or periodic oscillations [91]. Vibration-based motion kinematic illustration is in Fig. 10. These devices are particularly effective in environments where vibrations are common, such as machinery operations or natural oscillations caused by ocean waves [92]. In hybrid EMG-TENG systems, vibration energy harvesters typically integrate electromagnetic generators (EMG) and triboelectric nanogenerators (TENG), working in tandem to convert mechanical vibrations into electrical energy [93].

The focus of these devices is on adapting to the unpredictable characteristics of vibrations, ensuring efficient energy capture despite variations in frequency and intensity [94]. The electromagnetic component generates electricity through changes in the magnetic field, while the triboelectric component produces charges through contact and separation events caused by the vibrations [95]. As a result, these

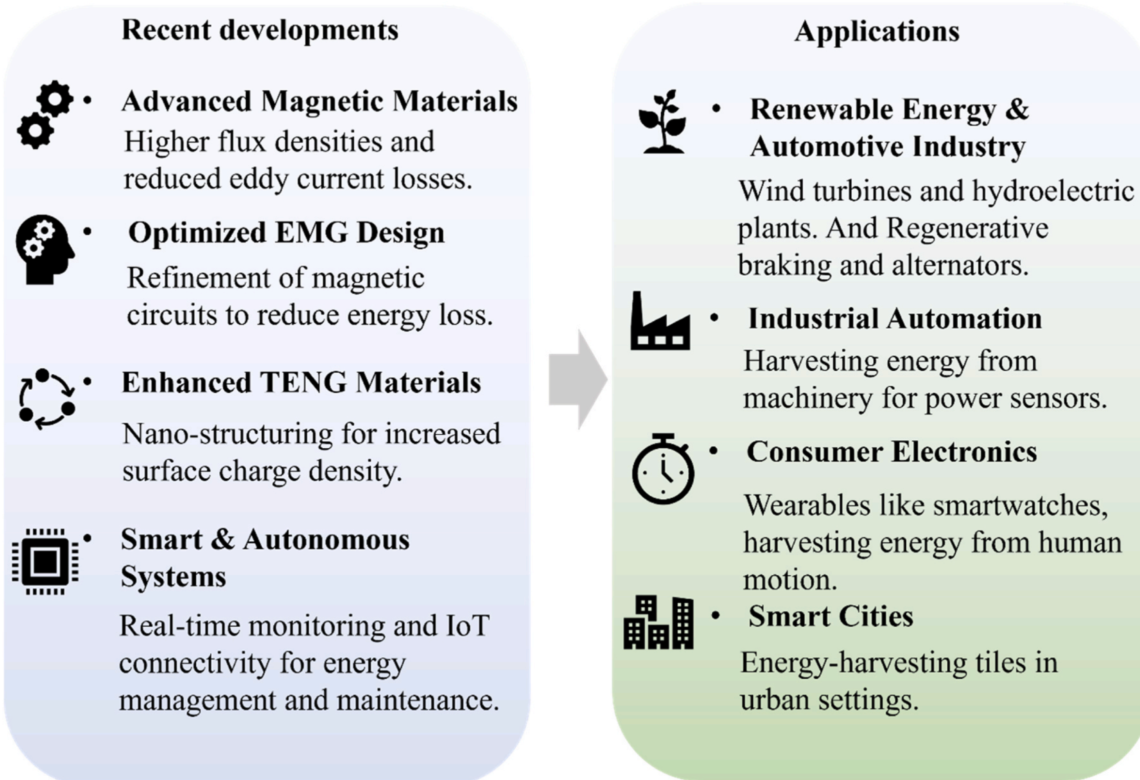

Fig. 9. Rotational motion devices in hybrid EMG-TENG systems.

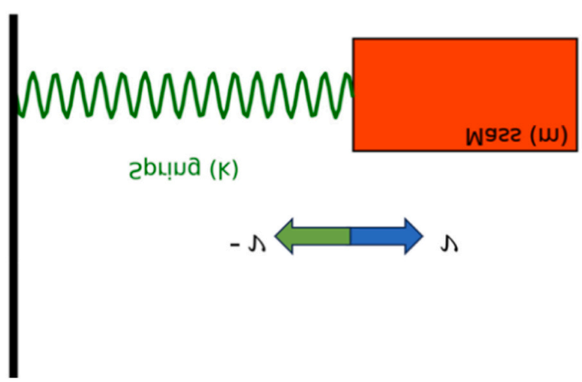

Fig. 10. Vibration-based motion kinematic illustration.

devices excel in environments with fluctuating vibration amplitudes or low-frequency oscillations, such as in industrial machinery or marine wave energy harvesting applications [96].

4.2. Vibration-based motion hybrid devices

4.2.1. Cantilever-based hybrid devices

Cantilever-based hybrid generators are designed to harness mechanical energy from low-frequency vibrations and oscillatory movements. These systems typically feature a cantilever structure that integrates triboelectric nanogenerators (TENG) and electromagnetic generators (EMG), allowing them to effectively convert energy from various mechanical sources. The cantilever's flexible design responds to external forces, enabling the device to capture energy across a range of applications, from marine settings to industrial environments.

A notable example is Prof. He's non-resonant hybrid electromagnetic-triboelectric nanogenerator (EMG-TENG), developed to efficiently harvest irregular and ultralow-frequency energy from sources such as ocean waves. This device incorporates a flexible pendulum structure to capture multidirectional vibrations, combining electromagnetic and triboelectric principles for enhanced energy conversion. Fig. 11(a) shows the device's schematic, highlighting key components like the NdFeB magnet, coils, springs, and multiple TENG units, which enable free oscillation and energy generation from multidirectional motion. Fig. 11(b) illustrates the pendulum's swing trajectory, showing how the magnet oscillates around a pivot, driving both triboelectric and electromagnetic generation, with power output reaching 523 mW, demonstrating its potential for large-scale marine energy applications.

Similarly, Prof. Kim's team developed a buoy-inspired hybrid energy harvester featuring a freestanding dielectric oscillator (FDO) for sustainable blue energy harvesting. This design integrates a magnetic-levitated TENG (ML-TENG) and an EMG to optimize energy collection. Fig. 11(c) depicts the key components, including the floating buoy structure, aluminum electrodes, copper windings, and the levitated FDO. The FDO minimizes friction, enabling smooth oscillations that generate both triboelectric and electromagnetic energy. This hybrid design efficiently captures wave-induced mechanical energy with minimal energy losses from friction.

In summary, cantilever-based hybrid generators are well-suited for harvesting energy from wave-induced vibrations and other mechanical motions, thanks to their ability to convert low-frequency vibrations into electrical energy. Their unique design allows them to perform effectively in challenging environments like oceans, where irregular motion is prevalent. However, factors such as mechanical wear, environmental conditions, and material fatigue in TENG components can affect performance over time. External factors like humidity and temperature fluctuations can also impact energy harvesting efficiency. Future advancements should focus on improving material durability and optimizing designs to maintain consistent performance across various applications.

