Rotating Triboelectric Nanogenerators for Energy Harvesting Applications

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Contributor: Apostolos Segkos , Christos Tsamis

Addressing the increasing development of IoT networks and the associated energy requirements, rotating triboelectric nanogenerators (R-TENGs) are proving to be strong candidates in the field of energy harvesting, as well as to that of self-powered devices and autonomous sensors.

triboelectric nanogenerators | rotating TENG | energy harvesting

1. Introduction

Energy harvesting is probably the most obvious field of application for TENGs in general and R-TENGs in particular. As illustrated above, R-TENGs are capable of being lightweight and simple in design, operating in either contact or noncontact mode. The potential of R-TENGs to provide high power density per unit volume and unit mass was illustrated earlier in the theoretical framework, as well. Over the years, many different designs have been proposed, from simple R-TENGs to more sophisticated designs incorporating wireless energy transmission systems, self-excitation modules, or even hybrid ones combining the triboelectric effect with other energy harvesting mechanisms, such as electromagnetism and piezoelectricity.

2. Radial Flaps

One of the earliest designs proposed is that of a collection of rotating radial flaps, coming into intermittent contact with other stationary ones. These types of R-TENGs take advantage of soft and flexible materials for the rotor and stiffer materials on the stator to maximize the effective area of contact, leading to an increase in charge separation and electrical output. Such designs can easily incorporate a propeller or a set of wind cups, enabling the harvester to be driven by the wind or the flow of liquids in a system [1][2][3].

In 2013, Xie et al. demonstrated one such design, fabricated from the combination of PTFE, PET, and aluminum [4]. The harvester used wind cups to drive the rotor, on which four PET flaps were situated, with PTFE endings acting as flexible electrification layers. To enhance the generation of triboelectric charges, the group treated the surface of PTFE films with inductively coupled plasma (ICP), creating nanowires and increasing their surface roughness. The triboelectric effect is induced by contact sliding electrification between PTFE and the aluminum stationary electrodes, resulting in single-electrode mode of operation.

The electrical output of the wind energy harvester was tested under different wind velocities ranging from 4 to 7 Bft ($v = 0.836\ B^{3/2}$ m/s), with the maximum output being delivered when operated at 7 Bft. The open-circuit voltage output reached a value of approx. 250 V, leading to a maximum charge difference of 140 nC. The peak current output was measured to be 0.25 mA when the device was connected to a 1 GΩ external load of resistance, while the maximum power output reached 12 mW when driven with an external load of 1 MΩ resistance.

Similar in design was the R-TENG harvester proposed by Rodrigues et al., for use in harvesting mechanical energy from water flow [5]. In this case, the rotating flaps were fabricated using indium tin oxide (ITO) as a flexible substrate, on which aluminum electrodes with PTFE endings were attached, whereas the stationary flaps were made of Nylon 6,6 to act as the second electrification layer. The harvesting unit was fitted with a fan on the bottom end of its shaft, to allow the R-TENG to be driven by water flow.

The group tested different designs containing different numbers of rotating flaps under various water flows, concluding that the best design for maximum electrical output was that of two rotating PTFE flaps and four stationary Nylon 6,6 flaps, for a water flux of 44 L/min. Under these conditions, the measured open-circuit potential reached a value of approx. 102 V with the charge difference and the short circuit current density output reaching 8.1 μC and 120 mA/m^2, respectively. The maximum power density output of the harvester was reported to be 6.1 W/m^2, allowing the group to light more than 50 serially connected LEDs and charging a 220 μF capacitor to approx. 9 V in a little over 15 min.

In 2018, Du et al. demonstrated an R-TENG harvester that utilizes radial flaps in contact-separation mode for the transformation of wind energy to electricity [6]. The group used the 3D printing technique to fabricate a PLA frame, consisting of a stationary cylinder, on which the TENG was built, and four rotating rollers that are used to induce the contact and separation between the triboelectric layers of the harvester. R-TENG was comprised of a copper electrode layer, on top of which PTFE film patches were placed, acting as electrification layers, the surface of which had been etched using ICP-RIE to enhance its surface roughness. A series of flaps were then placed on top of the PTFE patches, composed of a copper layer, acting as both an electrode and the second electrification layer, and polyimide as the external surface.

The device was tested at a range of rotation velocities, corresponding to wind speeds from approx. 3 to 7 Bft. The maximum electrical outputs of the harvester were determined to be obtained at 120 rpm, under which circumstances the output open-circuit voltage and closed-circuit current were measured to be 280 V and 78 μA, respectively, while the maximum power density output was 2.54 W/m^2 when the R-TENG was matched with an external load of 5 MΩ resistance.

3. Coaxial Cylinders

A popular design of R-TENGs, especially for applications regarding the transformation of liquid flow to electricity, is the one utilizing cylinders [7][8][9]. In its simplest form, two coaxial cylinders of different radii are fitted one within the other, with the TENG layers sandwiched in the area in between. The devices adopting this conformation can act directly as flow channels, where the fluids in question pass through the triboelectric structure, actuating the rotation of the rotator or even acting as an electrification material, while they are also capable of being fully encapsulated, allowing the harvesters to be directly deployed in harsh environments, without risking deterioration of the materials.

