



Recent advances in spring-assisted triboelectric nanogenerators

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Triboelectric nanogenerator, spring resonant structures, vibration energy harvesting, self-powered system, hybrid energy harvesting

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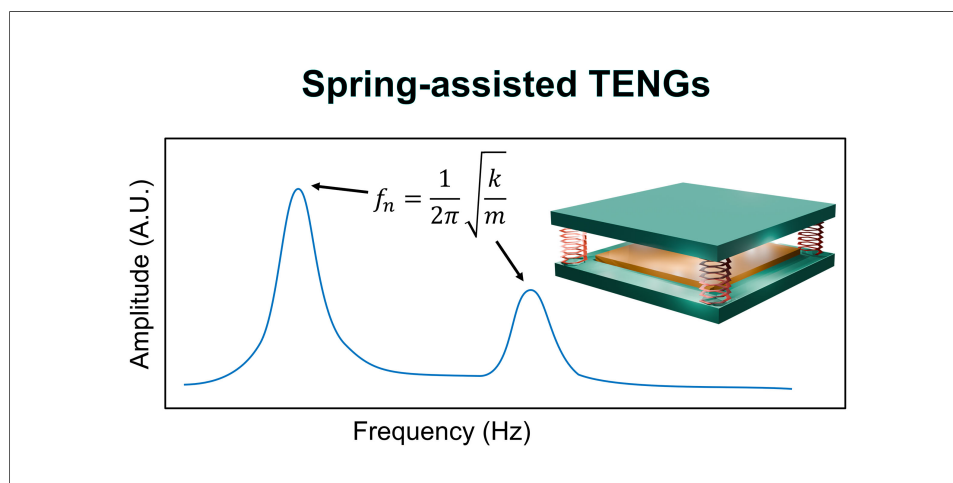
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Abstract

Spring-assisted triboelectric nanogenerators (S-TENGs) have emerged as effective energy harvesters of low-frequency, low-amplitude vibrations via resonance tuning, amplified relative motion, and enhanced contact force between triboelectric layers. Unlike conventional triboelectric nanogenerators (TENGs), S-TENGs uniquely harness elastic resonance through integrated spring structures to efficiently harvest low-frequency and subtle mechanical vibrations that are otherwise difficult to convert into electricity, thereby enhancing overall energy conversion efficiency. Recent innovations in triboelectric materials, electrode designs, and structures have enabled the development of high-performance TENGs for sustainable green energy. This review highlights the pivotal role of spring elements in improving S-TENG performance and provides design insights for constructing robust, self-powered, and maintenance-free sensing platforms. Diverse architectures include linear and multi-degree-of-freedom systems, as well as cantilever, tower, helical, magnetic, and composite designs. Each is engineered to optimize vibration response and maximize output performance, enabling it to be used as an independent power source. Hybrid triboelectric-electromagnetic integration, negative-stiffness mechanisms, and mechanical frequency regulation further extend the adaptability of S-TENGs to real-world conditions. Industrial equipment monitoring, wireless carbon dioxide sensing, omnidirectional vibration harvesting, and motor fault detection in

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unmanned aerial vehicles demonstrate the versatility and practical impact of S-TENGs.

INTRODUCTION

Rapid advancements in Internet of Things (IoT) technologies have increased interest in sustainable, independent energy solutions for powering distributed electronics and autonomous sensor networks^[1–5]. Green energy harvesting systems, such as wind-, solar-, thermal-, and water-power plants, capture and convert ambient energy from the surrounding environment into useful electrical power for large-scale power sources; however, these systems are limited by environmental dependence, space requirements, and discontinuous operation^[6–8]. In contrast, triboelectric nanogenerators (TENGs) offer a compact, adaptable platform that converts small-scale mechanical vibrations into electrical energy through the combined effects of triboelectrification and electrostatic induction. When two materials with distinct electron affinities come into contact and separate, charge transfer occurs, creating a potential difference that drives current through an external circuit^[9–11]. This mechanism enables efficient energy harvesting from diverse mechanical sources such as vehicle-induced vibrations, water flow, human motion, and pipeline oscillations, making TENGs promising for distributed IoT power^[12,13].

Fine vibrations are small, continuous mechanical oscillations that occur with low amplitude and often at low frequency, typically resulting from machinery, structures, or fluid flow. For example, fine vibrations from pipelines and industrial facilities exhibit amplitudes ranging from 20 μm to 4,000 μm over the 0–300 Hz frequency range^[14,15]. Furthermore, spring-assisted vibration sensors have been integrated into unmanned aerial vehicles (UAVs) to monitor motor vibration in real time and enable early-warning functions, offering high sensitivity and stability in a compact, low-cost form factor^[16–18].

Low-frequency and low-amplitude vibrations pose challenges for energy harvesting devices owing to reduced input kinetic energy and contact force between triboelectric layers during energy harvesting under the contact-separation mode, reducing charge transfer and considerably reducing output power density^[19,20]. To overcome the challenges associated with fine vibrations commonly present in practical environments, spring elements have been integrated into TENG architectures to tune resonance, amplify relative motion, and enhance contact forces under weak excitations^[21–23]. Recent examples include hybrid spring-assisted nanogenerators that couple triboelectric and electromagnetic mechanisms to generate high-voltage and high-current simultaneously^[24], and inertia-driven spring TENGs capable of powering wireless carbon dioxide (CO_2) sensors under fine vibrations^[25]. Multi-degree-of-freedom (DOF) spring systems have further expanded the operational frequency range by generating multiple resonant modes^[26].

