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Review Article

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Sustainable Energy Generation Using Triboelectric Nanogenerators: Recent Trends and Future Potential

Vivek K. Kamal[1]*, Jude Francis[1], S. Rani[1], Awadhesh Kiran[1], P. Kiran[1] and K. Bindu Kumar[2]

[1] *Advanced Tribology Research Center, Department of Mechanical Engineering, College of Engineering, Trivandrum, Kerala, India*
[2] *Deaprtment of Mechanical Engineering, Government Engineering College Barton Hill, Thiruvananthapuram, Kerala, India*

***Correspondence to:**
Vivek K. Kamal
Advanced Tribology Research Center,
Department of Mechanical Engineering,
College of Engineering,
Trivandrum, Kerala, India.
E-mail: vivekvkamal999@gmail.com

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Abstract

The staggering rate of increase in energy demands over the past decades has ushered in an era of novel energy harvesting techniques and devices, and the triboelectric nanogenerator (TENG) is one such concept that has proven its mettle. The underlying effect by which it operates is termed as triboelectric effect, whereby materials get electrically charged due to contact electrification, as soon as a momentary contact and separation occurs. Unlike other sustainable energy sources, the potential of TENGs lie in its ability to harvest energy from low-frequency ambient mechanical energy. Numerous sustainable energy generation methods exist, but very few explore its use in conjunction with TENGs and its subsequent benefits. This review seeks to bridge that gap, by briefly discussing the various applications employing TENGs to produce energy from sustainable sources such as wind, water, wave, and solar. The future scope of TENG design pointing to the potential of sustainable biodegradable materials and system-based simulation design is also elucidated.

Keywords

Small-scale energy harvesting Technologies, Triboelectric nanogenerators, TENG materials, TENG applications, Self-powered sensors

Introduction

Due to population growth, it is projected that the global energy consumption will reach upto 778 Etajoules by 2035 [1]. Researchers have started looking into alternative energy harvesting techniques that are both sustainable and economical. Consequently, the energy sector has seen a deviation towards non-conventional energy sources such as solar, tidal, and wind owing to their sustainable energy generation. These energy harvesting methods are suitable only on a large-scale and are not suitable for harvesting random mechanical energy. This is where the significance of harvesting energy using novel principles such as triboelectricity comes into play. Triboelectric effect is the phenomenon by which two dissimilar materials transfer charges when brought into contact and separated shortly thereafter. Fan et al. [2] was the first to employ this principle to develop a device capable of harvesting energy, which was called as TENG. TENG uses contact electrification and electrostatic induction to harvest almost any kind of ambient mechanical energy into electricity. Based on the relative motion of the two dissimilar materials in a TENG, there are 4 fundamental working modes: freestanding triboelectric layer mode [3], vertical contact mode [4], single electrode mode [5], and lateral sliding mode [6], which are given in figure 1.

The applications of TENGs span across numerous industries and use cases such as energy recovery of human movement as an energy supply for wearable equipment [8], medical equipment, and sensors, in the forms of watches, luminous shoes, and pacemakers [9] which is related to biomedical engineering [10].

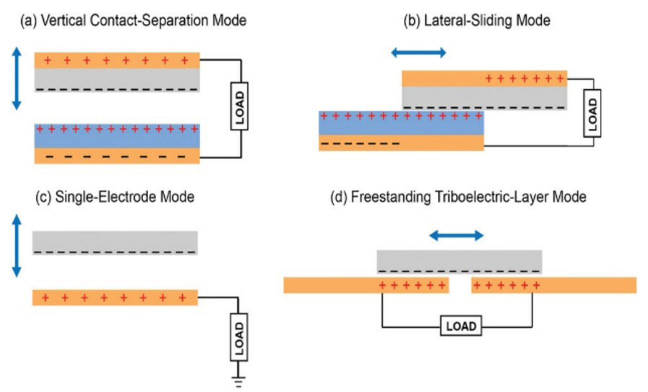

Figure 1: Modes of operation of TENG: **(a)** Vertical contact-separation mode (CS-mode) **(b)** Lateral sliding mode (LS-mode) **(c)** Single-electrode mode (SE-mode) and **(d)** Freestanding triboelectric-layer mode (FT-mode). Reproduced with permission from [7] Copyright 2018 Wiley License Number: 5415450772565.

The material selection for TENGs and the output generated are highly correlated. To obtain a higher output, it is advisable to choose materials farther apart in the triboelectric series [11] (shown in figure 2). The triboelectric series is essentially an ordered list of materials arranged in accordance with their triboelectric charge density which is a function of the material's ability to gain or lose electrons [12]. Over the years, the series has been expanded to accommodate even semiconductors, natural fibres, and biodegradable polymers [13].

To maximize the output performance, researchers have made numerous surface modifications physically as well as chemically [14-16]. Moreover, the recent focus on sustainability and environment-centric design have prompted researchers to explore biodegradable TENGs with chemical modifications yielding higher output. Plant-based [17], paper-based [18-20], animal-hair based [21], mustard seed [22] which has found a notable market in TENG design. Thus, TENGs provide a promising way to harvest energy sustainably.