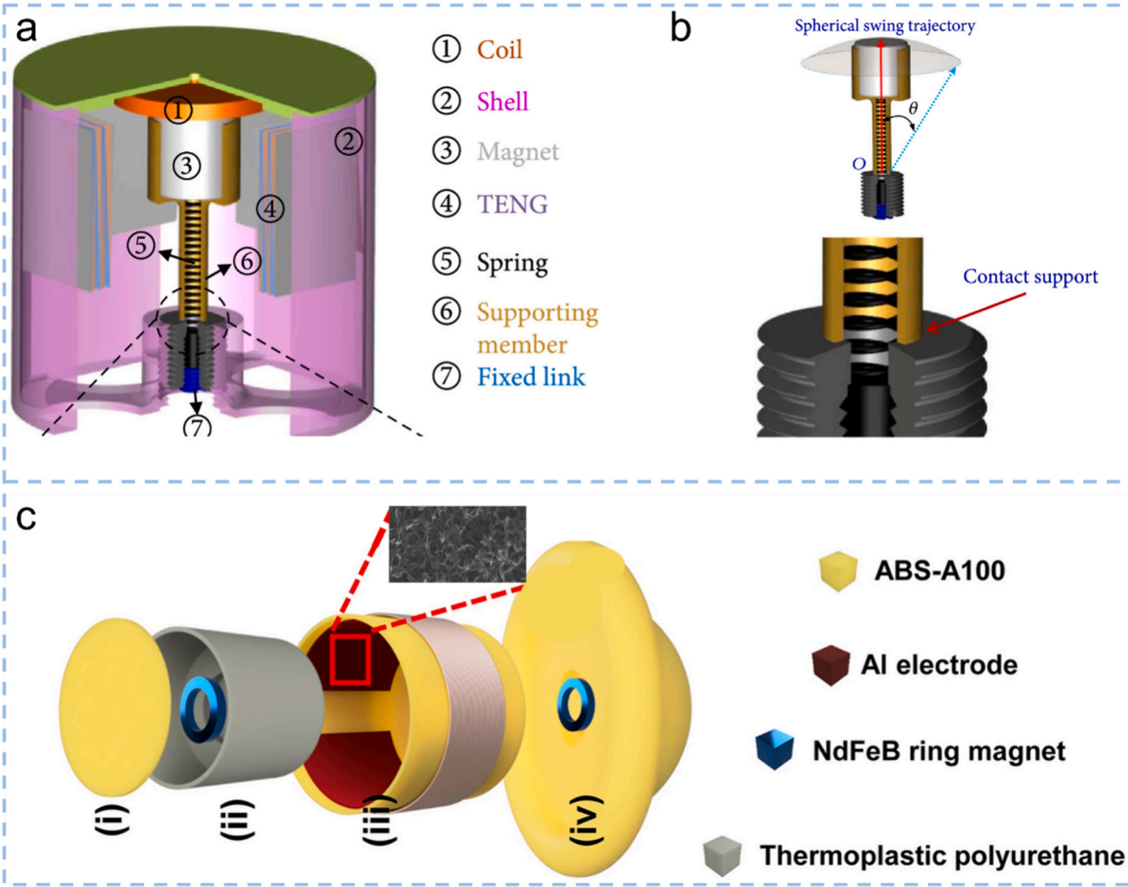

Fig. 11. (a) the schematic diagram of the device. (b) swing track diagram and contact support. Reproduced with permission Research. [45] (c) Schematic illustration for the blue energy harvesting device (ML-BEHD) composed of (i) lid of the container, (ii) freestanding dielectric oscillator (FDO) and ring magnet, (iii) container with two Al electrodes and 500 turns of copper windings, and (iv) floating buoy, respectively. Reproduced with permission springer. [97].

4.2.2. *Spring-mass system hybrid devices*

Spring-mass system hybrid generators are designed to capture energy from oscillatory motions, such as vibrations and shocks, using a mass-spring mechanism. These systems integrate both triboelectric and electromagnetic technologies, making them highly effective for converting mechanical energy into electrical power. Their versatility makes them suitable for applications ranging from portable electronics to structural health monitoring.

Prof. Ouyang's team developed a self-powered accelerometer with over-range detection, combining a freestanding triboelectric-layer TENG (FT-TENG), two contact-separation TENGs (CS-TENGs), and an EMG to monitor vibration and shock. Fig. 12(a) details the device's components, such as coils, magnets, and FEP films, while Fig. 12(b) shows the 3D view of its internal layout, including the oscillator and linear springs. Fig. 12(c) focuses on the CS-TENG structure, where movable plates and copper films detect acceleration levels beyond the measurement range. This hybrid system not only captures energy from vibrations but also provides reliable acceleration detection, ideal for structural health monitoring and wireless sensing.

Another example is a hybrid generator developed to capture vehicle suspension vibrations from random road excitations. It combines a sliding-mode TENG (S-TENG) with an EMG to maximize energy output and durability. Fig. 12(d) presents the Macpherson independent suspension system, where the hybrid generator is installed without affecting the suspension's original function. Fig. 12(e-f) details the generator's structure, featuring a slider, stator, and spring. Polyimide (PI) films and patterned Cu foils are used for TENG, while Halbach magnet arrays enhance EMG performance, ensuring efficient energy capture from diverse vibration sources.

Additionally, Prof. Djuric's team proposed a hybrid electromagnetic-triboelectric nanogenerator (EMG-TENG) for capturing energy from irregular mechanical motions. This design integrates a zig-zag contact-mode TENG, a sliding-mode TENG, and two EMGs for optimized energy output. Fig. 12(h) presents the schematic of the hybrid device, while Fig. 12(g) shows the assembled prototype, demonstrating how TENG and EMG components work together in a compact structure. This multi-mode design allows the generator to capture energy from a wide range of mechanical sources, showing its versatility for energy harvesting applications.

In conclusion, spring-mass system hybrid generators excel at harvesting energy from vibrations and shocks, thanks to their efficient conversion of oscillatory motion into electrical power. These devices are particularly suited for applications in marine environments, vehicles, and structural health monitoring. However, factors such as mechanical wear, material fatigue, and environmental conditions like humidity and temperature fluctuations can affect their performance. Future research should focus on enhancing material durability and optimizing designs to ensure reliable energy output in a variety of operational contexts.

Vibration-based devices are uniquely suited to environments with irregular, low-frequency motion, such as industrial machinery or ocean waves. However, their energy output is often less stable and lower compared to linear or rotational systems due to the sporadic nature of vibrations. Frequent contact-separation cycles in TENG components can also lead to material fatigue, further affecting long-term performance.

4.3. *Recent developments of vibration-based devices*

Recent advancements in vibration-based and nonlinear motion

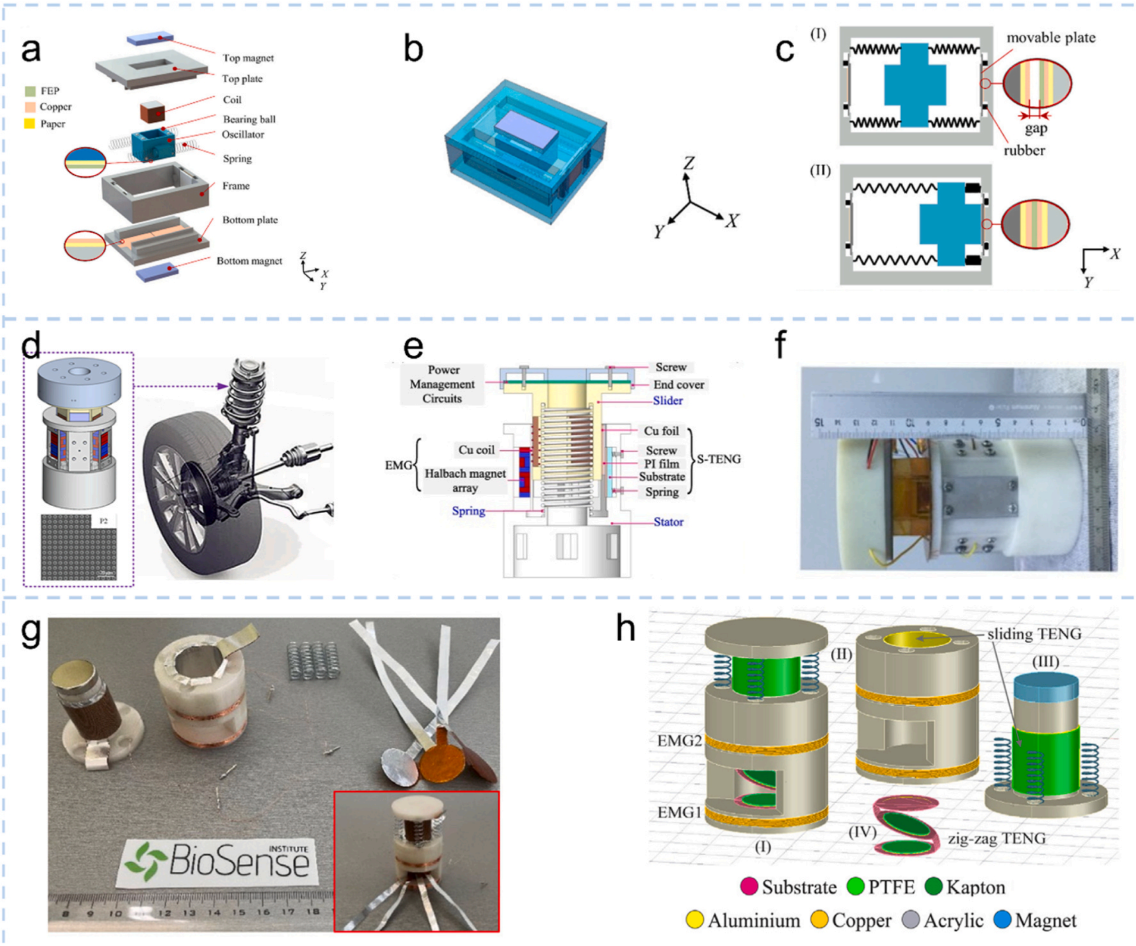

Fig. 12. (a) 3D view of the sensor. (b) Main components of the sensor. (c) The structure of the contact-separation TENGs. Reproduced with permission Elsevier [27]. (d) Hybrid generator diagram. (e) A schematic illustration of the hybrid generator alongside the assembled hybrid generator. (f) Device structure: (I) schematic illustration of a hybrid nanogenerator and its individual parts: (II) a stationary shell, (III) a moving shell, (IV) a flexible zig-zag TENG. Reproduced with permission Elsevier [67]. (g) Photograph of the individual parts assembled into a hybrid structure.(h) Photograph of the individual parts assembled into a hybrid structure. Reproduced with permission Elsevier [66].

devices, particularly in hybrid EMG-TENG systems, have significantly improved their ability to capture energy from ambient mechanical motions, including random or irregular vibrations commonly found in real-world environments [98]. One key area of progress is in material innovations, where new composite materials combining piezoelectric and triboelectric properties have been synthesized to optimize energy capture from non-linear vibrations [99]. These materials not only offer enhanced mechanical and electrical properties but also withstand diverse operational environments, allowing for more efficient energy generation from subtle movements. Material and design innovations have played a critical role in recent advancements in vibration-based devices. For instance, hybrid materials combining piezoelectric and triboelectric properties have been developed to capture energy from non-linear vibrations more effectively. Examples include piezoelectric-polydimethylsiloxane (PDMS) composites that provide high flexibility and durability under repetitive motion. In addition, freestanding dielectric oscillators (FDOs) have been designed to enhance energy absorption efficiency by minimizing mechanical friction, as demonstrated in marine wave energy applications. Furthermore, multi-modal vibration absorbers integrating spring-mass systems with magnetic levitation mechanisms have been introduced, ensuring stable operation even under irregular vibration amplitudes, thus broadening the range of potential applications [100]. Finely tuned resonant structures now amplify mechanical inputs, making it possible to harness even minimal vibrational forces. Additionally, significant strides have been made in system integration and miniaturization, enabling the combination of EMG and TENG technologies into smaller, more compact systems that are ideal for portable and wearable technologies [91]. These improvements have extended the application range of these devices, particularly in personal electronics and medical devices where space is limited.