This review focuses on spring structures applicable to TENGs as a key strategy for recovering initial status after deformation and enhancing input kinetic energy, highlighting structural designs, resonance tuning mechanisms, performance improvements, and real-world applications [Figure 1]. Various studies have reported that integrating tuned spring mechanisms can amplify relative motion and optimize contact-separation cycles, enhancing electrical output and broadening operational bandwidth^[27–29]. These advances present the crucial role of spring mechanisms in enhancing TENG performance, thereby expanding the application scope of TENGs. Specifically, spring-assisted TENGs (S-TENGs) demonstrate significant potential as independent energy solutions and offer pathways toward constructing robust, self-powered, and maintenance-free electronic platforms^[30–34].

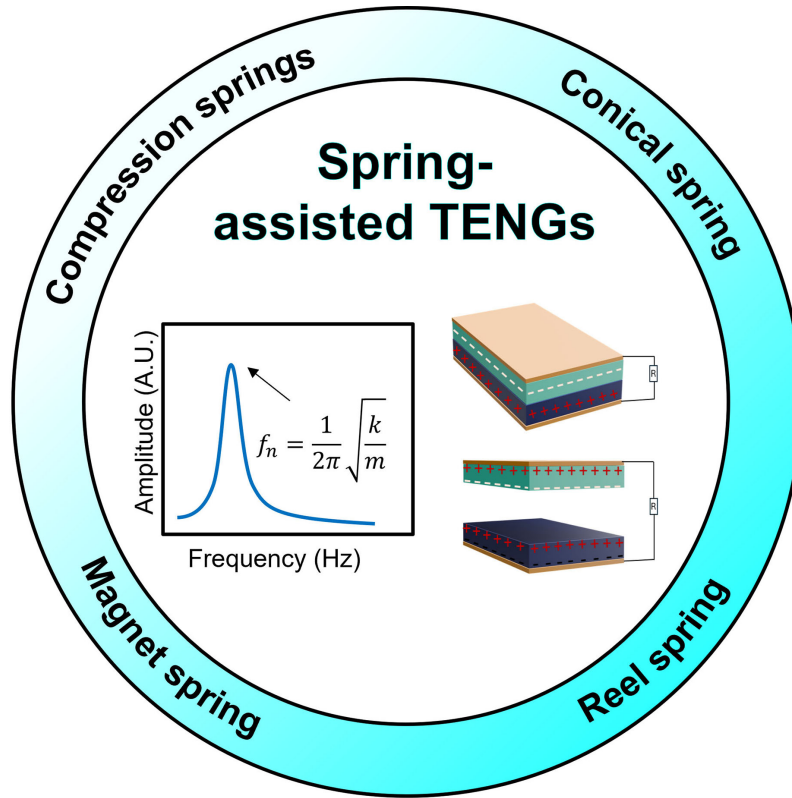


Figure 1. Different S-TENG structures.

SPRING STRUCTURES AND RESONANT BEHAVIOR OF TENGs

Spring structures play a vital role in overcoming the limitations of low-frequency and low-amplitude vibrations in TENGs via resonance tuning and motion amplification^[35]. In such systems, the spring-mass assembly stores mechanical energy during deformation and releases this energy to enhance relative motion between the triboelectric layers, improving contact force and displacement^[36–38]. Resonance occurs when the excitation frequency matches the natural frequency (f_n) of the system, allowing small external inputs to produce disproportionately large oscillations and considerably increasing energy conversion efficiency^[39–42]. The f_n of a simple spring-mass system is expressed as follows:

$$f_n = \frac{1}{2\pi} \sqrt{k/m}, \quad (1)$$

where k is the spring stiffness and m is the effective mass of the oscillating system. For multi-DOF, the spring constant and mass can be written in matrix form as follows^[26]:

$$[M]\{\ddot{x}\} + [K]\{x\} = \{F\} \quad (2)$$

$$[M] = m_1 \text{ or } \begin{bmatrix} m_1 & 0 \\ 0 & m_1 \end{bmatrix} \text{ or } \begin{bmatrix} m_1 & 0 & 0 \\ 0 & m_1 & 0 \\ 0 & 0 & m_n \end{bmatrix} \quad (3)$$

$$[K] = (k_1 + k_1) \text{ or } \begin{bmatrix} (k_1 + k_2) & -k_2 \\ -k_2 & (k_2 + k_3) \end{bmatrix} \text{ or } \begin{bmatrix} (k_1 + k_2) & -k_2 & 0 \\ -k_2 & (k_2 + k_3) & -k_3 \\ 0 & -k_3 & (k_3 + k_4) \end{bmatrix} \quad (4)$$

This relationship implies that the dynamic response of a S-TENG can be precisely tuned by adjusting the stiffness or the attached mass, allowing the resonant frequency to match environmental vibration frequencies. For example, reducing the spring stiffness or increasing the mass lowers the resonant frequency, enabling efficient energy harvesting from weak vibrations below. Conversely, higher stiffness or smaller mass increases the natural frequency. Achieving resonance maximizes the relative motion between triboelectric surfaces, especially under fine vibration conditions, to ensure minimum displacement. Multiple masses and springs in a single structure can facilitate multiple resonant frequencies.