One of the simplest uses of cylindrical geometry in R-TENGs is the one presented in 2014 by Zhang et al. who described a single-electrode R-TENG design that could be applied on bicycle tires in order to harvest mechanical energy from the spinning wheel [10]. The device contains an acrylic disk with PTFE blades that act as the electrification layer and an aluminum foil that is both the second electrification layer and the single electrode. An elastomer base ensures full contact between the electrode and the PTFE blades and the blades were modified by ICP to improve the surface roughness and consequently the charge separation process.

The device was tested at a range of rotation speeds between 100 rpm and 800 rpm, and the group reported a gradual increase in the output voltage, current, and power density with increasing velocity, reaching approx. 0.2 μA and 3.2 mW/m^2 at 800 rpm. The electrical output also showed a significant dependence on the symmetricity of the PTFE blades. When two blades were employed in symmetry, the maximum output voltage was measured to be approx. 20 V, which increased considerably when these blades were assembled in non-symmetric positions, to a maximum of 29 V for 800 rpm velocity. By expanding the design to include seven asymmetric PTFE blades, the maximum output voltage was achieved (approx. 55 V), allowing for directly powering 30 commercial LEDs.

In 2013, Bai et al. developed a core–shell structured R-TENG for harvesting air or water flow energy [11]. The inner cylinder of this harvester acted as the rotator and comprised of copper electrodes on top of which PTFE strips were employed as electrification layers, connected in parallel. In order to increase the effective surface area for the charge separation mechanism, PTFE nanoparticles were sprayed on top of the PTFE strips. The outer cylinder, acting as a stator, comprised of copper strips with a dual role, that of both electrodes and second electrification surface.

The group tested the harvester in a range of rotation velocities and the maximum electrical outputs of the device were obtained when driven at 1000 rpm. Specifically, the maximum open-circuit voltage and short-circuit current density output were measured at 400 V and 90 μA, respectively, while the maximum power density was found to be approx. 37 W/m^2.

Another cylindrical R-TENG, this time operating in non-contact sliding mode, was reported by Zhang et al. in 2020 [12]. The group developed a cylindrical, non-contact, and freely rotating TENG to harvest energy from water flow. The harvester consisted of two coaxial, hollow cylinders, with the inner cylinder acting as the stator and the outer one as the rotator. On the outer cylinder, the group placed blades to achieve rotational motion induced by the flow of water and patches of FEP film that had been previously nanostructured via ICP etching, to act as the electrification layer. On the stator, four copper foil patches connected in parallel in pairs act as the electrodes of the TENG.

The device, after the initial contact of the layers in order to induce charge separation, was operated in non-contact mode with a 1 mm gap at 400 rpm. Under these operating parameters, the transferred charges in a single cycle of operation were calculated to be 6.9 nC and the average output voltage and current were 994 V (V_{OC}) and 9 μA (I_{SC}), respectively. The output power of the tribogenerator was evaluated under different external loads of resistance and the maximum power density obtained was 0.33 W/m^2 when the device was matched with a 150 MΩ resistance. The group also investigated the effect of rotational frequency on the output electrical characteristics of the TENG, for rotation speeds of 400–2000 rpm. They observed that both variants increased monotonically with increasing the frequency, reaching 1661 V and 12 μA, respectively. After connecting the tribogenerator to a rectification bridge, the device was driven at 2000 rpm and provided a DC current of 16.5 mW/m^2, which was able to charge a 10 μF capacitor to a voltage of 65 V within 150 s. The TENG was also tested for its durability by measuring the output voltage after 3 h of continuous operation at 400 rpm. The open-circuit voltage after 3 h was reported to reach an equilibrium value of 598 V (approx. 42% attenuation), showcasing the robustness and long lifetime achieved by the non-contact design.

Feng et al. utilized the coaxial cylinder design to fabricate an oscillating, non-contact R-TENG that was used to harvest low frequency mechanical energy from water wave excitation [13]. R-TENG comprised of a six-bladed rotor with an FEP film on the surfaces of the blades acting as the electrification layer and a cylindrical stator shell on which copper electrodes were attached, acting as both electrodes and the second electrification material.

The harvester was shown to be able to convert water wave excitation as low as 0.033 Hz with a peak power density of 231.6 mW/m^3. The group reported the R-TENG was capable of delivering continuous output power for 85 s following a single excitation, with a maximum open-circuit voltage, generated charge, and short-circuit current output of 120 V, 46 nC, and 1.52 μA, respectively, whereas the maximum generated power was measured to be 159 μW when the R-TENG was matched with a 100 MΩ external resistance load.

A similar concept was showcased in 2022 by Jung et al., who introduced a cylindrical R-TENG that utilizes a set of magnets to induce a swinging motion to the rotator, similar to that of a pendulum [14]. The device is proposed as an energy harvesting solution to transform the mechanical energy of sea waves to electricity. A metallic mass placed on the rotor acts as a pendulum, while two neodymium magnets help to temporarily store potential energy, converting low-frequency input energy to high-frequency electrical output. In addition, a set of rabbit fur strips allow for soft partial contact with the electrification layer, increasing the generated charge.

The group tested their design for different angles of displacement, reporting average power outputs at an optimal load of 0.178 mW, 0.147 mW, and 0.117 mW for 60°, 45°, and 30° angles, respectively. The non-contact mode of operation of this design, in conjunction with the soft partial contact achieved with the fur segments provides considerably enhanced electrical output as well as increased robustness, with the output characteristics of the harvester reported to remain constant after 400,000 cycles of operation.