The problem with most existing sustainable energy harvesting sources such as wind, water and wave are that they often employ electromagnetic generators (EMG) for the final stage of energy conversion whose output is dependent on the rotor frequency. Consistently maintaining the minimum wind speed of 4 m/s required for wind energy harvesting turbines to generate output is a challenging task. Since majority of the random energy dissipated has low frequencies, EMGs are not as efficient as TENGs at such low values [23]. Similarly, in the case of solar energy harvesting devices, almost 90% of the solar cells in the market belong to the first-generation type made of silicon whose conversion efficiency is low [24]. The focus has shifted towards novelties in this area, such as ultra-thin solar films, multi-junction, perovskite, organic solar cells, etc. One such novel approach employed a droplet-based TENG in tandem with a solar cell thereby resulting in a boost in efficiency by 20% [25].

Thus, it is possible to seek out a middle ground employing TENGs in conjunction with other sustainable energy sources such as solar, wave, wind, tidal, and even biodegradable materials. This paper seeks to provide a comprehensive review of the different ways by which TENGs have been coupled with sustainable sources such as water, wind, sunlight and biodegradable materials to generate energy. Finally, a future paradigm shift in TENG design from physical fabrication to simulation-based outlook is touched upon to show sustainable design workflows can also be adopted for analysis and design.

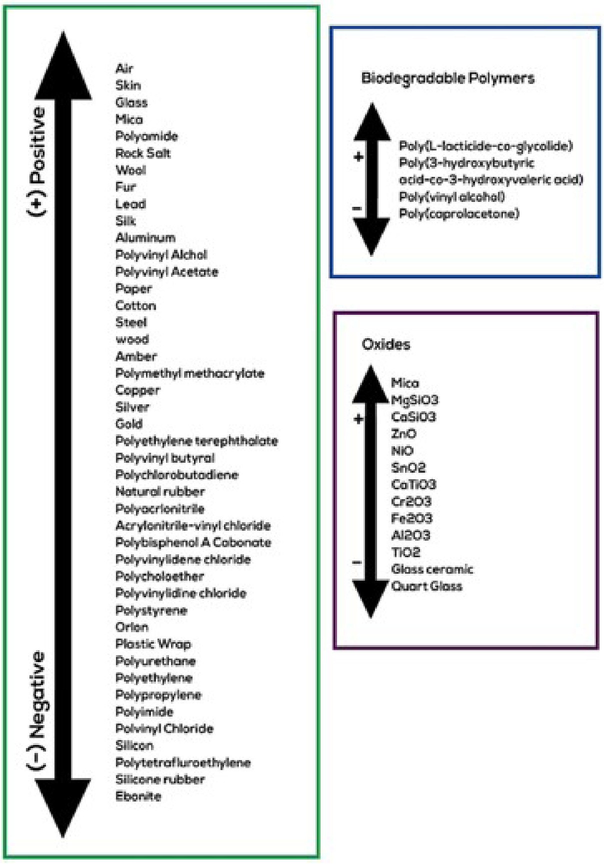

Figure 2: Triboelectric series [10, 13, 22] Copyright © 2019 American Chemical Society.

Energy Generation Using TENG from Water

Owing to the fact that more than 70% of the earth is covered by water in different forms, energy harvesting techniques based on water have been extensively used throughout the ages. Wave, tidal energy are just a few renewable energy sources to name. Waves breaking on coastal areas alone are estimated to be 2 - 3 TW worth of energy [26]. The concept of wave energy harvesting began around 200 years back and it further developed into EMG to harvest energy. Even though TENGS were fabricated in 2012, it was only after a year later that its use in wave energy applications became evident [27]. Zi et al. also studied the possibility of using TENG for harvesting low-frequency sources [23]. The spherical TENG designs were investigated more in the future to create a better output. In 2019, Cheng et al. proposed a soft contact structure for the inner sphere [28] which yielded an improved output of, V_{OC}- 90 V and I_{SC} - 0.8 μA on real-time waves with 2 Hz frequency. However, the output of most of these spherical TENGs was largely dependent on the water triggering directions. In 2020, a spring-assisted multi-layered structure comprising of a zigzag based Kapton film, was developed to collect multi-directional wave energy [29]. Recently, a biomimetic TENG based on butterfly wings was designed in the shape of a shell with bionic wings (5 pairs) connected to a rocking platform by means of a linear motor to facilitate the swinging action necessary for harvesting energy from the underwater environment. Realizing the importance of the size, shape and weight of the floating TENG, researchers have also extensively studied the nature of water-structure interactions and made modifications in these parameters, to improve the water energy absorption coefficient by means of inertial measurement units [30].

Interestingly, TENG can harvest energy from rain drops in two forms: mechanical impact energy and electrostatic energy. Utilizing this principle, Lin et al. developed a TENG that has a superhydrophobic PTFE layer. A water droplet of size 30 µl obtained 9.3 V, I_{SC} 17 µA, and power 145 µW, respectively. Another water-TENG was used to collect energy from flowing tap water, and the output current and instantaneous power densities obtained were 1.5 µA/cm^2 and 20 mW/cm^2, respectively (shown in figure 3a) [31]. A droplet-based electricity generator capable of harvesting energy from impinging water droplets was fabricated, where the constituent materials were PTFE and Al, on an ITO-coated glass substrate [32, 33]. Nie et al. [18] created a TENG that could harvest the kinetic energy of rainwater using superhydrophobic cellulose paper (Figure 3b), PTFE, and copper. It was observed that when the size of the water droplet increased, the generated voltage and charge increased. This is due to the change in kinetic energy because of the enlarged mass. As the separation distance from the ground rose, the generated voltage rose nearly 5 times. Wu et al. [34] proposed a fully biodegradable water droplet-based TENG made of leaves. As droplets strike the leaf surface, surface charges are developed, consequently bridging the disconnected components to form a closed circuit.