Energy efficiency in vibration-based devices has also been a major focus, with improvements stemming from better alignment of mechanical and electrical components, as well as the use of smart materials that dynamically adapt to changes in environmental conditions and vibration profiles. These devices now convert a broader spectrum of vibrational frequencies into usable energy, increasing their overall effectiveness. There has also been a notable push toward hybrid energy systems, integrating multiple energy-harvesting technologies such as solar and vibration energy to create multifunctional devices capable of operating in various conditions without relying on external power sources. The integration of smart technologies has further expanded the capabilities of these devices. Real-time analytics and control, enabled by IoT technology, allow for adaptive energy harvesting strategies that optimize performance based on vibration data and environmental changes. Wireless connectivity and remote monitoring have also been incorporated, making these devices particularly valuable in applications like structural health monitoring in civil engineering, where devices must operate in inaccessible or hazardous environments. These developments underscore the innovative progress being made in vibration-based and nonlinear motion devices, with continuous advancements in material science, system integration, and smart technologies driving their versatility and efficiency in harnessing ambient mechanical energy.

4.4. Applications of vibration-based devices

Vibration-based and nonlinear motion devices have proven to be incredibly versatile, expanding their utility across various industries by converting ambient vibrations and nonlinear movements into usable electrical energy. In industrial settings, these devices are used for machinery health monitoring, where they detect operational vibrations and identify anomalies or failures early, enabling predictive maintenance that can save companies significant costs in downtime and repairs. They also capture vibrational energy generated as a byproduct of mechanical processes in factories, converting it into electricity to power small sensors and devices, thus contributing to more energy-efficient operations. In transportation, vibration-based devices are deployed along railway tracks to monitor the structural integrity of the tracks by detecting vibrations caused by passing trains, ensuring the safety and reliability of rail transport. Within vehicles, these devices harvest energy from engine vibrations and road bumps to power sensors that monitor vehicle health, reducing reliance on the vehicle's electrical system and improving battery life.

Environmental factors such as mechanical shocks, varying temperatures, and high humidity significantly affect the performance of vibration-based devices. For example, sudden mechanical impacts can damage sensitive components like springs or cantilever beams, reducing the energy conversion efficiency. To counter this, vibration dampers made of high-durability materials have been integrated to absorb excessive shocks while maintaining functionality. Additionally, prolonged exposure to humid conditions can degrade triboelectric layers, leading to reduced energy harvesting efficiency. Advanced moisture-resistant materials, such as modified fluoropolymers, are being developed to address this issue. Temperature extremes, whether high or low, can also affect the elasticity and structural integrity of materials, necessitating the adoption of thermally stable composites. These innovations ensure that vibration-based devices remain reliable across diverse and harsh environments.

In the field of building and structural health monitoring, vibration-based devices are integrated into the structural components of buildings and bridges to monitor vibrations and stresses, providing real-time data on the health of the infrastructure. This application is particularly valuable in earthquake-prone areas, where early detection of structural weaknesses can prevent catastrophic failures. Additionally, they are used to harvest ambient vibrations from HVAC systems and foot traffic within buildings to power environmental monitoring sensors, improving energy efficiency. In consumer electronics, self-powered wearable devices like fitness trackers and smartwatches are equipped with these energy harvesters, generating power from the wearer's movements and reducing the need for frequent recharging. Furthermore, these devices are incorporated into interactive toys and gadgets, where user actions like shaking or tapping provide the power needed for new features, making the products more engaging and eco-friendly.

These devices are also crucial in remote and inaccessible locations, powering sensors for wildlife tracking and environmental monitoring where traditional power sources are impractical. In such applications, they collect valuable data on wildlife behavior or environmental conditions without the need for battery replacement. Urban environments and smart cities also benefit from vibration-based devices, which are integrated into pavements and public spaces to generate energy from pedestrian movements. This energy can be used to light street lamps, power public Wi-Fi networks, and enhance other smart city functionalities, reducing municipal energy costs while improving urban life. The diverse applications of vibration-based and nonlinear motion devices demonstrate their potential to transform how we harness energy from our surroundings, and as technology continues to evolve, these devices will play an even more critical role in driving innovation in energy harvesting and IoT deployments. Vibration-based Motion Devices in Hybrid EMG-TENG Systems show in Fig. 13.

5. Impact of motion types on energy output

The energy output of hybrid EMG-TENG devices is significantly influenced by the type of motion they capture, whether it be linear, rotational, or vibration-based [61]. Each motion type imposes specific demands on the design and performance of the energy harvesters, leading to distinct strengths and limitations. Linear motion devices, such as tubular linear hybrid generators, perform well in stable environments like wave energy harvesting, but often yield moderate energy outputs due to challenges like mechanical wear and alignment precision. However, their simple kinematic structure makes them suitable for applications involving consistent, repetitive movements. Rotational motion devices, including rotating disc hybrid generators, are optimized for high-speed, continuous environments such as wind turbines, allowing for higher total energy output due to their ability to capture energy steadily over time. Yet, these systems face challenges such as material wear and efficiency drops outside optimal speed ranges. Vibration-based devices, like cantilever-based hybrid generators, excel at harnessing energy from irregular or low-frequency vibrations in environments like industrial machinery or ocean waves, where motion is unpredictable. However, the sporadic nature of these vibrations limits their maximum energy output compared to rotational devices.

5.1. Energy efficiency and performance optimization

The energy efficiency of hybrid EMG-TENG devices is heavily influenced by the type of motion they harness and the specific kinematic structures used [101–114]. Rotational motion devices generally exhibit the highest energy efficiency, as they continuously capture kinetic energy from steady sources like wind or machinery. This steady flow of energy allows rotational devices to achieve consistent and reliable output. The rotating disc hybrid generator, for example, operates efficiently in environments with sustained high-speed motion, such as in wind turbines, where the rotational movement is constant. The efficiency of these systems is often enhanced by the use of optimized electromagnetic generators (EMGs), which capitalize on the continuous relative motion between magnets and coils. This enables rotational devices to maintain high output even over extended periods of operation. However, despite their inherent efficiency, rotational systems are sensitive to wear and tear due to constant motion, and their efficiency can drop significantly if operating outside of their optimal speed range. Therefore, optimizing the materials used in the construction of these systems to withstand continuous wear, as well as developing designs that can maintain high efficiency across a broader range of speeds, will be key areas for future research.

Linear motion devices, such as tubular linear hybrid generators, also provide stable energy capture, particularly in controlled environments like wave energy harvesting systems. Their efficiency, however, is often compromised by factors such as mechanical alignment issues and environmental conditions. In many cases, the precise alignment of components, such as the rails or guides used to direct motion, is critical to achieving high energy output. Misalignment or wear over time can cause significant losses in efficiency. Moreover, in marine environments, where these systems are often deployed, external factors such as saltwater corrosion and temperature fluctuations can further reduce their performance. Enhancing the durability of the materials used, especially in harsh conditions, and developing self-correcting alignment mechanisms could help improve their long-term energy efficiency. Additionally, the integration of more advanced triboelectric nanogenerators (TENGs) with linear motion systems could further boost their energy conversion rates, as TENGs can efficiently capture energy from even

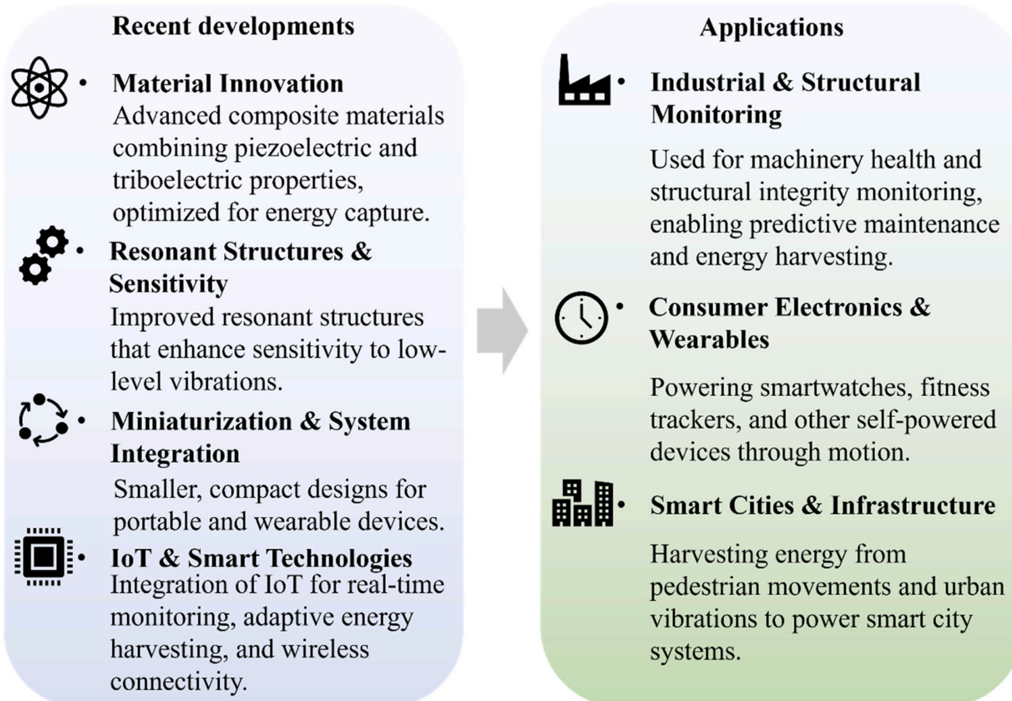

Fig. 13. Vibration-based motion devices in hybrid EMG-TENG systems.

small mechanical movements, which are common in fluctuating wave environments.