4. Liquid-Solid Contact

Although R-TENGs have often been suggested as a suitable energy harvester to convert the mechanical energy inherent in moving bodies of water (or other liquids), to date, little exploration has been done on the prospect of exploiting the friction generated when a liquid comes into contact with a solid surface [15][16][17].

One such design was proposed by Kim et al. in 2016 [18]. The operating principle of this harvester is based on the flow of water within a tube, using the fluid as an electrification layer. The design includes an acrylic cylinder with a number of patterned aluminum electrodes covered by PTFE to act as the second electrification layer. The cylinder was partially filled with tap water and the electrical output of the TENG was measured for different angular velocities and water volume ratios.

The device was tested at a range of angular velocities from 50 rpm to 300 rpm, showing increasing voltage and power output as the speed increased, as well for different water volume ratios. When operated at optimum conditions, TENG was found to produce up to approx. 27 V and 3.8 μA and 19.1 μW when coupled with an external load of 20 MΩ resistance, although these numbers can increase with the integration of mutliple triboelectric patches in the tube.

In 2021, Le et al. reported a sophisticated liquid–solid contact electrification R-TENG that was developed so as to not require the use of a rectifier circuit to transform AC output to DC [19]. R-TENG was comprised of a stator with stationary electrical contacts and a rotator with six independent TENG cells. These cell TENGs are in the form of a liquid storage compartment, each with its own lid made of a nanoporous PVDF membrane on copper electrodes. A phase inversion method was employed on commercial PVDF films to change their structure and increase the surface density, enhancing their capability of charge separation as electrification layers. The six TENGs were arranged in radial symmetry and were partially filled with DI water.

The interesting property of this design is the addition of motion-activated switches that are closed when water is in contact with one of two copper electrode surfaces in the cell and open during the transition from one electrode to the other. In this way, a unidirectional current is generated, suitable to be supplied directly to electronic devices without requiring a rectifier circuit. The harvester was tested at 18 rpm and was reported to have a maximum open-circuit voltage, generated charge, and short-circuit current density output of 1.5 V, 2.03 nC, and 11.94 nA/cm^2, while the maximum obtained power density was 18.48 nW/cm^2 for a matched external load of 20 MΩ resistance.

5. Radially Segmented Disk

The radially segmented disk configuration is probably the most popular design for R-TENGs [20][21][22]. One of the first reported R-TENGs of this kind was the one described by Lin et al., who reported a sandwiched structure segmented into four sectors [23]. Structurally, the R-TENG is composed of a PMMA substrate on top of which sits a Kapton® layer with gold electrode on its back side, while the rotator is fabricated by depositing aluminum electrode on a PMMA substrate. The Kapton® layer was processed with ICP in order to increase the effective contact area and enhance the electrical output of the device.

The maximum open-circuit voltage (230 V) and generated charges (40 μC/m^2) were obtained at 500 rpm, while the maximum current density output was reported to be 29 mA/m^2 when driven at 1000 rpm. The maximum power density output of the harvester was 1 W/m^2, when matched with an external load of 10 MΩ resistance.

Another radially segmented disk R-TENG was reported by Zhu et al., comprised of a copper rotator with 60 radially arrayed segments and a stationary disk with radial, interdigitated gold electrodes on top of which a FEP layer is used as an electrification layer. The rotator performs a lateral sliding motion on the upper surface of the FEP thin film inducing opposite charges on the copper IDEs and the FEP layer, due to the triboelectric effect [24].

The maximum electrical output was obtained at 3000 rpm with a reported V_{oc}, Q_{sc}, and I_{sc} output of 850 V, 0.32 μC, and 3 mA, respectively. Operating their triboelectric harvester under optimum parameters (3000 rpm, 0.8 MΩ), they successfully generated approx. 19 mW/cm^2, which is a considerable amount of power, suitable for powering simple electronic devices. Regarding device stability, the group included an adhesion layer and performed plasma treatment of their substrate before metal deposition to ensure increased material adhesion. As reported, their device displayed stable output even after 10^7 cycles of operation, showing reliable stability.

A different approach was proposed by Zhou et al., of a R-TENG that can be utilized in harvesting mechanical energy from the wheels of a bicycle during cycling and braking modes [25]. The R-TENG consists of a radially segmented steel rotator and a stator comprised of interdigitated copper electrodes with a PTFE layer on top of them acting as the electrification layer. Three brake clamps are also connected to the device, which, when activated, press the stator closer to the rotator, increasing the friction between the PTFE and steel layers.

The R-TENG was tested in two modes at 150 rpm, one non-contact sliding mode with a 0.5 mm gap between the stator and the rotor, representing the riding of the bicycle without braking, and the other in contact sliding mode when the brake clamps are activated. In non-contact mode, the harvester was capable of producing 0.3 mW when matched with a 46 MΩ external load. In contact mode, the electrical output of the device greatly increased; the maximum output open-circuit voltage, generated charge density, and closed-circuit current were measured at 300 V, 24 μC/m^2, and 60 μA, respectively, while the maximum output power in braking mode was 2.29 mW when the R-TENG was matched with a 20 MΩ external load of resistance. The robustness of this design was also demonstrated as its electrical characteristics were found to be stable after one million cycles of operation.