Linear spring-assisted structures

A spring-assisted hybrid nanogenerator (S-HNG), integrating a TENG and an electromagnetic generator (EMG), harvests low-frequency vibration energy to power small electronics and security systems^[24]. The S-HNG employed a sliding-mode TENG with concentric polytetrafluoroethylene (PTFE) and aluminum tubes, in which plasma-etched nanostructures on the PTFE surface enhanced charge generation, and a coaxial magnet-coil arrangement maximized magnetic flux variation during spring oscillation [Figure 2A]. The device used two aluminum cylinders with diameters of 5 cm and heights of 5.5 cm. Under 2 Hz operation, the TENG achieved an open-circuit voltage of 632 V_{peak} and short-circuit current of 12.2 μA_{peak}, delivering a power of 1.6 mW_{peak} under a 50 MΩ load. In contrast, the EMG generated 5.4 V and 36 mA, delivering a power of 57.6 mW under a 2 kΩ load. The spring structure supported fast recovery after compression, and a transformer matched the impedance between the TENG and EMG, enhancing the combined output and enabling rapid capacitor charging relative to those by the individual devices. The hybrid system continuously powered 40 light-emitting diodes (LEDs), a digital temperature-humidity meter, a liquid crystal display, and a wireless bicycle security alarm. Long-term cycling over 10,000 operations degraded the performance negligibly, and the electromagnetic damping effect inherent to the EMG coils additionally attenuated vibrations. This spring-assisted hybrid architecture offers a robust solution to achieve efficient low-frequency energy harvesting and self-powered sensing applications. Overall, this hybrid structure exhibits strong durability, impedance matching, and stable dual-mode energy conversion suitable for low-frequency vibration harvesting. However, its performance decreases under small vibration amplitudes, and full surface contact is difficult to maintain. Enhancing magnetic flux variation, increasing coil turns, and refining structural design are needed to further improve energy conversion efficiency and adaptability.

Multiple DOF TENGs can efficiently harvest vibration energy with a low amplitude and a broad frequency distribution to power battery-free wireless sensor systems [Figure 2B]^[26]. The DOF design increases the degrees of freedom, which creates multiple resonant frequencies in a single device, thereby enabling continuous and efficient energy harvesting, even when the ambient vibration frequency fluctuates. This device employs vertically stacked contact-separation TENG units supported by corner-mounted springs, with aluminum (Al) serving as the positive triboelectric layer and electrode and a perfluoroalkoxy alkane (PFA) film serving as the negative triboelectric material. Each weight layer (20 g) is coupled to springs with a