Vibration-based systems are typically less efficient in terms of total energy output when compared to rotational or linear systems, mainly because they are designed to capture energy from irregular, low-frequency vibrations. However, these systems offer unique advantages in environments where sporadic or unpredictable motion is common, such as in industrial machinery or natural settings like ocean waves. Cantilever-based hybrid generators, for example, are particularly adept at harnessing energy from low-frequency vibrations, making them ideal for applications where other motion types are less effective. While vibration-based systems may not achieve the same high energy outputs as rotational systems, they compensate for this by being highly adaptable to a variety of environments. One of the key challenges for improving the efficiency of vibration-based devices lies in increasing their sensitivity to low-frequency vibrations without sacrificing durability. The contact-separation mechanisms used in TENGs within these systems can degrade over time due to constant friction, reducing the overall lifespan of the device. Future innovations could focus on the development of wear-resistant materials or self-healing surfaces that can prolong the operational lifespan of vibration-based systems while maintaining high energy efficiency.

Another critical factor influencing energy efficiency across all motion types is the integration of energy storage systems. Hybrid devices are often deployed in environments where energy capture is intermittent, such as in wave energy systems or environments with fluctuating winds. By integrating advanced energy storage technologies, such as supercapacitors or advanced batteries, hybrid EMG-TENG systems can store excess energy generated during peak motion periods and release it during periods of inactivity. This ensures a more consistent energy supply, even when the motion source is irregular. For example, in rotational systems used in wind turbines, energy storage could help smooth out the power supply during periods of low wind speeds. In vibration-based systems, energy storage would allow these devices to collect energy during sporadic vibration events and provide a continuous output over time.

Optimizing the kinematic structures of these devices also plays a critical role in enhancing their performance. For example, in linear motion systems, reducing friction between moving parts and ensuring precise alignment can significantly improve energy capture efficiency. In rotational systems, optimizing the geometry of the rotating components to minimize air resistance and friction can lead to higher energy outputs. In vibration-based systems, adjusting the mass and stiffness of the cantilever or spring components can make the devices more sensitive to a broader range of vibration frequencies, increasing their ability to capture energy from varying motion sources.

In conclusion, improving the energy efficiency of hybrid EMG-TENG systems requires a multifaceted approach that considers the specific challenges of each motion type. For rotational systems, extending the operational range and enhancing material durability will be key to maintaining high efficiency. For linear motion devices, advancements in material science and alignment technologies will be essential. For vibration-based systems, increasing sensitivity to low-frequency vibrations and integrating durable, wear-resistant materials will help maximize energy capture. Across all motion types, the integration of advanced energy storage solutions will ensure that these devices can provide consistent energy output, even in fluctuating conditions. By addressing these specific challenges, hybrid EMG-TENG systems can be optimized for a wide range of applications, from renewable energy harvesting to industrial monitorin. Different types of power generation output is in Table 1.

5.2. Energy absorption techniques and kinematic structure

The efficiency of hybrid EMG-TENG devices largely depends on the energy absorption techniques and the specific kinematic structures used in each system. These elements directly influence how effectively mechanical motion can be converted into electrical energy, as well as the long-term performance and durability of the devices. The energy absorption process varies significantly across different motion types, such as linear, rotational, and vibration-based movements, and optimizing this process is essential for maximizing energy output.

Linear motion devices typically rely on systems that involve direct, reciprocating movement. Tubular linear hybrid generators, for instance,

Table 1
Different types of power generation output.

Mode	Generator Type	Reference	Major material	Power source	Output	Applications
EMG TENG	Vibration Motion	[45]	FEP Cu Coil Spring Magnet	Wave	523.47 mw	Ocean energy harvesting
EMG TENG	Vibration Motion	[97]	Magnet ABS-A100 Al	Wave	560 mW/m3	Ocean energy harvesting
EMG TENG	Rotational Motion	[61]	FEP Magnet Coil Bearing	Wind	750 mW/kg	Harvesting wind energy
EMG TENG	Rotational Motion	[90]	Coil FEP PTFE PA Magnet	Water flow	17.49mw	River monitoring
EMG TENG	Linear Motion	[72]	Coils Iron core Teflon layer	Wave	76.7 mW	Ocean buoy power supply
EMG TENG	Rotational Motion	[64]	Al Coil Magnet	Wind	12.75 mW	Harvesting wind energy
EMG TENG	Vibration Motion	[27]	FEP Copper Coil Spring Magnet	vibration-based	443.8 W/m^3	Accelerometers
EMG TENG	Vibration Motion	[67]	Spring Cu coil Screw Pifilm	vibration-based	40.63uw/g	Car suspension energy harvesting
EMG TENG	Linear Motion	[75]	PTFE PM ball Cu coil Al	Wave	$162Wm^{-3}$	Ocean buoy power supply
EMG TENG	Linear Motion	[68]	PMMA PTFE Cu Coil Magnet PLA	Wind Sun	8mw	Harvesting wind and solar energy
EMG TENG	Rotational Motion	[86]	Al Cu Coil PDMS FPCB PU	Wind	6.02mw/cm3	Monitoring sensor
EMG TENG	Rotational Motion	[87]	FEP ABS Cu Coil Magnet	Wind	16.4 mW	Smart sensor
EMG TENG	Linear Motion	[69]	PMMA Magnet Coil Kapton Steel rod	Mechanical motion	125uW	Human motion monitoring sensors

utilize a combination of electromagnetic induction and triboelectric effects to convert energy from linear motion into electricity. In these devices, the motion of magnets through coils induces an electrical current in the EMG component, while the movement of triboelectric materials in contact-separation cycles generates charges through the TENG. The efficiency of these systems is influenced by several factors, including the alignment of moving parts, the consistency of the linear motion, and the surface properties of the triboelectric materials. If the alignment is even slightly off, or if the contact-separation process is impeded by friction or wear, the overall energy absorption and output can be significantly reduced. Additionally, the surface roughness, material durability, and environmental factors like humidity and temperature can influence the triboelectric effect, further affecting energy absorption. Therefore, optimizing the contact-separation dynamics and ensuring precise alignment of components is key to enhancing energy efficiency in linear motion devices.

Rotational motion devices, such as rotating disc hybrid generators, utilize rotational kinetic energy to drive energy absorption through both electromagnetic induction and triboelectric effects. The rotating components, such as discs or drums, interact with stationary coils and triboelectric surfaces to generate electricity. The continuous nature of rotational motion provides a more consistent energy source compared to linear or vibration-based systems, which often deal with more intermittent movements. The primary energy absorption technique in rotational systems involves the relative motion between magnets and coils in the EMG, which induces a current as the magnetic field changes with rotation. The triboelectric effect, on the other hand, is generated through the contact-separation cycle between rotating surfaces.

One of the key challenges in these systems is maintaining high efficiency across a range of rotational speeds. Rotational devices are typically optimized for a specific speed range, and when operated outside this range, energy absorption efficiency can drop dramatically. At lower speeds, the rate of contact-separation events in the TENG decreases, and the electromagnetic induction becomes less effective due to slower changes in the magnetic field. At higher speeds, wear and tear on moving parts, particularly on triboelectric surfaces, can reduce the lifespan of the device and decrease its energy output over time. Enhancing the durability of these components, as well as developing systems that can operate efficiently across a broader range of speeds, will be crucial for improving the performance of rotational hybrid devices.

Vibration-based devices, such as cantilever-based hybrid generators, rely on the oscillatory motion of components to absorb energy from vibrations. These systems typically include a cantilever beam or a spring-mass system that responds to external vibrations by moving back and forth. The energy absorption technique in these systems involves converting the mechanical energy from oscillations into electrical energy via electromagnetic induction and the triboelectric effect. In the EMG, the relative motion between a magnet and a coil generates an electrical current, while in the TENG, the periodic contact and separation of triboelectric materials generate charges.