The radially segmented disk design has been adopted by many research groups to date, who have developed different R-TENGs using a range of triboelectric materials and structures to address the needs of specific applications. Some researchers have studied designs of the basic architecture, such as the one described by Kuang et al. [26], while others have reported more complex ones, such as the one demonstrated by Yong et al. in 2021 [27], which incorporates more than one R-TENGs in a single design, or the ones proposed by Cao et al. [28] and Li et al. [29], which utilize the Curie effect or the structural response of shape memory alloys to changes in temperature, resulting in devices that transform thermal energy to electrical.

One such design is the R-TENG harvester proposed by Lin et al. in 2020, which was developed to transform water wave energy to electricity [30]. Lin's harvester is a freestanding electrode R-TENG that uses a combination of contact electrification and a reciprocal swinging motion, similar to that observed in a pendulum. The TENG is comprised of a stator made of ICP-etched PTFE and copper, and an acrylic rotator with radial segments made of nylon, which functions as the electrification layer. An impeller translates the energy of water waves into a pushing motion, bringing the rotator and the stator into contact with each other and leading to charge transfer between the layers, while a spring restores the gap between the two components. Subsequently, the rotator follows the rotating motion of the shaft, leading to the typical freestanding electrode mode of operation, while an iron mass installed on the rotator leads to an oscillating, pendulum-like motion.

The device was reported to require some time to reach a steady state of charge separation, with the charge at saturation reaching 75 nC. Regarding the electrical output characteristics of TENG, the open circuit voltage was reported to be up to 160 V, depending only on the space charge density of the triboelectric materials, while the short circuit current output was reported to reach approx. 1.5 μA for the maximum trigger acceleration. The device was found to match at 100 MΩ external load, producing 74 μW. An interesting property of this design is the slow attenuation of its voltage output with respect to the mechanical trigger, owing to the pendulum-like motion induced by the iron mass on the rotator, which enables the device to convert mechanical input of a very small frequency to electrical energy. In addition, the contactless mode of operation imparts robustness to the generator, with the authors reporting a stable performance after 500,000 working cycles.

Another such variation was presented by Zhang et al., for harvesting energy from the drafts created by rail trains along their path [31]. The basic TENG design comprised of a stator and a rotator, and the group also detailed and advanced device where the rotator was sandwiched between two stators, thus creating two TENGs operating in phase. In this application, the stators were made of copper IDEs, while the rotator consisted of folds made of PTFE and Kapton® on an acrylic disk.

In this design, the polyimide layer adds to the rigidity of the folds and ensures proper mechanical contact, while PTFE acts as the electrification layer. The authors studied different devices using PTFE, PVC, and FEP as electrification layers and tested them for their electrical output in conjunction with their mechanical properties, namely their friction coefficient and durability. Although FEP showed increased current and voltage output compared with PTFE, the latter was preferred by the group for its superior transferred charge versus applied forces. This means that PTFE-based designs required a smaller driving force to operate and consequently suffered less material wear, proving the material ideal for this type of application. Specifically, the single R-TENG design fabricated from PTFE had an output of 160 nA and an open circuit voltage of 126 V when operated at 200 rpm, while maintaining 89.04% of its output after 50,000 cycles of operation. The advanced, double layered design was thus fabricated using PTFE as the electrification layer. This double TENG design was shown to be able to produce a closed-circuit voltage and short-circuit current of up to approx. 1200 V and 0.35 mA, respectively, with the generated charges having been measured to be approx. 2.2 μC. When matched with an optimum external resistance load (1 MΩ), the harvester had an average output power of 47 mW and peak power of 114 mW.

An interesting variation of these types of R-TENGs addresses the lower triboelectric charge that is generated in the case of non-contact mode of operation. While non-contact mode R-TENGs tend to be more robust due to the minimized friction between the materials, they also have a lower electrical output than their contact mode counterparts. To this end, various groups have added small patches of soft materials such as paper or polyester fur, which come into contact with the electrification layer, increasing the generated charges. One example of a such design was presented by Feng et al., who showed that by adding a paper strip in their design, the R-TENG's open-circuit voltage and short circuit current output increased from 702 V to 2352 V and from 25 μA to 133 μA, respectively, when operated at 600 rpm, while the generated charges increased from 36 nC to 197 nC. This increase in electrical output was paired with significant robustness of the device, which showed 100% stable output after 1,000,000 cycles [32].

In another example, Li et al. presented a similar concept using polyester fur in their design [33]. The group tested their design at 900 rpm, reporting a DC voltage output of 15 kV (and an AC voltage output of 10 kV), with the generated charges reaching a value of 516 nC. Regarding the power output of R-TENG, it was found to match with an external load of 110 MΩ, due to the inherent high internal impedance of non-contact TENGs, providing an output of 201.83 mW. To further test their design, the group reported they used the harvester to charge a 5.5 nF capacitor from 0 V to 6.8 kV in just 38 s.

Another approach to increase the amount of generated charges on the triboelectric surfaces of R-TENGs is the one proposed by Long et al. in 2021 [34]. In this design, a rotating, freestanding electrode R-TENG is coupled with a voltage-multiplying circuit (VMC) that can be charged by the rotating TENG and can subsequently induce a fast increase in charge density on the R-TENG itself, greatly enhancing its output. The TENG's stator consists of 12 radially arranged aluminum electrodes, whose surface is covered with a thin polyamide film. The rotator was fabricated by covering six radial segments of an acrylic disk with PTFE, covering the rest of the disk with copper electrodes to act as excitation electrodes, which are also covered with a thin layer of polyamide. TENG was operated in non-contact mode, with a 350 μm gap between the stator and the rotator.