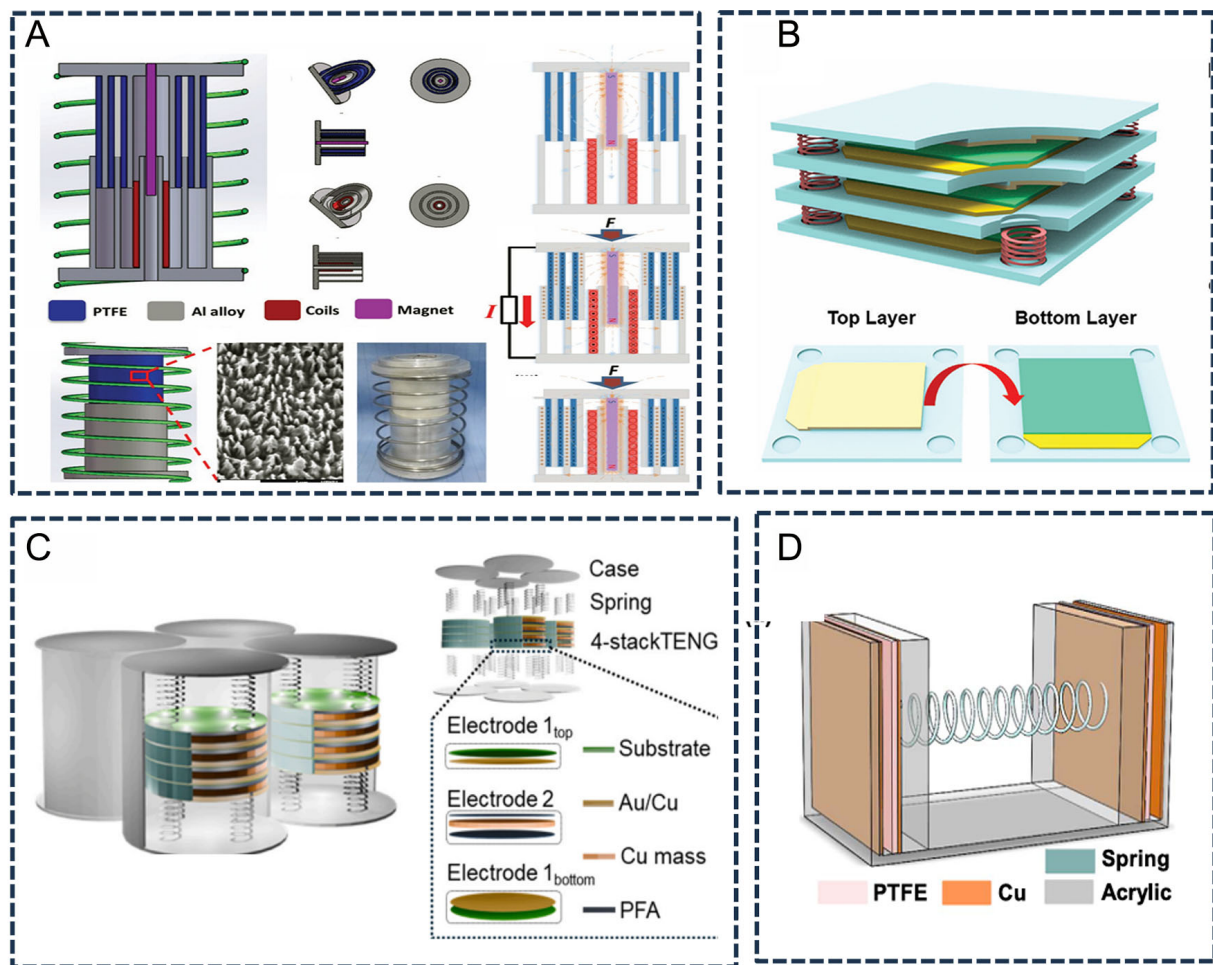


Figure 2. (A) S-HNG for powering small electronic devices. Used with permission^[24]. Copyright 2009 Nanoscale. (B) Multi-DOF TENG with stacked layers and multiple resonant frequencies. Used with permission^[26]. Copyright 2024 John Wiley and Sons. (C) Compact I-TENG for self-powered CO₂ monitoring. Used with permission^[25]. Copyright 2025 Elsevier. (D) S-TENG for efficient water-wave energy harvesting. Used with permission^[43]. Copyright 2017 Elsevier.

stiffness of 82.712 N m^{-1} , creating tunable vibration modes that generate multiple resonant frequencies, i.e., one for 1-DOF (20.47 Hz), two for 2-DOF (12.63 and 33.17 Hz), and three for 3-DOF (9.12, 25.55, and 36.87 Hz). Frequency-sweep tests confirmed increased displacement and output at these resonant frequencies, with phase differences between stacked layers directly influencing contact separation and electrical output. COMSOL Multiphysics® simulations (COMSOL AB, Stockholm, Sweden) yielded phase-dependent potential distributions, confirming the periodic contact-separation mechanism across a range of input frequencies. For the application, six 3-DOF TENGs connected in parallel with a power management integrated circuit and a 4.7 mF capacitor powered a wireless temperature and humidity sensor module, enabling data transmission every 30 min using only the DOF TENGs.

Tiruneh *et al.* developed a highly compact inertia-driven TENG (ITENG) tailored to harvest fine vibrations from industrial pipelines, enabling self-powered wireless CO₂ monitoring [Figure 2C]^[25]. The device featured a vertically stacked structure composed of four triboelectric layers, each integrating a freestanding copper (Cu) mass attached to a plasma-treated PFA film that generated friction against electroless nickel immersion gold (ENIG)-plated Cu electrodes in the vertical contact-separation mode. The device has a cylindrical housing with a diameter of 75 mm and a height of 65 mm, corresponding to an approximate volume of 287 cm³. To enhance sensitivity to subtle mechanical vibrations, the structure was coupled with coil springs

on both ends, enabling resonance behavior centered at 13 Hz, amplifying vertical motion, and increasing effective charge transfer. Amplifying vertical vibration maximized the vertical motion of the freestanding Cu masses, resulting in an approximately threefold increase in output voltage. Structural optimization, including the Cu mass and electrode separation, improved electrical output, and oxygen/argon (O₂/Ar) plasma and corona discharge treatments on the PFA surface further boosted charge density and energy conversion efficiency. Parallely, integrating the four I-TENGs achieved a power of 16 mW_{peak} and successfully harvested energy under 0.08 g acceleration conditions at the resonant frequency. Operational testing validated stable device performance over 240,000 cycles and confirmed the ability of the I-TENGs to autonomously harvest vibration energy and power a Bluetooth-enabled CO₂ sensor. The harvested energy powered the periodic wireless transmission of data on indoor CO₂ concentration to a smartphone interface. The vibration-driven I-TENGs charged a 10 mF supercapacitor through a rectifier and a direct current (DC)/DC converter. When the voltage reached 12 V, the I-TENGs supplied a regulated 3.6 V to the CO₂ sensor and a Bluetooth low-energy system on a chip. The system was subsequently activated for approximately 17 s to sense and transmit CO₂ data before resuming energy harvesting, with the cycle repeating every 70 min. The device shows stable long-term performance, a lightweight structure, and scalability suitable for fine vibration environments in pipelines. However, continued improvement of triboelectric material properties and fabrication integration is required to enhance large-scale applicability.