Hybrid TENGs for Blue Energy

In 2014, Su et al. proposed one of the first hybrid TENGs that included a water-TENG and an impact TENG to harvest wave energy as well as work as a distress signal emitter [35]. Lee et al. proposed a spherical TENG which could work in single-electrode mode, freestanding mode, and work as water-TENG [36]. The proposed design was easy to construct, which led to the possibility of hassle-free manufacturing and applications. By 2019, the spherical structure of hybridized TENGs evolved to oblate spheroids which were more efficient than conventional spherical TENGs [37] which consist of an upper half with an arch without spring support and a lower half with PET/Cu film and FEP film.

Hybridization of TENG with EMG started around 2014 by Zhang et al. [38], in which the properties of TENG and EMG were first evaluated from a purely theoretical standpoint. Later, they also designed the first hybrid TENG-EMG energy harvesting system. Various designs have been proposed thereafter, such as a fully enclosed energy harvester (in which a rolling TENG and an EMG were integrated into one single unit) [39], a hybrid TENG-EMG by Guo et al. [40] which was water-proof, a hybrid nanogenerator where the TENG had a spiral-interdigitated-electrode and a wrap-around EMG by Wen et al. [41]. In pursuit of optimal structures, innovative designs such as the Edinburgh duck were later used. Here, Saadatnia et al. [42] merged a TENG and an EMG to create a hybrid generator having an efficiency close to 55% at low frequencies (about 2.5Hz). Different hybrid nanogenerators such as hybrid TENG-piezoelectric nanogenerator [43], hybrid TENG-pyroelectric nanogenerator, etc. were used. Even devices simultaneously incorporating TENG-EMG and PEG have been developed to obtain synergistic output from all 3 mechanisms [44].

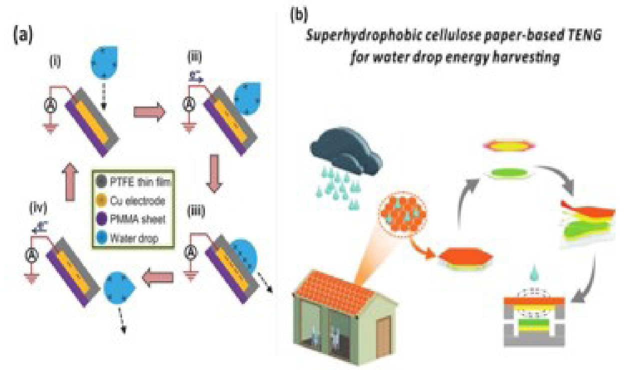

Figure 3: (a) Contact electrification induced working mechanism of the water droplet based TENG. Reproduced with permission from [31] Copyright 2014, John Wiley Sons License Number: 5415480024444. **(b)** Super hydrophobic cellulose paper-based triboelectric nanogenerator. Reproduced with permission from [18] Copyright 2020, John Wiley Sons License Number: 5416880480990.

Energy Generation Using TENG from Wind Energy

Traditionally wind power plants use an EMG to harvest the rotational energy of the rotor blades. With the advent of TENG, wind energy harvesters soon started to see innovative designs that could emulate one of the four fundamental modes of TENG, thus generating energy using the principles of triboelectricity. By 2013, there were a plethora of such wind energy harvesting TENGs [45, 46].

Xie et al. [46] proposed a hybrid structure combining two different working modes of TENGs to harvest wind energy. With this structure, they were able to produce a V_{OC} of 250 V and I_{SC} 0.25 mA. By 2014 the research evolved, and Bae et al. [47] were able to create a flutter-driven TENG using PTFE and Au (Figure 4). They showed that even the energy from a flag fluttering in the wind can be harvested properly. The electricity generation in the proposed F-TENG is due to varying contact separation with which they got 250 V and I_{SC} 70 µA, along with 17.5 mW.

Meng et al. [50] suggested another design with a thin film based on segmented contact electrification in which they observed that with proper segmentation of the electrodes, the output can be enhanced up to 502% compared to one TENG with the non-segmented electrode. With further investigations, an improved design of a tree that could harvest wind energy was proposed by Feng et al. [51] for rural hilly areas.

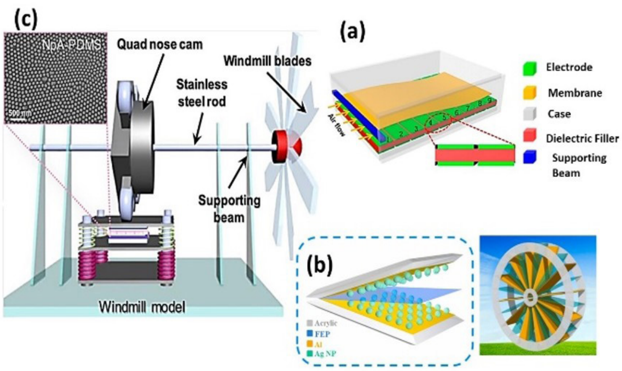

Figure 4: (a) Fluttering type TENG structure based on segmented contact. Reprinted with permission from [47] Copyright American Chemical Society. **(b)** Angle-shaped TENG. Reprinted with permission from [48] Copyright (2019) Elsevier License Number: 5415190295825. **(c)** TENG integrated with windmill model comprising of nanopillar-array architecture. Reprinted with permission from [49] Copyright (2017) Elsevier. License Number 5415190659152.