The operating principle of this design is that as the TENG starts to rotate, it also starts charging the VMC, which in turn starts injecting increasing charges to the copper excitation electrodes, up to the point where it reaches a saturation state and maximum output. When the device was operated at 300 rpm, its voltage output under external load of 10 MΩ, current and charge were measured to be 470 V, 76 μA and 1 μC, respectively, while the peak power of 34.68 mW was obtained when the TENG was matched with a 30 MΩ external load resistance. The tribogenerator was also tested at different rotation velocities (60–600 rpm), and its output AC current and voltage amplitudes were found to increase up to approx. 120 μA and 700 V, respectively. The group also tested the stability and structural integrity of their device and showed that after intermittent operation for 15 days the stability of charge on PTFE decreased only slightly and the electrical output of the device after 100,000 cycles was also reported to be relatively stable.

Another approach to enhancing the output of R-TENGs of the radially segmented disk structure has been demonstrated by Han et al., whose design featured a combination of an energy storage unit, an escapement mechanism and a resonator connected with a R-TENG [35]. The arrangement of this generator allows the capturing of sporadic and low-frequency ambient mechanical energy, which it subsequently transmits to a non-contact, freestanding electrode R-TENG.

The above structure results in an electrical output of fixed frequency regardless of the frequency of the mechanical input, while additionally it is capable of up-converting it resulting in enhanced electrical output. The group tested different materials combinations before settling for a combination of micropatterned Nylon and PTFE for the rotator, over aluminum electrodes on the stator. The maximum output voltage, charge density and current density of the harvester for input rotation of 0.067 Hz were reported 320 V, 2.84 μC/m^2 and 0.59 mA/m^2, respectively. The average output power density under these operating parameters was calculated to be 41 mW/m^2 when matched with an external load of 33 MΩ resistance.

The radially segmented disk design has proven to be extremely versatile due also to the stacking possibility which allows the development of vertical architectures, by introducing new components on additional disk layers. One such example is the wireless transmission module coupled on a R-TENG, presented in 2018 by Jie et al. [36]. In this novel design a freestanding electrode TENG is coupled with ferroalloys acting as collectors, which utilize Maxwell's displacement currents, thus developing a wireless energy delivery (WED) system. In fact, their work combines a previously demonstrated wireless TENG developed by the same group [37]. The system consisted of two parts, a contact mode, freestanding electrode TENG and a contactless part. The contact mode TENG consists of a rotator and a stator, similar to the designs studied earlier. The rotator was made of PCB with radial Au electrodes on its backside and four polypropylene (PP) sectors on its top side, which are used to preserve the electrostatic charges generated by the sliding motion of the TENG. The stator, on the other hand, was made of PCB with radial Sn electrodes on its backside and a PTFE film on its top side, acting as the electrification layer.

The contact mode TENG operates in a similar way to the ones previously reported by other authors. In this case, however, by utilizing the periodically changing electric displacement field, the group managed to transfer the triboelectric energy from the contact mode TENG to the ferroalloy collectors in a wireless manner. The device was operated at 500 rpm, with the contact type TENG producing approx. 2 mA and 110 V, while for the wireless TENG the reported rectified current was reported to reach approx. 3 μA and its maximum power density was calculated at 21.8 mW m^{-2}.

6. Hybrid Nanogenerators

Regardless of their specific design triboelectric nanogenerators in general and R-TENGs in particular exhibit a low current output as compared to their voltage. This has a significant impact on the amount of power R-TENGs are capable of delivering in a given system. An approach to address this matter is to couple the R-TENG with another type of power generator, so that they may operate complementary to one another. The most obvious association in this case is the design of electromagnetic generators (EMG). Many research groups have explored hybrid designs which include a R-TENG and an EMG operating simultaneously, although other types of energy harvesters such as piezoelectric ones have been also explored [38][39][40][41].

Many researchers have developed hybrid energy harvesters aiming to convert wind energy to electricity, which can be implemented from small scale to large scale installation, or even used as portable energy sources for low-power electronic devices. Cao et al. reported the development of a rotating-sleeve type hybrid generator, which combined a R-TENG and an EMG [42]. The R-TENG in this design has a coaxial cylinder structure, with FEP film on the stator acting as an electrification layer and radially arrayed copper strips acting as both electrodes and as the second electrification layer. On the outer surface of the stator, a series of also radially arrayed magnets were fitted, which when coupled with the intertwined coils placed on the rotor grooves complete the EMG. The hybrid harvester is driven by a fitted propeller, which converts wind energy to rotational motion and subsequently to electrical, exploiting both the triboelectric and the electromagnetic effect.

While the electrical output of the EMG depends on the rotation speed of the rotor, the voltage output of the R-TENG remains constant, as is expected by the theoretical analysis of the triboelectric effect. In order for both types of harvesters to be exploited simultaneously, however, a step-down transformer is required to achieve impedance matching between them, which in this case the group reported to result at a load resistance of 8 kΩ and 7 kΩ for the R-TENG and the EMG, respectively. The device was tested for its electrical output at various rotating speeds and the group reported that the maximum power output was obtained at 250 rpm. The output V_{oc} and I_{sc} at 250 rpm were determined to reach 48 V and 1 mA, while when the hybrid harvester was matched with an external load of 8 kΩ resistance it put out 13 mW.