Vibration-based devices are particularly well-suited for environments with irregular or unpredictable motion, such as industrial machinery or ocean waves. However, their energy absorption efficiency is often lower than that of linear or rotational systems due to the sporadic nature of the motion they capture. The key to optimizing the energy absorption in vibration-based devices lies in maximizing the sensitivity of the system to low-frequency vibrations while maintaining durability. The frequency and amplitude of the vibrations directly influence the energy output, so tuning the mechanical properties of the cantilever or spring-mass system to resonate with the natural frequency of the vibrations can significantly enhance energy capture. Additionally, the use of more durable materials that can withstand repeated contact-separation cycles in the TENG will help improve the long-term performance of these devices.

Contact-separation mechanisms in triboelectric nanogenerators play a critical role in the energy absorption process across all motion types. These mechanisms rely on the transfer of charges between two surfaces that come into contact and then separate. The efficiency of this process depends on several factors, including the material properties of the surfaces, the size of the contact area, and the force applied during contact. Larger contact areas generally result in higher energy absorption because they allow for more charge transfer during each contact-separation event. However, this also increases the potential for wear and tear, which can reduce the efficiency of the system over time. Developing materials that are both highly efficient at charge transfer and resistant to wear will be essential for improving the performance of TENGs in hybrid devices.

In contrast, electromagnetic generators (EMGs) absorb energy through the relative motion between magnets and coils, which induces an electrical current via electromagnetic induction. This method is generally more durable than contact-separation mechanisms because it does not involve direct physical contact between components, reducing the potential for wear and tear. However, the efficiency of EMGs is still influenced by factors such as the strength of the magnetic field, the speed of relative motion, and the distance between the magnets and the coils. In rotational systems, for example, optimizing the positioning of the magnets and coils to maximize the change in the magnetic field during each rotation is key to improving energy absorption efficiency.

In summary, optimizing the energy absorption techniques and kinematic structures in hybrid EMG-TENG devices is essential for improving their overall performance. Linear motion systems benefit from precise alignment and minimal friction, while rotational systems need to maintain efficiency across varying speeds. Vibration-based devices require enhanced sensitivity to low-frequency vibrations and durable materials to withstand repeated motion. By refining these mechanisms and structures, hybrid energy harvesting systems can achieve higher energy outputs and longer operational lifespans across a range of applications. The Energy Efficiency and Challenges Analysis is in Table 2.

5.3. Challenges and future research directions by motion type

Hybrid EMG-TENG systems are a promising technology for energy harvesting across various motion types, including linear, rotational, and vibration-based motion. However, each motion type presents unique challenges that can affect the efficiency, durability, and scalability of these systems. Addressing these challenges is essential for improving the performance and broadening the application of hybrid energy harvesters.

Linear motion devices, such as tubular linear hybrid generators, face several key challenges, primarily related to mechanical wear, environmental exposure, and alignment precision. These devices often operate in harsh environments, such as marine settings, where they are subject to constant mechanical stress from ocean waves or industrial machines. Continuous operation in these conditions can lead to significant wear and tear, reducing both the efficiency and lifespan of the devices. For instance, the friction between moving parts in the triboelectric components can degrade the surfaces over time, leading to reduced charge generation and energy output. Furthermore, alignment precision is critical for ensuring optimal energy capture in linear motion systems. Any misalignment between moving components, such as rails or sliders, can introduce frictional losses and reduce the overall energy conversion efficiency.

Another major challenge is environmental exposure, particularly in outdoor or marine environments where devices are exposed to saltwater, humidity, temperature fluctuations, and other corrosive elements. These conditions can degrade both the materials used in the energy harvesters and the sensitive electronics required for energy conversion and storage. For instance, saltwater can corrode metal parts, and temperature variations can cause materials to expand and contract, leading to mechanical failure over time. Maintaining the integrity of the devices in these environments requires the development of materials that are both corrosion-resistant and durable enough to withstand continuous operation.

Table 2
Energy efficiency and challenges analysis.

Device Type	Energy Efficiency Characteristics	Suitable Environment	Challenges Impacting Energy Output
Linear Motion Devices	Moderate efficiency, suitable for stable wave energy collection	Marine environments, stable linear motion	Alignment precision, mechanical wear
Rotational Motion Devices	High efficiency, suitable for continuous wind or rotating machinery	High-speed environments, such as wind turbines	Mechanical wear, alignment issues
Vibration-based Devices	Excellent at capturing irregular low-frequency vibrations	Industrial environments, vehicle applications	Unstable energy output

Future research in linear motion devices will need to focus on several key areas to overcome these challenges. One promising direction is the development of advanced materials, such as self-healing composites or nano-enhanced coatings, that can resist wear and environmental degradation. These materials would extend the operational lifespan of the devices and reduce maintenance costs. Additionally, improving the alignment and calibration of linear motion devices will be critical for optimizing energy conversion efficiency. The use of smart sensors and real-time feedback systems could help maintain precise alignment even in dynamic environments, ensuring consistent performance. Finally, innovations in device modularity could allow for easier maintenance and scalability. By designing devices with interchangeable parts, components that experience the most wear could be replaced without the need to replace the entire system, improving both longevity and cost-efficiency. Future Research Dirertions show in Fig. 14.

Rotational motion devices, such as rotating disc hybrid generators, are highly effective at capturing energy from continuous, high-speed rotational motion, but they face their own set of challenges, particularly related to material durability and speed optimization. The constant rotation in these devices can cause significant wear on moving parts, especially in the triboelectric components where surfaces repeatedly come into contact and separate. Over time, this wear can reduce the energy capture efficiency and shorten the lifespan of the device. Additionally, many rotational devices are optimized for a specific range of rotational speeds. Outside this range—either at very high or low speeds—energy capture efficiency can drop significantly. For example, at lower speeds, the relative motion between magnets and coils in the EMG may not generate sufficient current, while at higher speeds, increased wear and heat generation can negatively impact performance.

Another challenge with rotational motion devices is the integration of these systems into existing infrastructure. The complexity of the mechanical and electrical components often makes installation and maintenance costly and technically demanding. For instance, aligning the rotating parts with the stationary coils and ensuring that the magnetic field changes optimally during each rotation requires precision engineering. Any misalignment can lead to inefficiencies in energy conversion or even mechanical failure. Furthermore, ensuring that these systems remain operational in fluctuating environmental conditions, such as varying wind speeds in wind turbine applications, adds another layer of complexity.

Future research in rotational motion devices should focus on several key areas. First, the development of more durable materials for triboelectric components is essential for reducing wear and extending the lifespan of these devices. Materials such as high-strength polymers or coatings that reduce friction could help mitigate the impact of constant motion. Additionally, researchers could explore ways to optimize energy capture across a broader range of rotational speeds, such as through the use of adaptive designs that can adjust to different speed conditions. This could involve integrating advanced magnetic materials that generate stronger electromagnetic fields, allowing for more efficient energy capture even at lower speeds. The incorporation of IoT and smart monitoring technologies could also improve the maintenance and integration of these devices by providing real-time data on performance and enabling predictive maintenance strategies. Finally, future designs should aim to simplify the mechanical and electrical integration of rotational devices, reducing installation costs and making these systems more accessible for widespread use.

Vibration-based devices, including cantilever-based hybrid generators, offer significant potential for capturing energy from irregular and low-frequency motion, but they face unique challenges related to energy output consistency, material wear, and system integration. One of the primary limitations of vibration-based devices is their relatively low energy output compared to linear or rotational systems. This is largely due to the intermittent and often unpredictable nature of the vibrations they capture. While these devices are effective at harnessing energy from

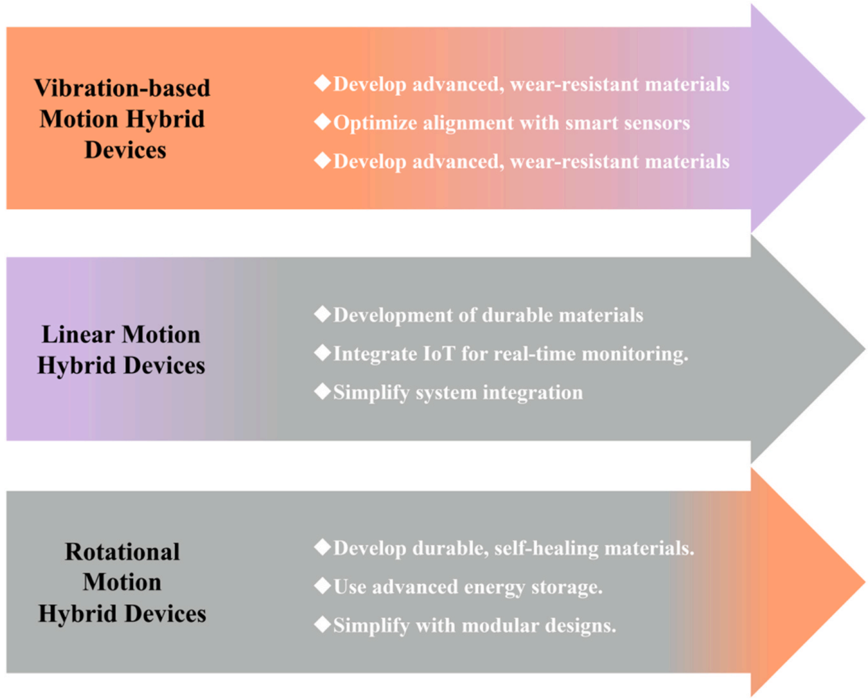

Fig. 14. Future research dirertions by Motion Type.

sporadic movements, such as those found in industrial machinery or natural environments like ocean waves, they may not provide a consistent power supply, limiting their application in environments that require steady energy output.