Bian et al. also designed a tree-like wind energy harvester using TENG for the subway tunnels [52]. Looking for greener revolutions, a lawn-structured TENG was constructed to capture the random wind energy from rooftops [53]. With time, TENG also started to evolve with better output densities and efficient designs. Even though various designs have been proposed most of them fall under either flutter-based design or rotary TENG. The model proposed by Quan et al. [54] could even reach up to a V_{OC} 334 V and an I_{SC} 67 μA and could harvest wind bidirectionally. The main issue with flutter-based TENG was that the energy harvesting efficiency was affected by the contact area of TENG layers. Lin et al. [48] proposed an angle-shaped structure inside a wind wheel structure with the ability to tackle this issue as shown in figure 4b. The windmill structures were also investigated to host TENGs by Dudem et al. [49] by providing a contact separation for the TENG using the blade's rotation (Figure 4c). They were one of the first to investigate the effect of contact stress at the contact area and its effects on the performance of TENG. Various hybrid designs have also been proposed such as piezoelectric-triboelectric hybrid nanogenerators [55, 56], EMG-TENG hybrids [57], etc., and TENGs in combination with other modes of energy harvesting such as solar energy [58], etc. Thus, for low-frequency wind energy harvesting, such hybridisations offer a promising future.

Energy Generation Using Solar Hybrid TENG

Solar energy, being a quite prevalent non-conventional energy source, has had several developments over the years, with recent applications claiming to achieve an efficiency close to 25% using perovskite-based solar cells [59]. Initially, efforts were made to create a solar cell combined with TENG that could also tap energy due to raindrops, this was achieved by covering the solar cell with a PDMS (polydimethylsiloxane) layer [60], however it was not a compact integrated unit but rather an amalgam of two distinct units. The veiled nature of the cells reduced the amount of light falling on it, and consequently, the output also was low. Later, Liu et al. [61] proposed a heterojunction silicon photovoltaic module made up of poly(3,4-ethylenedioxythiophene): poly(styrenesulfonate) (PEDOT: PSS) electrode working on a single electrode mode resulting in I_{SC} 33 nA and V_{OC} 2.14 V. However, such organic semiconductors are found to be prone to damage in the presence of ultraviolet, and humid conditions. Hence, concerted efforts have been made in the direction of transition metal oxides (V_2O_5, MoS_2, and ZnO) due to their large work function [62]. Perceiving this, in 2019, Zhang et al. [63] designed a flexible ultravioelt detector powered by a TENG, wherein an interdigital ITO electrode, and flexible PET adhered by FEP (as shown in figure 5b) is used to form the triboelectric part and ZnO NP film forms the photo-sensing part. An improvement in the energy conversion efficiency was observed on using nano-wrinkled PDMS as the triboelectric layer from 12.55% to 13.57%, with an increase of 385.5% and 299.1%, for the open circuit voltage and short circuit current, respectively [65]. Furthermore, in 2020, a carbon dot-based composite layer was created to improve the transmittance of the photovoltaic cell combined with the ionic conductor of the droplet-based TENG (Figure 5a). This resulted in a rise in efficiency from 13.6% to 14.6% [64]. A silver/ PDMS sub-cell coupled on top of a monocrystalline silicon solar cell sharing an aluminum electrode mutually has shown an increase in conversion efficiency to 22.04% [25]. All these studies indicate the potential of incorporating TENGs into solar cells to enhance energy generation and thereby extend the range of applications and devices that can be powered sustainably.

Future Trends in Triboelectric Energy Generation

Biodegradable TENGs

Apart from using TENGs in conjunction with other sustainable energy sources, another way to generate energy sustainably is by directly using a TENG that is biodegradable. The energy thus generated would solely rely on triboelectricity. There are different biodegradable polymers like polycaprolactone, polyvinyl alcohol (PVA), poly(3-hydroxybutyric

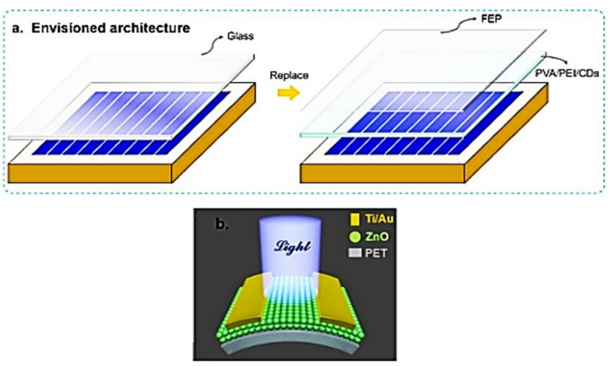

Figure 5: (a) Solar-droplet hybrid TENGs with carbon-dot based TENGs for enhanced output power. Reprinted (adapted) with permission from [64]. Copyright (2020) American Chemical Society. **(b)** Flexible hybrid UV photodetector TENG. Reprinted (adapted) with permission from [63]. Copyright (2020) American Chemical Society.

acid-co-3-hydroxyvaleric acid), which can be used as friction layers for biodegradable TENG. These synthetic degradable polymers have been used to develop *in-vivo* biomechanical energy harvesters [10]. It was the first time a fully biodegradable TENG was employed for powering a medical device that could be implanted into the body without any adverse effects on the patient. Biodegradable materials like papers are also largely developed as friction layers for TENGs. Chi et al. [66] used rice paper along with transparent ink as friction materials which gave a V_{OC} 244 V and an I_{SC} 6 μA. Even before that, Feng et al. [19] used the gum wrapper, [67] to develop a TENG that had various applications like self-powered cathodic protection for corrosion prevention, antifouling, etc. Similarly, an interlocking Kirigami pattern [68] was used for developing a simple printer paper-based TENG that can generate a maximum V_{OC} of 115.49 V (Figure 6a).