Jiang *et al.* developed an S-TENG for efficient water wave energy harvesting by transforming low-frequency wave motion into high-frequency oscillations [Figure 2D]^[43]. The device comprised a box structure containing two Cu-PTFE-coated acrylic blocks connected by a spring and sliding between Cu electrodes fixed to opposite walls, generating electricity based on contact-separation. The integrated S-TENG device was encapsulated in an acrylic box with an outer dimension of 21.5 cm × 21.5 cm × 8.5 cm. Optimizing the spring parameters (a length of 4.5 cm and moderate stiffness) enabled effective storage of elastic potential energy, resulting in multiple oscillations per wave impact and improving overall charge generation. The spring-assisted design increased charge transfer by 113% and enhanced total electrical energy by 150% relative to the rigid-body configuration, with a measured resonant frequency of approximately 4.75 Hz. A single unit achieved 458 V_{peak}, 45.8 μA_{peak}, and 5.38 mW_{peak} at a matched resistance of 10 MΩ, whereas the integrated system of four optimized units packaged in a sealed acrylic enclosure achieved 562.8 V_{peak}, 71.8 μA_{peak}, and 7.22 mW_{peak} (power density 726.48 mW_{peak}/m³). Each S-TENG was connected to its rectifier for power management. The harvested energy successfully powered 70 LEDs and charged capacitors up to 30 V within 100 s, demonstrating potential for scalable blue energy harvesting from ocean waves.

Cantilever, tower, and helical spring-based structures

Wang *et al.* developed a TENG using a crank-rocker mechanism integrated with a spring cantilever structure (denoted as CRSC TENG) to efficiently harvest low-frequency, small-amplitude vibrations. Additionally, this structure was used to enable self-powered sensing applications primarily in the vertical direction transmitted through the spring cantilever and converted into rotational-sliding motion by the crank-rocker [Figure 3A]^[44]. The design featured two independent power generation units as follows: (1) a vertical contact-separation unit driven by the cantilever spring beam operating under vertical vibration input; and (2) a sliding-mode unit actuated through the crank-rocker lever system operating through lateral sliding displacement. In the former unit (under the contact-separation mode), the cantilever spring beam vibrated vertically under external excitation, causing periodic contact and separation between the Cu and food-grade silicone doped with titanium dioxide (TiO₂)-food-grade silicone film (FGSF). Charge transfer occurred as the films touched and then separated, driving electrons through the external circuit and producing an alternating current at each cycle. In the second unit (sliding mode), the sliding rod, driven by the crank-rocker, moved the TiO₂-FGSF film across the Cu electrode. The movement redistributed charges between the electrodes, generating current as the film slides back and forth. This coordinated action transformed weak vibrations