A similar approach for harvesting low-frequency mechanical energy from sea waves was described by Feng et al. in their work of 2021, featuring a swinging-motion energy harvester [43]. The harvester was based on coaxial cylinders structure, with a non-contact R-TENG made of FEP and copper electrodes, with a set of hair brushes for soft, partial contact and a set of magnets and coils comprising the EMG. On the exterior of the outer cylinder, three vertical flaps were used to transform the mechanical energy of waves to rotation.

The R-TENG consists of copper electrodes and FEP which acts as the electrification layer of the non-contact TENG, and a set of rabbit fur patches which allow for soft contact electrification, enhancing the generation of triboelectric charges on FEP. On the other hand, three copper coils are paired with equivalent in number neodymium magnets to compose the EMG, with the magnets also acting as proof masses, leading to an oscillating motion, similar to that of a pendulum. The two individual generators were connected in parallel and the hybrid energy harvester was reported to achieve a peak power density output of 10.16 W/m^3 and an average power density of 0.23 W/m^3 for an external agitation of 0.1 Hz and a matched external load of approx. 100 MΩ.

A different approach to harvesting the energy available in water waves was put forward by Zhao et al. in 2021, whose work featured a hybrid R-TENG/EMG energy generator based on the conversion of heaving motion due to buoyancy to rotational [44]. A set of gears is used to convert the heaving of a buoy to a unidirectional motion of a belt, with the assistance of two pulleys. The belt, which is connected to the shaft of the harvester, drives the rotation of the cylindrical structure allowing the subsequent transformation of mechanical energy to electrical by the R-TENG and the EMG.

The R-TENG design is based on coaxial cylinders design, where a set of nylon brushes situated on the rotator come into contact with PTFE segments placed on the stator, inducing triboelectric charges, which in turn induce a charge difference between a pair of copper electrodes, in a mechanism similar to that of a freestanding electrode. For EMG, six copper twined coils on the stator are coupled with twelve magnets of opposing pole direction on the driving plate, generating electricity via electromagnetic induction. The group tested the hybrid energy harvester at various rotation speeds, reporting an average power density output of 10 W/m^3 for the R-TENG element, when attached to an external load of 8 MΩ resistance, and 4.19 W/m^3 for the EMG matched with a 100 Ω external load. Studying the charging capabilities of the hybrid energy harvester, the group reported they observed that in the early charging stages, EMG was the prevalent charger, while R-TENG took over in the later stages, providing increasing electricity to the capacitor. The device was shown to be capable of charging a 1 mF capacitor up to a potential of 10 V within 150 s.

Fang et al. developed a wind-cup-driven hybrid R-TENG/EMG harvester, in which a radially segmented disk R-TENG is coupled with vertically installed, cone-shaped rollers containing the magnets of the EMG, while eight twined copper coils are placed on the inner walls of the device's casing [45].

The group tested PTFE, PVDF, and FEP as electrification materials for R-TENG before settling on FEP as the material of choice, owing to the combination of significantly increased charge generation, output voltage, and current. The design was also tested for its sizing parameters, i.e., the number of coils and magnets, as well as the electrical output of the hybrid harvester for different wind speeds. The maximum power density output of the hybrid design was reported to be 0.27 W/m^3 when matched with an external load of 60 MΩ resistance. It is worth mentioning that the individual harvesters displayed vastly different optimum matching impedances, with the maximum power for the R-TENG being 1.8 mW at 60 MΩ and that of EMG 62 mW at 660 Ω. The group also studied the robustness of the hybrid energy harvester, reporting a constant electrical output after approx. 35,000 cycles of operation.

Another design of a hybrid harvester aimed at transforming wind energy to electricity was presented by Guo et al. in 2019 [46]. In their work, a pinwheel-based design is presented, incorporating a radially segmented disk type R-TENG and a stator-rotator configuration of intertwined coils and magnets, with the magnets having been fitted on the rotator and the coils on the stator.

This pinwheel hybrid R-TENG/EMG energy harvester was reported to provide uninterrupted electrical output in a range of measured wind speeds, owing to its dual energy conversion mechanism. At low wind speeds, the output of EMG was negligible, but the R-TENG was proven capable of providing 24 V (V_{oc}) and 1.8 μA (I_{sc}). At higher wind speeds, the power-to-weight ratio of R-TENG and EMG were reported to be 0.12 W/g and 0.26 W/g, respectively, showcasing the device's capability to be used as a light-weight, portable energy harvester for low-power electronics.

The use of external blades to the design of R-TENGs has already been demonstrated to be a popular design feature for harvesting the mechanical energy from both wind and water currents. One such design was presented by Zhang et al. in 2016, who expanded the simple design of radially segmented disk R-TENGs by adding a set of twined coils and magnets to benefit from a hybrid energy generation mechanism [47].