A lightweight single-electrode based on edible materials was proposed by Khandelwal et al. [69] using rice paper as the substrate and edible silver leaf layer acted as the active layer. Similarly, Sun et al. [70] used degradable cellulose easily obtained from plant vegetation to develop a triboelectric-piezoelectric nanogenerator. Recently researchers have used biodegradable TENGs by layering poly lactic-co-glycolic acid with silver nanowire on PVA in between to develop self-powered electronic skin (e-skin). It can aid in the real-time monitoring of a person's whole-body joint movement and physiological signal (Figure 6b) [71]. Wang et al. produced a DB-TENG with polyimide and different doped PVA films capable of sensing the stress of about 0.6 N/cm^2 on the skin while simultaneously monitoring the pulse accurately [72].

A silk fiber-based implantable TENG has been used for epilepsy attack monitoring and drug delivery [73]. One study employed chemically modified cellulose and lignin as the dissimilar triboelectric material and graphitized lignin as the charge-capturing electrode [74]. A TENG based on ionically cross-linked gelatin offers exceptional power output (325 Mw/m^2) and efficiency of energy conversion is also commendable (~70%) and is self-healing, thereby giving it the property to recuperate back to its initial electrical properties [67].

Simulation-based structural modeling and design

Optimizing the output performance of TENGs require intensive experimentation involving variations in the process parameters. However, physically fabricating these devices could be time-consuming and can even pose environmental damages. Recently, a shift from the physical fabrication of TENGS to simulation-based methods has been observed for judging the efficacy of the developed design. Software packages, such as COMSOL, ANSYS and SPICE (Simulation program with integrated circuit emphasis), capable of tackling finite element formulations at a faster pace have risen over the years. A simulation study was done for the triboelectric pair PDMS and nylon and multiple parameters such as dielectric thickness, dielectric constant and even micro-surface patterns were simulated using COMSOL [75]. Even multiple modes including vertical contact-separation, linear sliding, and rotary-freestanding can be simulated using COMSOL [76]. Some of the more commonly used SPICE programs for TENGs are OrCAD and Multisim [77]. TENG can be simulated using the SPICE software by embedding a capacitor connected in series with a voltage source and a mathematical function of the mechanical motion input (sinusoidal waveform) [78].

Most simulation-based approaches take the liberal assumption of a capacitor model for the charge transfer process in a TENG. However, in reality, different factors such as temperature, humidity, surface morphology, etc., all have a direct effect on the output generated.

Hence, a system-based approach should be followed to capture the effect of these factors present in the system. A schematic representation of this system-based simulation methodology is shown in figure 7. This paradigm shift in modelling can be brought about by employing Modelica. Modelica is an object-oriented modelling language used to model and simulate complex multi-domain systems [79].

Conclusion

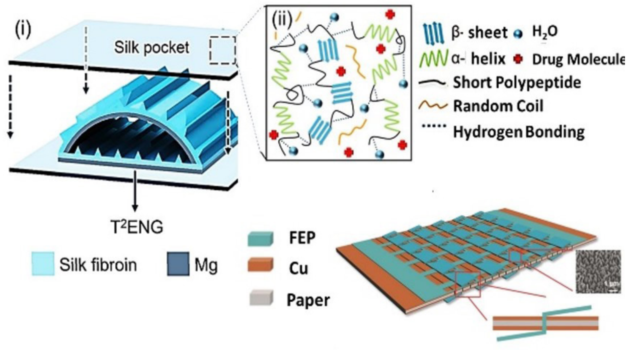

Figure 6: **(a)** Stretchable TENGs with Kirigami based-interlocking patterns made of paper. Reprint with copyright from [68]. **(b)** Self-powered multifunctional transient bioelectronics. Reproduced with permission from [68, 73]. Copyright 2018, John Wiley and Sons, License Number: 5415241318375.

The rising energy demand has necessitated the advent of alternate energy harvesting techniques that are both sustainable and economical. To address this, alternate energy harvesting devices called TENGs have been developed. TENGs are devices capable of harvesting mechanical ambient energy to generate high voltage low current. However, it offers the most promising result when used in conjunction with other sustainable sources. Numerous sustainable energy generation

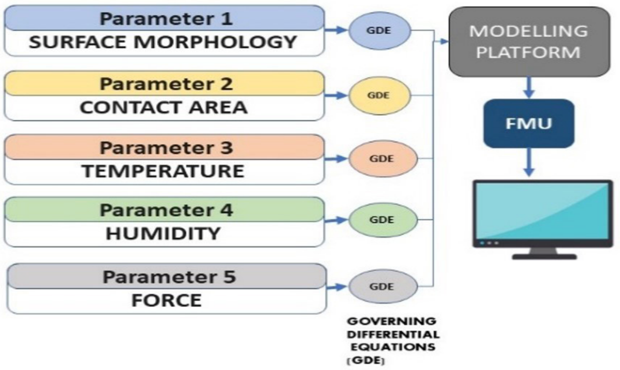

Figure 7: Schematic representation of system-based simulation.