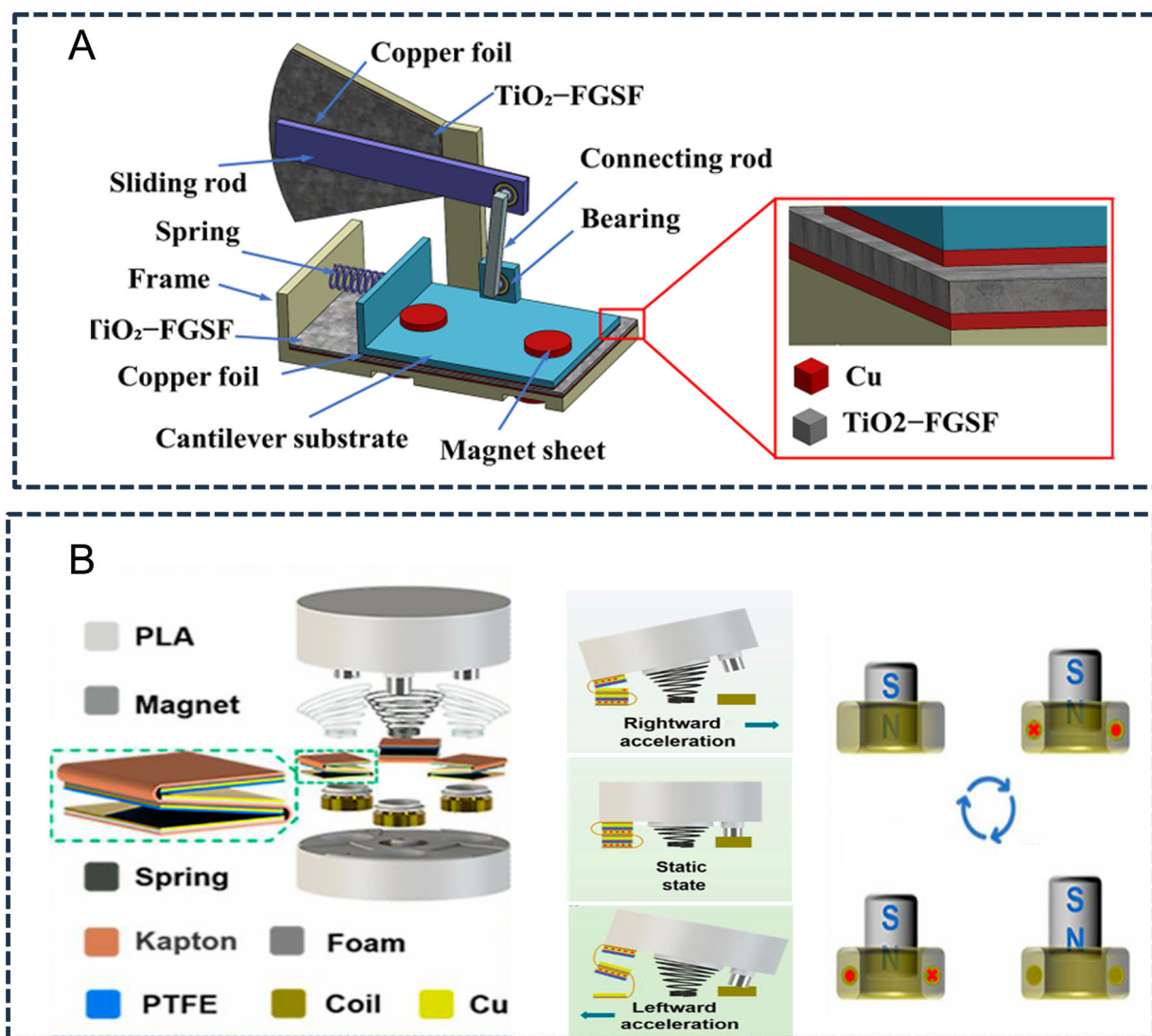


Figure 3. (A) CR-SC TENG for dual-mode energy harvesting and vibration sensing. Used with permission^[44]. Copyright 2024 by the authors (CC BY 4.0). (B) OD-HNG combining multilayer TENGs and EMGs with a tower spring for broadband vibration harvesting. Used with permission^[45]. Copyright 2022 American Chemical Society.

into amplified mechanical motion and an efficient electrical output. Frequency tests (1–50 Hz) revealed a strong output peak at 35 Hz, at which the first unit produced $150 V_{peak}$, $8 \mu A_{peak}$, and the second unit delivered $60 V_{peak}$, $5 \mu A_{peak}$ under $6 m/s^2$ acceleration. The CR SC TENG, installed on an air compressor (24.8 Hz vibration), powered 118 serially connected LEDs and charged a capacitor through an LTC3588 power management circuit, providing a stable 3.6 V output for a small electronic stopwatch. The fast Fourier transform of the generated signals confirmed accurate vibration frequency sensing, demonstrating the device's dual functionality for monitoring the health of industrial equipment and for self-powered energy harvesting applications.

The omnidirectional-hybrid nanogenerator (OD-HNG) integrates three multilayered zigzag TENGs and three EMG units coupled through a tower-shaped conical spring to efficiently harvest low-frequency vibration energy from random directions [Figure 3B]^[45]. The tower spring (with a height of 25 mm) provides structural stability and a large swing angle; therefore, the device can respond to both horizontal and vertical excitations. Moreover, the zigzag polyimide (PI)-Cu/PTFE-based multilayer TENG units (PI and PTFE

thickness: 50 μm) increased the effective contact area, and the EMG units (magnet size: 10 mm $\times$ 10 mm) enhanced high-current output via magnet-coil motion. Frequency tests demonstrated effective energy harvesting within a broadband frequency range (0.4–10 Hz), with the TENG output peaking at 6 Hz (65 μW at 100 M Ω) and the EMG output reaching 6.8 mW at 150 Ω . The hybrid design broadened the operational bandwidth and enabled efficient conversion of micro-vibrations from multiple directions into electricity through complementary operation. Moreover, the TENG units performed optimally at low frequencies, and the EMG units increased output with high frequencies. In practical use, the OD-HNG charged a 1 mF capacitor to 1.75 V in 20 s when mounted on a bicycle and successfully powered 35 LEDs, a temperature sensor for real-time environmental monitoring, and an electronic watch. These findings indicate that the swing-structured hybrid nanogenerator provides an efficient and stable energy harvesting strategy for low-frequency mechanical motion. However, its output performance is affected by swing amplitude and magnetic coupling strength, and further optimization of the mechanical structure and magnetic configuration is needed to enhance energy conversion efficiency.

Other spring structures

A self-powered vibration sensor (AV-TENG) with a magnetic spring structure enabled real-time monitoring and generated early warnings for UAVs^[16]. This sensor employed a vertical contact-separation mode, in which a silicone film on the vibrating plate contacted and separated from a PI-Cu electrode on the base. Magnetic repulsion between permanent magnets replaced conventional mechanical springs, eliminating mechanical fatigue and improving stability for long-term UAV operation. The optimized structure (30 mm $\times$ 30 mm $\times$ 35 mm, 50 g) exhibited a resonant frequency of 43.6 Hz and a peak output voltage of 10.9 V under 2 g acceleration. It maintained output stability with only 6% degradation after 1.2 million cycles. The AV-TENG demonstrated a wide detection bandwidth of 20–400 Hz, with excellent linearity (maximum error: 0.0062%). A low-cost (\$7) wireless signal acquisition system integrated with an Arduino and an ESP8266 Wi-Fi module enabled real-time transmission of frequency and acceleration data to a MATLAB-based monitoring panel, providing visual indicators and alarm triggers during abnormal vibration events. Field testing on UAV motors confirmed that the AV-TENG could detect early vibration anomalies more rapidly than the built-in internal accelerometers, supporting proactive fault detection and improving the operational safety of UAVs.