Another significant challenge for vibration-based systems is the durability of materials in the triboelectric nanogenerators (TENGs). The frequent contact and separation cycles between the surfaces in TENGs lead to gradual material degradation, which reduces the system's ability to capture energy over time. This wear is especially problematic in harsh environments, such as outdoor settings or industrial plants, where vibrations may be strong and continuous. Additionally, integrating vibration-based systems into larger infrastructure projects can be complex and costly. The devices often need to be customized to match the specific vibration frequencies of the environment, making large-scale deployment more difficult and less economically viable.

Future research directions for vibration-based devices should focus on several areas. Developing more durable, wear-resistant materials for the triboelectric layers will be crucial for extending the operational lifespan of these systems. Self-healing materials that can repair surface damage from repeated contact and separation could provide a significant boost in durability. Another promising area is the development of multi-modal energy harvesting systems that combine vibration-based energy capture with other sources, such as thermal or solar energy. This would allow for more consistent energy generation and broaden the application potential of these devices. Additionally, integrating advanced energy storage solutions, such as supercapacitors, could help smooth out the power supply by storing excess energy during periods of high vibration and releasing it when needed. Finally, simplifying the integration of vibration-based systems through modular designs that can be easily customized and scaled would reduce installation costs and make these systems more accessible for large-scale use in industrial and infrastructure projects.

The impact of motion types on energy output is a complex interplay of kinematic structure, energy absorption techniques, and environmental factors. Each type of motion—linear, rotational, and vibration—presents unique advantages and challenges, which influence the overall performance of hybrid EMG-TENG systems. Future research should focus on the deep integration of energy storage technologies with hybrid power generation systems to enhance their stability and continuity in environments with intermittent energy sources. Currently, supercapacitors, known for their high charging and discharging efficiency and long lifespan, are ideal for immediate energy storage, while high-efficiency lithium-ion batteries meet the demands of long-term energy storage. The development of intelligent energy management systems (IEMS) enables dynamic optimization of energy allocation, such as in rotational motion generators, where the charging and discharging balance of storage units ensures stable power supply during fluctuating energy inputs. Future directions should also include the development of advanced storage materials, such as solid-state batteries and flexible storage devices, as well as the miniaturization and modular design of storage systems to support broader applications, including wearable devices, smart sensor networks, and energy supply in remote areas. This multi-technology integration will significantly enhance the efficiency and application potential of hybrid power generation systems.The summary of motion-based mixed energy harvesting is in Fig. 15.

6. Conclusion

This review highlights the integration of electromagnetic generation (EMG) and triboelectric nanogeneration (TENG) technologies, focusing on the impact of motion types—linear, rotational, and vibration-based—on the performance and applicability of hybrid energy harvesting devices. Linear motion devices, such as tubular and rail-based generators, excel in capturing energy from predictable sources like ocean waves, yielding moderate outputs while facing challenges like mechanical wear and environmental stressors. In contrast, rotational motion devices, including rotating disc and drum-type generators, demonstrate superior energy conversion efficiencies in high-speed environments, vital for wind energy systems and structural health monitoring, though they require precise alignment and robust materials to maximize performance. Vibration-based devices, such as cantilever-based and spring-mass systems, effectively harness energy from irregular and low-frequency vibrations, making them versatile for applications in vehicle monitoring and wearable electronics, yet they must

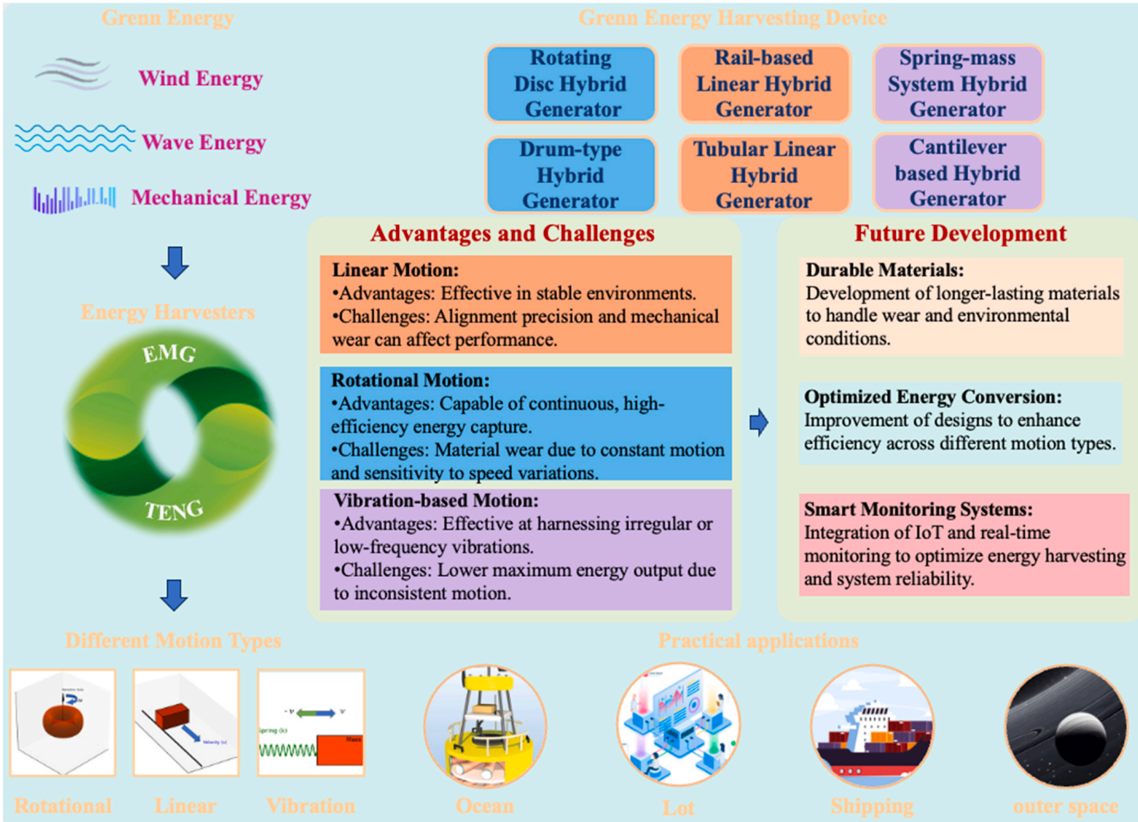

Fig. 15. Summary of motion-based mixed energy harvesting.

overcome mechanical wear and adaptability issues. Overall, advancing hybrid EMG-TENG systems depends on understanding the interplay between motion types and energy harvesting mechanisms, necessitating ongoing research to optimize these systems for diverse applications and address their inherent challenges, thereby fostering sustainable energy harvesting solutions.

CRediT authorship contribution statement

Mengwei Wu: Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Project administration, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Man Wang:** Writing – original draft, Visualization, Validation, Supervision, Software, Resources. **Minyi Xu:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Funding acquisition, Formal analysis, Data curation. **Fuzhen Xing:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Project administration, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Hao Wang:** Visualization, Validation, Supervision, Software. **Guoqiang Tang:** Resources, Project administration, Investigation, Funding acquisition, Formal analysis.

Ethics declarations

The manuscript does not contain clinical studies or patient data.

Declaration of Competing Interest

The authors declare no interest conflict. They have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

References

[1] N. Zhou, G. Ma, In ICEMS 2008: Proceedings of the 11th International Conference on Electrical Machines and Systems, Vols 1–8 (Eds.: Gu, C. L.; Yang, K.; Wang, J.), World Publishing Corporation, Beijing, 2008, pp. 4018–4021.
[2] C. Sezenoglu, A. Balikci, In 2015 9th International Conference on Electrical and Electronics Engineering (ELECO), IEEE, New York, 2015, pp. 595–598.
[3] X. Yang, Y. Wang, Y. Cao, S. Liu, Z. Zhao, G. Dong, IEEE Trans. Appl. Supercond. 24 (2014) 5000204.
[4] J.Z. Li, J.Bin Wen, In 2015 IEEE International Conference on Applied Superconductivity and Electromagnetic Devices (ASEMD), IEEE, New York, 2015, pp. 106–107.
[5] X. Cao, Y. Wang, H. Wang, In 2022 25th International Conference on Electrical Machines and Systems (ICEMS 2022), IEEE, New York, 2022.
[6] J. Bernatt, S.A. Gawron, M. Glinka, Prz. Elektrotech. 88 (2012) 66.
[7] L. Zhu, Q. Wu, W. Li, W. Wu, C.-S. Koh, F. Blaabjerg, IEEE Trans. Energy Convers. 39 (2024) 1202.
[8] L. Zhou, D. Liu, Z. Zhao, S. Li, Y. Liu, L. Liu, Y. Gao, Z.L. Wang, J. Wang, Adv. Energy Mater. 10 (2020) 2002920.
[9] N. Zheng, J. Xue, Y. Jie, X. Cao, Z.L. Wang, Nano Res. 15 (2022) 6213.
[10] Z. Zhao, D. Liu, Y. Li, Z.L. Wang, J. Wang, Nano Energy 102 (2022) 107745.
[11] Z. Xu, J. Ge, Q. Wang, X. Yu, Y. Hu, J. Wen, W. Han, T. Cheng, Sustain. Energ. Fuels 7 (2023) 2841.
[12] S. He, W. Wang, X. Zhang, X. Zhao, L. Guo, In ICEMS 2008: proceedings of the 11th international conference on electrical machines and systems, VOLS 1-8 (Eds.: Gu, C. L.; Yang, K.; Wang, J.), World Publishing Corporation, Beijing, 2008, pp. 2423-+.