methods exist, but very few explore its use in conjunction with TENGs and its subsequent benefits. Different hybridizations of TENGs coupling EMGs, piezoelectric nanogenerators, etc., have also been fabricated for different applications. The output of EMG wind turbines can be enhanced by incoperating TENGs of different modes such as sliding contact and free-standing mode. Even solar cells can act as droplet energy harvesters by using triboelectric panels which can enhance the output. Apart from using TENGs along with sustainable energy sources, it is possible to design sustainable TENGs by using biodegradable materials. To scale the production of TENGs, it is essential to reinvent the whole process of TENG design. One way of practically implementing this is by switching towards simulation-driven approaches instead of physically fabricating each model. Commercial software such as COMSOL and LT SPICE, have been used to build an equivalent circuit to study the effect of charge generation with variations in parameters. Modelica, an open-source object-oriented programming language, is a popular option for system-based simulation in the industry. By adopting it for TENG simulation, one could potentially incorporate several distinct design parameters into a single system working synergistically. Thus, TENGs have the potential of revolutionizing the world by offering sustainable alternatives to energy generation.

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Conflict of Interest

The authors declare no conflict of interest.

References

1. Zohuri B. 2020. Nuclear Fuel Cycle and Decommissioning. In Ud-Din Khan S, Nakhabov A (eds) Nuclear Reactor Technology Development and Utilization. Woodhead Publishing, pp 61-120.
2. Fan FR, Tian ZQ, Wang ZL. 2012. Flexible triboelectric generator. *Nano Energy* 1(2): 328-334. https://doi.org/10.1016/j.nanoen.2012.01.004
3. Azad P. 2017. Triboelectric nanogenerator based on vertical contact separation mode for energy harvesting. In International Conference on Computing, Communication and Automation, Greater Noida, India.
4. Wang ZL, Lin L, Chen J, Niu S, Zi Y, et al. 2016. Triboelectric Nanogenerator: Lateral Sliding Mode. In Wang ZL, Lin L, Chen J, Niu S, Zi Y (eds) Triboelectric Nanogenerators. Springer Cham, pp 49-90.
5. Akram W, Chen Q, Xia G, Fang J. 2023. A review of single electrode triboelectric nanogenerators. *Nano Energy* 106: 108043. https://doi.org/10.1016/j.nanoen.2022.108043
6. Wang ZL, Lin L, Chen J, Niu S, Zi Y, et al. 2016. Triboelectric Nanogenerator: Freestanding Triboelectric-layer Mode. In Wang ZL, Lin L, Chen J, Niu S, Zi Y (eds) Triboelectric Nanogenerators. Springer Cham, pp 109-153.
7. Wu C, Wang AC, Ding W, Guo H, Wang ZL. 2019. Triboelectric nanogenerator: a foundation of the energy for the new era. *Adv Energy Mater* 9(1): 1802906. https://doi.org/10.1002/aenm.201802906
8. Wang L, Liu W, Yan Z, Wang F, Wang X. 2021. Stretchable and shape-adaptable triboelectric nanogenerator based on biocompatible liquid electrolyte for biomechanical energy harvesting and wearable human–machine interaction. *Adv Funct Mater* 31(7): 2007221. https://doi.org/10.1002/adfm.202007221
9. Ouyang H, Liu Z, Li N, Shi B, Zou Y, et al. 2019. Symbiotic cardiac pacemaker. *Nat Commun* 10: 1821. https://doi.org/10.1038/s41467-019-09851-1
10. Zheng Q, Zou Y, Zhang Y, Liu Z, Shi B, et al. 2016. Biodegradable triboelectric nanogenerator as a life-time designed implantable power source. *Sci Adv* 2(3): e1501478. https://doi.org/10.1126/sciadv.1501478
11. Zhou Y, Deng W, Xu J, Chen J. 2020. Engineering materials at the nanoscale for triboelectric nanogenerators. *Cell Rep Phy Sci* 1(8): 100142. https://doi.org/10.1016/j.xcrp.2020.100142
12. Zou H. 2023. Quantification of Triboelectric Charge Density for a Solid. In Wang ZL, Yang Y, Zhai J, Wang J (eds) Handbook of Triboelectric Nanogenerators. Springer, Cham, pp 243-291.
13. Zhang X, Chen L, Jiang Y, Lim W, Soh S. 2019. Rationalizing the triboelectric series of polymers. *Chem Mater* 31(5): 1473-1478. https://doi.org/10.1021/acs.chemmater.8b04526
14. Xu J, Zou Y, Nashalian A, Chen J. 2020. Leverage surface chemistry for high-performance triboelectric nanogenerators. *Front Chem* 8: 577327. https://doi.org/10.3389/fchem.2020.577327
15. Jeon YP, Park JH, Kim TW. 2018. Highly-enhanced triboelectric nanogenerators based on zinc-oxide nanoripples acting as a triboelectric layer. *Appl Surf Sci* 445: 50-55. https://doi.org/10.1016/j.apsusc.2018.03.125
16. Jeon YP, Park JH, Kim TW. 2019. Highly flexible triboelectric nanogenerators fabricated utilizing active layers with a ZnO nanostructure on polyethylene naphthalate substrates. *Appl Sur Sci* 466: 210-214. https://doi.org/10.1016/j.apsusc.2018.09.249
17. Babu A, Rakesh D, Supraja P, Mishra S, Kumar KU, et al. 2022. Plant-based triboelectric nanogenerator for biomechanical energy harvesting. *Res Sur Interfaces* 8: 100075. https://doi.org/10.1016/j.rsurfi.2022.100075
18. Nie S, Guo H, Lu Y, Zhuo J, Mo J, et al. 2020. Superhydrophobic cellulose paper-based triboelectric nanogenerator for water drop energy harvesting. *Adv Mater Technol* 5(9): 2000454. https://doi.org/10.1002/admt.202000454
19. Feng Y, Zheng Y, Rahman ZU, Wang D, Zhou F, et al. 2016. Based triboelectric nanogenerators and their application in self-powered anticorrosion and antifouling. *J Mater Chem A* 4(46): 18022-18030. https://doi.org/10.1039/C6TA07288G
20. Zhang XS, Su M, Brugger J, Kim B. 2017. Penciling a triboelectric nanogenerator on paper for autonomous power MEMS applications. *Nano Energy* 33: 393-401. https://doi.org/10.1016/j.nanoen.2017.01.053
21. Singh M, Sheetal A, Singh H, Sawhney RS, Kaur J. 2020. Animal hair-based triboelectric nanogenerator (TENG): a substitute for the positive polymer layer in TENG. *J Electron Mater* 49: 3409-3416. https://doi.org/10.1007/s11664-020-08031-y
22. Singh SK, Kumar P, Magdum R, Khandelwal U, Deswal S, et al. 2019. Seed power: natural seed and electrospun poly (vinyl difluoride) (PVDF) nanofiber based triboelectric nanogenerators with high output power density. *ACS Appl Bio Mater* 2(8): 3164-3170. https://doi.org/10.1021/acsabm.9b00348
23. Zi Y, Guo H, Wen Z, Yeh MH, Hu C, et al. 2016. Harvesting low-frequency (< 5 Hz) irregular mechanical energy: a possible killer application of triboelectric nanogenerator. *ACS Nano* 10(4): 4797-4805. https://doi.org/10.1021/acsnano.6b01569
24. Gangopadhyay U, Jana S, Das S. 2013. State of art of solar photovoltaic technology. *Int Conf Sol Energy Photovoltaics* 2013: 764132. https://doi.org/10.1155/2013/764132