Tan *et al.* developed a magnetic tri-stable TENG (MT-TENG) that used a negative-stiffness mechanism induced by a magnetic spring configuration to efficiently harvest low-frequency vibration energy^[46]. The design integrated a sliding-mode triboelectric structure composed of Cu and fluorinated ethylene propylene (FEP) films with a proof mass, dual springs, and three strategically arranged magnets, forming a tri-stable potential profile. This configuration enabled large-amplitude inter-well oscillations under small external excitations, considerably amplifying relative motion between the triboelectric layers and improving charge transfer. Experimental characterization showed a transition from small intra-well oscillation between 4–4.5 Hz to large aperiodic inter-well oscillation at 6 Hz, generating an open-circuit voltage of 240 V_{peak} and maximum output power of 0.322 mW_{peak} at 5.5 Hz and a 100 M Ω load. Adjusting system parameters, such as proof mass, magnet spacing, and excitation amplitude, tuned the frequency band and broadened the low-frequency energy harvesting window. Model validation using a Simulink-based circuit confirmed the agreement between experimental and simulated data. This tri-stable design can effectively improve the harvesting performance of low-frequency vibration energy, particularly for powering distributed wireless sensors.

Hwang *et al.* developed an integrated power generation, conversion, and communication system (power generation, conversion, and communication system (PGCS)-temperature monitoring system (TMS)-passive near-field communication (pNFC)) based on TENGs for sustainable building energy applications [Figure 4]

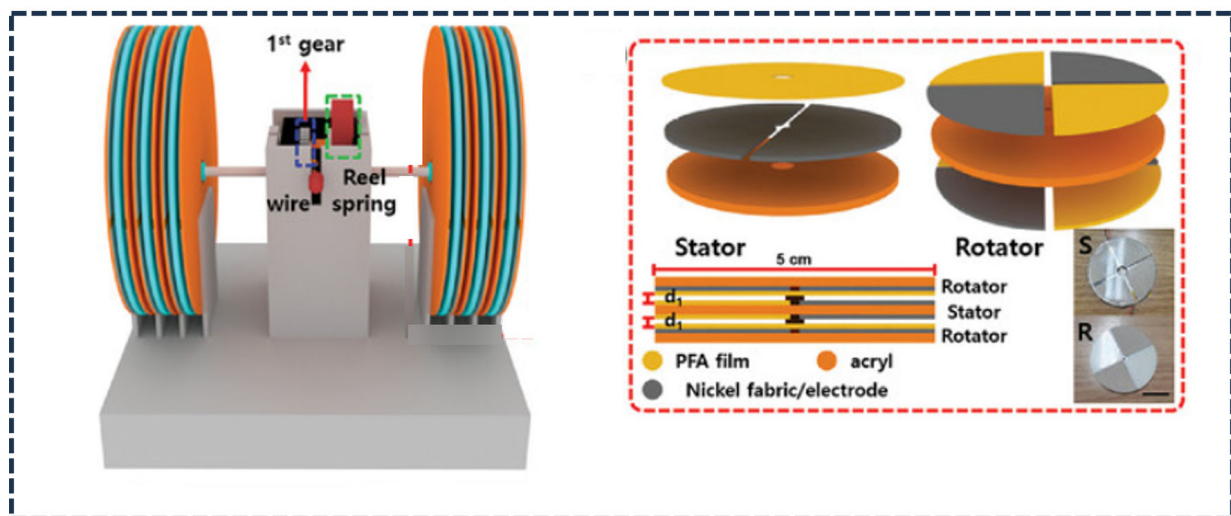


Figure 4. Integrated TENG-based PGCS-TMS-pNFC system for smart building energy and wireless sensing applications. Used with permission^[47]. Copyright 2024 John Wiley and Sons.

^[47]. The system comprised three subsystems. The first subsystem was a mechanical regulation system (MRS) that contained a reel spring, gear train, and automatic switch to convert low-frequency (1–2 Hz) inputs such as door opening and closing or bicycle motion into high-frequency (> 1 kHz) oscillations. The integrated PGCS-TMS-pNFC system features a mechanical regulation module (MRS) with overall dimensions of 80 mm $\times$ 80 mm $\times$ 70 mm, corresponding to a total device volume of approximately 448 cm³. The second involved a phase-control rectifying circuit and a battery charging circuit that delivered a stable DC output with minimal ripple (root-mean-square voltage and current of 423 V and 46 μ A for 2 s, with crest factors of 1.15 and 1.08, respectively). The third subsystem included a temperature monitoring and memory system with passive near-field communication (TMS-pNFC) for low-power data transmission. The MRS-driven TENG operated for up to 10 s/single pull and charged a 20 mAh lithium-ion battery from 2.1 to 2.36 V within 40 min under a 1.5-Hz input. The PGCS-TMS-pNFC harvested mechanical energy from door motion to enable autonomous temperature monitoring and storage for over 29 min, and data were retrieved wirelessly using near-field communication via a smartphone. Moreover, portable devices - such as the charging case of wireless earbuds - were powered during bicycle operation. This integrated approach demonstrated that combining mechanical frequency regulation, electrical power conditioning, and ultra-low-power wireless sensing can extend the practicality of TENG-powered smart building and mobility applications.