[13] G. Duan, H. Wang, H. Guo, G. Gu, IEEE Trans. Appl. Supercond. 20 (2010) 1883.
[14] Y. Lou, M. Li, J. Hu, Y. Zhao, W. Cui, Y. Wang, A. Yu, J. Zhai, Nano Energy 121 (2024) 109240.
[15] S. Tian, X. Wei, L. Lai, B. Li, Z. Wu, Y. Dai, Nano Energy 102 (2022) 107669.
[16] Q. Xu, C. Shang, H. Ma, Q. Hong, C. Li, S. Ding, L. Xue, X. Sun, Y. Pan, T. Sugahara, Y. Yalikun, Y.-C. Lai, Y. Yang, Nano Energy 109 (2023) 108240.
[17] L. Xu, M.A.M. Hasan, H. Wu, Y. Yang, Energies 14 (2021) 6219.
[18] J.H. Ahn, J.Y. Hwang, C.G. Kim, G.H. Nam, K.K. Ahn, Nano Energy 67 (2020) 104269.
[19] X. Fu, Y. Qin, Z. Zhang, G. Liu, J. Cao, B. Fan, Z. Wang, Z. Wang, C. Zhang, Energy Environ. Mater. 7 (2024).
[20] G. Li, G. Liu, W. He, L. Long, B. Li, Z. Wang, Q. Tang, W. Liu, C. Hu, Nano Res. 14 (2021) 4204.
[21] Q. Xu, C. Shang, H. Ma, Q. Hong, C. Li, S. Ding, L. Xue, X. Sun, Y. Pan, T. Sugahara, Y. Yalikun, Y.-C. Lai, Y. Yang, Nano Energy 109 (2023) 108240.
[22] K. Lee, J. Lee, K. Kim, D. Yoo, D.S. Kim, W. Hwang, I. Song, J.-Y. Sim, Micromachines 9 (2018) 598.
[23] Y. Pang, Y. Fang, J. Su, H. Wang, Y. Tan, C. (Chase) Cao, Adv. Mater. Technol. 8 (2023) 2201246.
[24] Z. Wu, H. Guo, W. Ding, Y.-C. Wang, L. Zhang, Z.L. Wang, ACS Nano (2019) acsnano.8b09088.
[25] C. Zhang, W. Yuan, B. Zhang, O. Yang, Y. Liu, L. He, J. Wang, Z.L. Wang, Adv. Funct. Mater. 32 (2022) 2111775.
[26] F. Zheng, Y. Sun, X. Wei, J. Chen, Z. Yuan, X. Jin, L. Tao, Z. Wu, Nano Energy 90 (2021) 106631.
[27] H. Zhao, L.Q. Machado, Y. Fu, H. Ouyang, J. Mo, Nano Energy 128 (2024) 109788.
[28] W. Wang, D. Yang, X. Yan, L. Wang, H. Hu, K. Wang, Front. Chem. Sci. Eng. 17 (2023) 635.
[29] A. Nawaz, M. Kang, H.W. Choi, R.T.M. Ahmad, S.-W. Kim, D.H. Yoon, Chem. Eng. J. 454 (2023) 140262.
[30] D. Vera Anaya, M.R. Yuce, Nano Energy 111 (2023) 108366.
[31] I.-W. Tcho, S.-B. Jeon, S.-J. Park, W.-G. Kim, I.K. Jin, J.-K. Han, D. Kim, Y.-K. Choi, Nano Energy 50 (2018) 489.
[32] B. Zhu, H. Wu, H. Wang, Z. Quan, H. Luo, L. Yang, R. Liao, J. Wang, Nano Energy 124 (2024) 109446.
[33] L. Zhou, D. Liu, Z. Zhao, S. Li, Y. Liu, L. Liu, Y. Gao, Z.L. Wang, J. Wang, Adv. Energy Mater. 10 (2020) 2002920.
[34] N. Zheng, J. Xue, Y. Jie, X. Cao, Z.L. Wang, Nano Res. 15 (2022) 6213.
[35] Z. Zhao, D. Liu, Y. Li, Z.L. Wang, J. Wang, Nano Energy 102 (2022) 107745.
[36] K. Zhao, Z. Song, Z. Gao, W. Gao, M.-J. Liu, B. Gu, J. Guo, Y.-L. Chueh, Chem. Eng. J. 489 (2024) 150763.
[37] L. Zhai, H. Wen, H. Liu, D. Guo, G. Liu, H. Qu, L. Wan, H. Yao, J. Zhai, Nano Energy 125 (2024) 109546.
[38] Z. Xu, J. Ge, Q. Wang, X. Yu, Y. Hu, J. Wen, W. Han, T. Cheng, Sustain. Energ. Fuels 7 (2023) 2841.
[39] Z. Xu, D. Zhang, H. Cai, Y. Yang, H. Zhang, C. Du, Nano Energy 102 (2022) 107719.
[40] Z. Xie, Z. Qin, Y. Wang, D. Yu, Z. Li, Energy Technol. (2024).
[41] Z. Wu, X. Chen, Z. Wan, J. Chi, R. Zhang, M. Wang, D. Song, X. Xiao, Mater. Today Sustain. 26 (2024) 100781.
[42] Y. Kim, M.U. Mehmood, H.J. Han, Y.J. Kim, S.J. Oh, S.-H. Lim, Energies 15 (2022) 2817.
[43] H. Wang, C. Xu, X. Pan, T. Cheng, J. Mater. Sci. 57 (2022) 21143.
[44] Z. Xi, H. Yu, H. Du, H. Yang, Y. Wang, M. Guan, Z. Wang, H. Wang, T. Du, M. Xu, Adv. Mater. Technol. (2024) 2400451.
[45] W. Xie, L. Gao, L. Wu, X. Chen, F. Wang, D. Tong, J. Zhang, J. Lan, X. He, X. Mu, Y. Yang, Research 2021 (2021), 2021/5963293.
[46] L. Zhu, Q. Wu, W. Li, W. Wu, C.-S. Koh, F. Blaabjerg, IEEE Trans. Energy Convers. 39 (2024) 1202.
[47] B. Zhang, W. Li, J. Ge, C. Chen, X. Yu, Z.L. Wang, T. Cheng, Nano Res. 16 (2023) 3149.
[48] F. Xue, L. Chen, C. Li, J. Ren, J. Yu, X. Hou, W. Geng, J. Mu, J. He, X. Chou, Sci. China Technol. Sci. 65 (2022) 893.
[49] Q. Wang, G. Yu, Y. Lou, M. Li, J. Hu, J. Li, W. Cui, A. Yu, J. Zhai, Sensors 24 (2024) 3770.
[50] B. Li, Y. Qiu, P. Huang, W. Tang, X. Zhang, Sci. China Technol. Sci. 65 (2022) 2348.
[51] L. Hu, Z. Duan, J. Song, B. Wu, H. Wang, J. He, Electronics 12 (2022) 34.
[52] M. Huang, C. Liu, Z. Zhang, J. Wang, Q. Zu, L. Zhou, X. Zhou, L. Yu, S. Guo, Nano Energy 128 (2024) 109819.
[53] J. Liu, G. Pan, C. Wu, Y. Feng, Appl. Sci. 14 (2024) 5014.
[54] W. Nie, Energy Rep. 8 (2022) 617.
[55] S. Pongampai, P. Pakawanit, T. Charoonsuk, S. Hajra, H.J. Kim, N. Vittayakorn, J. Sci.: Adv. Mater. Devices 8 (2023) 100618.
[56] Y. Zhu, Y. Zhao, L. Hou, P. Zhang, Micromachines 13 (2022) 2053.
[57] L. Zhai, H. Wen, H. Liu, D. Guo, G. Liu, H. Qu, L. Wan, H. Yao, J. Zhai, Nano Energy 125 (2024) 109546.
[58] K. Zhao, C. Liu, T. Shao, Y. Fan, R. Chen, X. Pan, Mater. Today Sustain. 23 (2023) 100476.
[59] H. Dang, Y. Wang, S. Zhang, Q. Gao, X. Li, L. Wan, Z.L. Wang, T. Cheng, Mater. Today Energy 29 (2022) 101136.
[60] L. Dong, J. Zhu, H. Li, J. Zhang, D. Zhao, Z.L. Wang, L. Gu, T. Cheng, Nano Energy 127 (2024) 109783.
[61] K. Fan, C. Chen, B. Zhang, X. Li, Z. Wang, T. Cheng, Z. Lin Wang, Appl. Energy 328 (2022) 120218.
[62] Z. Saadatnia, E. Esmailzadeh, H.E. Naguib, Nano Energy 50 (2018) 281.
[63] S. Gao, X. Luo, H. Wei, R. Wang, X. Chen, J. Zhang, Nano Energy 128 (2024) 109831.
[64] Z. Wu, X. Chen, Z. Wan, J. Chi, R. Zhang, M. Wang, D. Song, X. Xiao, Mater. Today Sustain. 26 (2024) 100781.