25. Zhao L, Duan J, Liu L, Wang J, Duan Y, et al. 2021. Boosting power conversion efficiency by hybrid triboelectric nanogenerator/silicon tandem solar cell toward rain energy harvesting. *Nano Energy* 82: 105773. https://doi.org/10.1016/j.nanoen.2021.105773
26. Wang ZL, Chen J, Lin L. 2015. Progress in triboelectric nanogenerators as a new energy technology and self-powered sensors. *Energy Environ Sci* 8(8): 2250-2282. https://doi.org/10.1039/C5EE01532D
27. Wang ZL. 2014. Triboelectric nanogenerators as new energy technology and self-powered sensors–principles, problems and perspectives. *Faraday Discuss* 176: 447-458. https://doi.org/10.1039/C4FD00159A
28. Cheng P, Guo H, Wen Z, Zhang C, Yin X, et al. 2019. Largely enhanced triboelectric nanogenerator for efficient harvesting of water wave energy by soft contacted structure. *Nano Energy* 57:432-439. https://doi.org/10.1016/j.nanoen.2018.12.054
29. Liang X, Jiang T, Liu G, Feng Y, Zhang C, et al. 2020. Spherical triboelectric nanogenerator integrated with power management module for harvesting multidirectional water wave energy. *Energy Environ Sci* 13(1): 277-285. https://doi.org/10.1039/C9EE03258D
30. Wang X, Gao Q, Zhu M, Wang J, Zhu J, et al. 2022. Bioinspired butterfly wings triboelectric nanogenerator with drag amplification for multidirectional underwater-wave energy harvesting. *Appl Energy* 323: 119648. https://doi.org/10.1016/j.apenergy.2022.119648
31. Lin ZH, Cheng G, Lee S, Pradel KC, Wang ZL. 2014. Harvesting water drop energy by a sequential contact- electrification and electrostatic-induction process. *Adv Mater* 26(27): 4690-4696. https://doi.org/10.1002/adma.201400373
32. Xu W, Zheng H, Liu Y, Zhou X, Zhang C, et al. 2020. A droplet-based electricity generator with high instantaneous power density. *Nature* 578(7795): 392-396. https://doi.org/10.1038/s41586-020-1985-6
33. Guo X, Chen M, Zheng Y, Cui H, Li X. 2023. Triboelectric nanogenerators: theoretical calculations, materials, and applications in net-zero emissions. *J Phys D Appl Phys* 56(50): 504001. https://doi.org/10.1088/1361-6463/acf770
34. Wu H, Chen Z, Xu G, Xu J, Wang Z, et al. 2020. Fully biodegradable water droplet energy harvester based on leaves of living plants. *ACS Appl Mater Interfaces* 12(50): 56060-56067. https://doi.org/10.1021/acsami.0c17601
35. Su Y, Wen X, Zhu G, Yang J, Chen J, et al. 2014. Hybrid triboelectric nanogenerator for harvesting water wave energy and as a self-powered distress signal emitter. *Nano Energy* 9: 186-195. https://doi.org/10.1016/j.nanoen.2014.07.006
36. Lee K, Lee JW, Kim K, Yoo D, Kim DS, et al. 2018. A spherical hybrid triboelectric nanogenerator for enhanced water wave energy harvesting. *Micromachines* 9(11): 598. https://doi.org/10.3390/mi9110598
37. Liu G, Guo H, Xu S, Hu C, Wang ZL. 2019. Oblate spheroidal triboelectric nanogenerator for all-weather blue energy harvesting. *Adv Energy Mater* 9(26): 1900801. https://doi.org/10.1002/aenm.201900801
38. Zhang C, Tang W, Han C, Fan F, Wang ZL. 2014. Theoretical comparison, equivalent transformation, and conjunction operations of electromagnetic induction generator and triboelectric nanogenerator for harvesting mechanical energy. *Adv Mater* 26(22): 3580-3591. https://doi.org/10.1002/adma.201400207