CONCLUSION AND PERSPECTIVE

S-TENGs have been widely adopted to power autonomous electronic systems and construct battery-free sensing platforms in diverse real-world scenarios. They can effectively overcome the limitations of low-frequency and low-amplitude vibration energy harvesting [Table 1]. Spring mechanisms considerably enhance charge transfer and broaden operational bandwidth by enabling resonance tuning, amplifying relative displacement, and strengthening contact-separation cycles. Magnetic spring mechanisms offer unique benefits such as tunable stiffness, nonlinear response, fatigue-free operation, and long-term durability. Adjusting magnet spacing or geometry enables precise resonance matching, whereas negative-stiffness and tri-stable configurations broaden bandwidth and amplify oscillations under weak excitations. Structural designs including linear and cantilever systems, as well as tower, helical, and multi-DOF configurations, have demonstrated high power density and stability. Although spring structures are not essential, adding them can enhance TENG energy conversion efficiency. Many current S-TENG



Figure 5. Application demonstrations of S-TENGs. (A) Omnidirectional hybrid energy harvesting for portable electronics. Used with permission^[45]. Copyright 2022 American Chemical Society. (B) UAV vibration sensing and early warning generation. Used with permission^[16]. Copyright 2024 Elsevier. (C) Pipeline-driven wireless carbon dioxide monitoring. Used with permission^[25]. Copyright 2025 Elsevier. (D) Industrial equipment monitoring with predictive maintenance. Used with permission^[44]. Copyright 2024 by the authors (CC BY 4.0).

designs are optimized for laboratory-scale vibrations. In contrast, actual environmental sources often provide only low-amplitude excitations, making it difficult to sustain sufficient output for continuous IoT operation. This gap indicates that further structural optimization - such as enhancing displacement amplification, resonance tuning, or implementing multi-stable configurations - is essential to improve energy conversion efficiency under realistic vibration levels and to ensure reliable power delivery in practical deployments.

Several studies have demonstrated that S-TENGs facilitate self-powered electronics for future applications [Figure 5]^[16,25,44,45]. One such application involved powering portable electronics, environmental sensors, and multiple LEDs in mobile platforms such as bicycles and vehicles. In another application, fine mechanical vibrations from industrial pipelines drove a wireless carbon dioxide monitoring system, enabling periodic indoor air quality reporting via Bluetooth communication without requiring external power supplies or battery replacement. Another application involved industrial equipment monitoring, in which low-frequency vibrations from air compressors were harvested to generate electrical energy to power monitoring modules under real-time vibration sensing for predictive maintenance and fault diagnosis. These applications

Table 1. Comparison of TENGs based on their working mechanisms, operating modes, output voltages, materials, and resonance frequencies

Spring type	Operating mode	Resonance frequency	Output voltage/power	Output voltage performance per unit device volume	Materials	Ref.
Linear spring	Sliding	10.4 Hz	632 V _{peak}	5.85 V _{peak} /cm ³	PTFE, aluminum alloy	[24]
Linear spring	Contact/separation	13 Hz	16 mW _{peak}	0.244 V _{RMS} /cm ³	PFA, ENIG-plated copper	[25]
Linear spring	Contact/separation	9.12, 25.55, and 36.87 Hz	-	-	PFA, Al	[26]
Linear spring	Contact/separation	4.75 Hz	562.8 V _{PEAK}	0.143 V _{peak} /cm ³	PTFE, Cu	[43]
Cantilever and spring	Contact/separation, sliding	35 Hz	150 V _{peak}	62.2 W/m ³	TiO ₂ -doped silicone, Cu	[44]
Tower or helical spring	Contact/separation	6 Hz	65 μW _{peak}	-	polyimide-Cu/PTFE	[45]
Magnet spring	Contact/separation	43.6 Hz	10.9 V _{peak}	0.346 V _{peak} /cm ³	Polyimide, Cu, silicone	[16]
Magnet spring	Sliding	6 Hz	240 V _{peak}	-	FEP, Cu	[46]
Reel spring	Sliding	-	423 V _{RMS}	0.96 V _{RMS} /cm ³	PFA, Ni	[47]

demonstrate that S-TENGs can effectively convert weak or broadband vibrations into usable electrical energy, supporting sustainable, maintenance-free operation of distributed sensing networks and autonomous electronic devices. Future progress will depend on structural innovations that maximize energy generation under weak vibrations, especially using spring architectures that can amplify displacement and maintain resonance at low frequencies. The use of magnetic spring configurations, owing to their tunable stiffness and multi-stable dynamics, can be distinguished as a central strategy for achieving high output performance and advancing TENGs for application in practical, durable, and self-powered systems. Furthermore, incorporating a spring structure amplifies vibration-induced deformation, and pre-formed microstructures on the triboelectric layer surfaces further enhance deformation concentration, maximizing charge transfer and improving energy conversion efficiency. Also, magnetic composite materials, nanofiber structures, and corona charge injection methods can facilitate additional magnetic resonance behaviors^[48–51].

DECLARATIONS

Authors' contributions

Writing, review & editing: Tiruneh, D. M.; Ryu, H.

Availability of data and materials

Not applicable.

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Conflicts of interest

All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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