[65] X. Rui, H. Li, X. Han, L. Zhang, Y. Zhang, Z. Zeng, Sustain. Energy Technol. Assess. 68 (2024) 103859.
[66] J.M. Bjelica, N.M. Djuric, S.M. Djuric, Energy Rep. 8 (2022) 9184.
[67] Y. Hu, X. Wang, Y. Qin, Z. Li, C. Wang, H. Wu, Appl. Energy 309 (2022) 118506.
[68] Z. Wang, X. Liu, M. Yue, H. Yao, H. Tian, X. Sun, Y. Wu, Z. Huang, D. Ban, H. Zheng, Nano Energy 102 (2022) 107681.
[69] S. Li, J. Qian, J. Liu, Y. Xue, J. Zhang, Y. Liu, X. Hu, X. Jing, W. Zhang, Mech. Syst. Signal Process. 201 (2023) 110679.
[70] J. Zheng, Z. Cao, C. Han, X. Wei, L. Wang, Z. Wu, Nanoenergy Adv. 3 (2023) 126.
[71] X. Wang, Z. Wen, H. Guo, C. Wu, X. He, L. Lin, X. Cao, Z.L. Wang, ACS Nano 10 (2016) 11369.
[72] D. Yu, C. Sun, K. Wang, S. Yin, L. Sun, H. Chen, F. Kong, Appl. Nanosci. 12 (2022) 1697.
[73] D. Clemente, C. Rodrigues, R. Esteves, J. Correia, A.M. Pereira, J.O. Ventura, P. Rosa-Santos, F. Taveira-Pinto, P. Martins, JMSE 10 (2022) 1924.
[74] C. Hao, J. He, C. Zhai, W. Jia, L. Song, J. Cho, X. Chou, C. Xue, Nano Energy 58 (2019) 147.
[75] C. Zhu, M. Wu, C. Liu, C. Xiang, R. Xu, H. Yang, Z. Wang, Z. Wang, P. Xu, F. Xing, H. Wang, M. Xu, Adv. Energy Mater. 13 (2023) 2301665.
[76] G. Tang, Z. Wang, X. Hu, S. Wu, B. Xu, Z. Li, X. Yan, F. Xu, D. Yuan, P. Li, Q. Shi, C. Lee, Nanomaterials 12 (2022) 1168.
[77] X. Sun, C. Shang, H. Ma, C. Li, L. Xue, Q. Xu, Z. Wei, W. Li, Y. Yalikun, Y.-C. Lai, Y. Yang, Nano Energy 100 (2022) 107540.
[78] L. Gao, X. Xu, H. Han, W. Yang, R. Zhuo, Q. Wei, Q. Deng, N. Hu, Nano Energy 127 (2024) 109697.
[79] D. Wang, D. Zhang, M. Tang, H. Zhang, F. Chen, T. Wang, Z. Li, P. Zhao, Chem. Eng. J. 446 (2022) 136914.
[80] K. Zhang, Y. Yang, Nano Res. 9 (2016) 974.
[81] D. Zhu, X. Guo, H. Li, Z. Yuan, X. Zhang, T. Cheng, Nano Energy 108 (2023) 108233.
[82] K. Zhao, Z. Song, Z. Gao, W. Gao, M.-J. Liu, B. Gu, J. Guo, Y.-L. Chueh, Chem. Eng. J. 489 (2024) 150763.
[83] Q. Shi, Z. Zhao, J. Yang, H. Gui, M. Cai, C. Yao, Chem. Eng. J. 477 (2023) 146886.
[84] Y. Ra, Y. Kim, S. Yang, N. Kang, G. Oh, C. Cho, S. Lee, D. Choi, Nano Energy 119 (2024) 109052.
[85] Z. Qu, X. Wang, M. Huang, C. Chen, Y. An, W. Yin, X. Li, Nano Energy 107 (2023) 108094.
[86] W. Meng, Y. Yang, R. Zhang, Z. Wu, X. Xiao, Chem. Eng. J. 473 (2023) 145465.
[87] S. Gao, X. Zeng, G. Zhang, J. Zhang, Y. Chen, S. Feng, W. Lan, J. Zhou, Z.L. Wang, Nano Energy 101 (2022) 107530.
[88] T. Bhatta, G.B. Pradhan, K. Shrestha, S. Lee, S.S. Rana, S. Sharma, H. Song, S. Jeong, J.Y. Park, Nano Energy 103 (2022) 107860.
[89] Q. Shi, Z. Zhao, J. Yang, H. Gui, M. Cai, C. Yao, Chem. Eng. J. 477 (2023) 146886.
[90] S. Gao, Y. Chen, S. Feng, X. Chen, J. Zhang, R. Wang, H. Wei, X. Luo, X. Zeng, Nano Energy 113 (2023) 108530.
[91] M. Toyabur Rahman, S. Sohel Rana, Md Salauddin, P. Maharjan, T. Bhatta, H. Kim, H. Cho, J.Y. Park, Appl. Energy 279 (2020) 115799.
[92] M. Salauddin, R.M. Toyabur, P. Maharjan, M.S. Rasel, J.W. Kim, H. Cho, J. Y. Park, Nano Energy 51 (2018) 61.
[93] J. He, X. Fan, D. Zhao, M. Cui, B. Han, X. Hou, X. Chou, Sci. China Inf. Sci. 65 (2022) 142401.
[94] J. Shen, Y. Yang, Z. Yang, B. Li, L. Ji, J. Cheng, Nano Energy 116 (2023) 108818.
[95] M. Salauddin, R.M. Toyabur, P. Maharjan, J.Y. Park, Nano Energy 45 (2018) 236.
[96] T. Quan, Y. Yang, Nano Res. 9 (2016) 2226.
[97] S.T. San, J. Yun, D. Kim, Int. J. Precis. Eng. Manuf. Green Technol. 10 (2023) 757.
[98] T. Quan, Y. Wu, Y. Yang, Nano Res. 8 (2015) 3272.
[99] J. He, T. Wen, S. Qian, Z. Zhang, Z. Tian, J. Zhu, J. Mu, X. Hou, W. Geng, J. Cho, J. Han, X. Chou, C. Xue, Nano Energy 43 (2018) 326.
[100] J. He, X. Fan, J. Mu, C. Wang, J. Qian, X. Li, X. Hou, W. Geng, X. Wang, X. Chou, Energy 194 (2020) 116871.
[101] Y. Gui, W. Zhang, S. Liu, Y. Li, J. Yang, G. Jin, H. Huang, P. Yang, M. Gao, Nano Energy 124 (2024) 109498.
[102] W. Wang, S. Zhang, Q. Liu, Y. Bai, T. Jiang, B. Guo, C. Liu, Z.L. Wang, D. Luo, Cell Rep. Phys. Sci. 5 (2024) 101871.
[103] W. Wang, D. Yang, X. Yan, L. Wang, H. Hu, K. Wang, Front. Chem. Sci. Eng. 17 (2023) 635.
[104] I.-W. Tcho, S.-B. Jeon, S.-J. Park, W.-G. Kim, I.K. Jin, J.-K. Han, D. Kim, Y.-K. Choi, Nano Energy 50 (2018) 489.
[105] W. Wang, Y. Zhang, G. Wu, Z. Zhao, Y. Wu, H. Zheng, Nanoscale Adv. (2024).
[106] Y. Wang, Q. Gao, W. Liu, C. Bao, H. Li, Y. Wang, Z.L. Wang, T. Cheng, ACS Appl. Mater. Interfaces 16 (2024) 20652.
[107] X. Lu, B. Leng, H. Li, X. Lv, X. Zhang, T. Qu, S. Li, Y. Wang, J. Wen, B. Zhang, T. Cheng, Adv. Mater. Technol. 9 (2024).
[108] J. Liu, G. Pan, C. Wu, Y. Feng, Appl. Sci. -Basel 14 (2024) 5014.
[109] D. Liu, P. Yang, Y. Gao, N. Liu, C. Ye, L. Zhou, J. Zhang, Z. Guo, J. Wang, Z. L. Wang, Small 20 (2024).
[110] X. Liu, A. Yu, A. Qin, J. Zhai, Adv. Mater. Technol. 4 (2019) 1900608.
[111] H. Moon, J. Chung, B. Kim, H. Yong, T. Kim, S. Lee, S. Lee, Nano Energy 31 (2017) 525.

[112] T. Li, C. Li, K. Wang, J. Wang, X. Wang, M. Li, F. Zhao, Y. Yao, ACS Appl. Mater. Interfaces 16 (2024) 33347.
[113] T. Li, C. Li, K. Wang, J. Wang, X. Wang, M. Li, F. Zhao, Y. Yao, ACS Appl. Mater. Interfaces (2024).
[114] G. Li, G. Liu, W. He, L. Long, B. Li, Z. Wang, Q. Tang, W. Liu, C. Hu, Nano Res. 14 (2021) 4204.