The device was intended to be used in driveways, harvesting the air drafts generated by passing vehicles. The group tested the hybrid harvester at various rotation speeds, reporting a maximum 10.8 W/m^3 volume power density output for the R-TENG when matched with a 50 MΩ external load, while the EMG reached 51.5 W/m^3 at a 400 Ω matching impedance. A step-down transformer was included to decrease the impedance of the R-TENG, leading to a maximum output of 55.7 W/m^3 for the hybrid design when matched at 700 Ω, while the maximum voltage and current output were measured to be 3.5 V and 5 mA, respectively.

A different type of hybrid R-TENG-based energy harvester was proposed by Zhao et al., who expanded the radial flap design of an R-TENG by incorporating a piezoelectric nanogenerator (PENG) in the rotating flaps [48]. The simple yet versatile structure of this R-TENG is comprised of a series of radial flaps fabricated by a number of sandwiched layers, driven by wind cups attached to the mutual shaft. The layered structure consists of a single-electrode, contact-separation R-TENG based on PTFE and aluminum, and alternating PVDF and gold layers that constitute the PENG.

The group tested reference PENG and R-TENG devices and compared them to the hybrid structure under different rotation speeds, while also exploring the effect of external loads of resistance on the output of each design. The hybrid harvester displayed superior voltage and current output, and its matching impedance, after incorporating a transformer for the R-TENG, was determined to be at approx. 250 kΩ. The maximum electrical output of the hybrid harvester was reported to be 210 V (V_{oc}) and 395 μA (I_{sc}) when driven at 100 rpm, and the corresponding surface power density output was 6.04 mW/cm^2.

From the works presented so far, it becomes apparent that rotating triboelectric generators are versatile energy harvesters. The large range of possible designs and configurations allows their use in various different environments and makes possible the transformation of mechanical energy from a wide range of sources, from wind and water flow, to rotating machinery parts and even human motion. In addition, the performance of these energy generators can be further improved following different strategies, by enhancing the properties that are intrinsic to the triboelectric effect, such as the effective area of contact of the electret materials or the induced charges on their surfaces, or by coupling the R-TENGs with other types of energy harvesters for a synergistic effect. A collection of energy harvesters based on R-TENGs is presented below in **Table 1**, along with key characteristics of their structure and electrical output.

Table 1. R-TENGs in energy harvesting applications.

Reference	Dielectrics	Electrodes	Mode of Operation	Electrical Output Characteristics
Xie et al. [49]	PTFE (ICP) PET	Aluminum	Contact	V_{oc}: 250 V Q_{sc}: 140 nC

				I_{sc}: 0.25 mA (1 GΩ) P: 12 mW (1 MΩ)
Rodrigues et al. [5]	PTFE Nylon 6.6 Kapton	Aluminum	Contact	V_{oc}: 102.2 V (44 L/min) Q_{sc}: 8.1 μC (44 L/min) I_{sc}: 120 mA/m^2 (44 L/min) Pd: 6.1 W/m^2 (44 L/min)
Du et al. [6]	Kapton PTFE (ICP)	Copper	Contact	V_{oc}: 280 V (120 rpm) Q_{sc}: - I_{sc}: 78 μA (120 rpm) Pd: 2.54 W/m^2 (120 rpm, 5 MΩ)
Zhang et al. [10]	PTFE (ICP)	Aluminum	Contact	V_{oc}: 55 V (800 rpm) Q_{sc}: - I_{sc}: 20 μA (800 rpm) Pd: 3.1 mW/m^2 (800 rpm)
Bai et al. [50]	PTFE (PTFE nanoparticles)	Copper	Contact	V_{oc}: 400 V (1000 rpm) Qd_{sc}: 24.5 μC J_{sc}: 90 μA (1000 rpm) Pd: 36.9 W/m^2 (1000 rpm)
Zhang et al. [12]	FEP (ICP)	Copper	Non-Contact	V_{oc}: 1661 V (2000 rpm) Q_{sc}: 46 nC I_{sc}: 12 μA (2000 rpm) Pd: 16.5 mW/m^2 (2000 rpm)
Feng et al. [13]	FEP	Copper	Non-Contact	V_{oc}: 120 V Q_{sc}: 46 nC I_{sc}: 1.52 μA P: 159 μW (100 MΩ)
Jung et al. [14]	FEP	Aluminum	Non-Contact	V_{oc}: 395 V (0.33 Hz) Q_{sc}: 46 nC I_{sc}: 7.3 μA (0.33 Hz) Pd: 117 μW (0.33 Hz, 70 MΩ)
Kim et al. [18]	PTFE Water	Aluminum	Contact	V_{oc}: 27.2 V (200 rpm) Q_{sc}: - I_{sc}: 3.84 μA (200 rpm) P: 19.1 μW (200 rpm, 20 MΩ)
Le et al. [19]	PVDF (phase inversion) Water	Copper	Contact	V_{oc}: 1.5 V (18 rpm) Q_{sc}: 2.03 nC (18 rpm) J_{sc}: 11.94 nA/cm^2 (18 rpm) Pd: 18.48 nW/cm^2 (18 rpm, 20 MΩ)
Lin et al. [23]	Kapton (ICP)	Gold Aluminum	Contact	V_{oc}: 230 V (500 rpm) Qd_{sc}: 40 μC/m^2 (500 rpm)

				J_{sc}: 29 mA/m^2 (1000 rpm) Pd: 1 W/m^2 (10 MΩ)
Zhu el al. [24]	FEP	Gold Copper	Contact	V_{oc}: 850 V (3000 rpm) Q_{sc}: 0.32 μC I_{sc}: 3 mA (3000 rpm) Pd: 19 mW/m^2 (3000 rpm, 0.8 MΩ)
Zhou et al. [25]	PTFE	Copper Steel	Contact & Non-Contact	V_{oc}: 300 V (150 rpm) Q_{sc}: 24 μC/m^2 (150 rpm) I_{sc}: 60 μA (150 rpm) P: 2.29 mW (150 rpm, 20 MΩ)
Kuang et al. [26]	PTFE	-	Contact	V_{oc}: 200 V (500 rpm) Q_{sc}: - I_{sc}: 0.75 mA (500 rpm) Pd: -
Yong et al. [27]	FEP	Copper	Contact	V_{oc}: 306 V Q_{sc}: - I_{sc}: 32 μA P: 5.2 mW
Cao et al. [28]	FEP Rabbit fur	Copper	Contact	V_{oc}: - Q_{sc}: 389 nC (30 rpm) I_{sc}: 3.23 μA (30 rpm) P: 14. 8 μW (30 rpm, 1.1 GΩ)
Lin et al. [30]	PTFE (ICP) Nylon	Copper	Non-Contact	V_{oc}: 160 V Q_{sc}: 75 nC I_{sc}: 1.5 μA P: 74 μW (100 MΩ)
Zhang et al. [31]	PTFE Kapton	Copper Aluminum	Contact	V_{oc}: 1200 V (600 rpm) Q_{sc}: 2.2 μC I_{sc}: 0.35 mA (600 rpm) P_{avg}: 47 mW (1 MΩ)
Feng et al. [32]	PTFE Paper	Aluminum	Non-Contact	V_{oc}: 2352 V (600 rpm) Q_{sc}: 197 nC (600 rpm) I_{sc}: 133 μA (600 rpm) P: 120 mW (600 rpm, 30 MΩ)
Li et al. [33]	PTFE Nylon Polyester fur	Copper	Non-Contact	V_{AC}: 10 kV (900 rpm) Q_{sc}: 516 nC (900 rpm) I_{sc}: 71 μA (900 rpm) P: 201.8 mW (600 rpm, 110 MΩ)
Long et al. [34]	PTFE Nylon	Copper Aluminum	Non-Contact	V_R: 470 V (300 rpm, 10 MΩ) Q_{sc}: 1 μC (300 rpm)

				I_{sc}: 76 µA (300 rpm) P: 34.68 mW (300 rpm, 30 MΩ)
Han et al. [35]	PTFE (nanopatterned) Nylon (nanopatterned)	Aluminum	Non-Contact	V_{oc}: 320 V (0.067 Hz) Qd_{sc}: 2.84 µC/m^2 (0.067 Hz) J_{sc}: 0.59 mA/m^2 (0.067 Hz) Pd: 41 mW/m^2 (0.067 Hz, 33 MΩ)
Jie et al. [36]	PTFE PP	Tin Gold	Non-Contact	V_{oc}: 17.5 V (500 rpm) Q_{sc}: - I_{sc}: 3 µA (500 rpm) Pd: 21.8 mW/m^2 (500 rpm, 7 MΩ)
Hybrid Energy Harvester Designs				
Reference	Combination	Dielectrics	Electrodes	Maximum electrical output characteristics
Li et al. [29]	R-TENG and EMG	FEP	Copper	V_{oc}: - I_{sc}: - Pd_{TENG}: 313 µW (6 MΩ) Pd_{EMG}: 4.3 mW (680 Ω)
Cao et al. [42]	R-TENG and EMG	FEP	Copper	V_{oc}: 48 V (250 rpm) I_{sc}: 1 mA (250 rpm) P_{Hybrid}: 13 mW (250 rpm, 8 kΩ)
Feng et al. [43]	R-TENG and EMG	FEP Rabbit fur	Copper	V_{oc}: - I_{sc}: - Pd_{Hybrid}: 0.23 W/m^3 (0.1 Hz, ~100 MΩ)
Zhao et al. [44]	R-TENG and EMG	PTFE Nylon	Copper	V_{oc}: - I_{sc}: - Pd_{TENG}: 10 W/m^3 (8 MΩ) Pd_{EMG}: 4.19 W/m^3 (100 Ω)
Fang et al. [45]	R-TENG and EMG	FEP Nylon	Aluminum	V_{oc}: 683 V (47.4 V) I_{sc}: - Pd_{Hybrid}: 0.27 W/m^3 (267 rpm, 60 MΩ)
Guo et al. [46]	R-TENG and EMG	FEP	Copper	V_{oc}: - I_{sc}: - Pd_{TENG}: 0.12 mW/g Pd_{EMG}: 0.26 mW/g
Zhang et al. [47]	R-TENG and EMG	PTFE (ICP) Polyurethane	Aluminum	V_R: 3.5 V (700 Ω) I_R: 5 mA (700 Ω)

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				P_{Hybrid}: 55.7 W/m^3 (1000 rpm, 700 Ω)
Zhao et al. [48]	R-TENG and Piezoelectric	PTFE PET	Gold Aluminum	V_{oc}: 210 V (100 rpm) I_{sc}: 395 μA (100 rpm) Pd_{Hybrid}: 6.04 mW/cm^2 (100 rpm, ~250 kΩ)

Friction Self-

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