39. Wang X, Wen Z, Guo H, Wu C, He X, et al. 2016. Fully packaged blue energy harvester by hybridizing a rolling triboelectric nanogenerator and an electromagnetic generator. *ACS Nano* 10(12): 11369-11376. https://doi.org/10.1021/acsnano.6b06622
40. Guo H, Wen Z, Zi Y, Yeh MH, Wang J, et al. 2016. A water-proof triboelectric–electromagnetic hybrid generator for energy harvesting in harsh environments. *Adv Energy Mater* 6(6): 1501593. https://doi.org/10.1002/aenm.201501593
41. Wen Z, Guo H, Zi Y, Yeh MH, Wang X, et al. 2016. Harvesting broad frequency band blue energy by a triboelectric–electromagnetic hybrid nanogenerator. *ACS Nano* 10(7): 6526-6534. https://doi.org/10.1021/acsnano.6b03293
42. Saadatnia Z, Asadi E, Askari H, Zu J, Esmailzadeh E. 2017. Modeling and performance analysis of duck-shaped triboelectric and electromagnetic generators for water wave energy harvesting. *Int J Energy Res* 41(14): 2392-2404. https://doi.org/10.1002/er.3811
43. Jurado UT, Pu SH, White NM. 2020. Grid of hybrid nanogenerators for improving ocean wave impact energy harvesting self-powered applications. *Nano Energy* 72: 104701. https://doi.org/10.1016/j.nanoen.2020.104701
44. Tang G, Wang Z, Hu X, Wu S, Xu B, et al. 2022. A Non-resonant piezoelectric–electromagnetic–triboelectric hybrid energy harvester for low-frequency human motions. *Nanomaterials* 12(7): 1168. https://doi.org/10.3390/nano12071168
45. Yang Y, Zhu G, Zhang H, Chen J, Zhong X, et al. 2013. Triboelectric nanogenerator for harvesting wind energy and as self-powered wind vector sensor system. *ACS Nano* 7(10): 9461-9468. https://doi.org/10.1021/nn4043157
46. Xie Y, Wang S, Lin L, Jing Q, Lin ZH, et al. 2013. Rotary triboelectric nanogenerator based on a hybridized mechanism for harvesting wind energy. *ACS Nano* 7(8): 7119-7125. https://doi.org/10.1021/nn402477h
47. Bae J, Lee J, Kim S, Ha J, Lee BS, et al. 2014. Flutter-driven triboelectrification for harvesting wind energy. *Nat Commun* 5(1): 4929. https://doi.org/10.1038/ncomms5929
48. Lin H, He M, Jing Q, Yang W, Wang S, et al. 2019. Angle-shaped triboelectric nanogenerator for harvesting environmental wind energy. *Nano Energy* 56: 269-276. https://doi.org/10.1016/j.nanoen.2018.11.037
49. Dudem B, Huynh ND, Kim W, Kim DH, Hwang HJ, et al. 2017. Nanopillar-array architectured PDMS-based triboelectric nanogenerator integrated with a windmill model for effective wind energy harvesting. *Nano Energy* 42: 269-281. https://doi.org/10.1016/j.nanoen.2017.10.040
50. Meng XS, Zhu G, Wang ZL. 2014. Robust thin-film generator based on segmented contact-electrification for harvesting wind energy. *ACS Appl Mater Interfaces* 6(11): 8011-8016. https://doi.org/10.1021/am501782f
51. Feng Y, Zhang L, Zheng Y, Wang D, Zhou F, et al. 2019. Leaves based triboelectric nanogenerator (TENG) and TENG tree for wind energy harvesting. *Nano Energy* 55: 260-268. https://doi.org/10.1016/j.nanoen.2018.10.075
52. Bian Y, Jiang T, Xiao T, Gong W, Cao X, et al. 2018. Triboelectric nanogenerator tree for harvesting wind energy and illuminating in subway tunnel. *Adv Mater Technol* 3(3): 1700317. https://doi.org/10.1002/admt.201700317
53. Zhang L, Zhang B, Chen J, Jin L, Deng W, et al. 2016. Lawn structured triboelectric nanogenerators for scavenging sweeping wind energy on rooftops. *Adv Mater* 28(8): 1650-1656. https://doi.org/10.1002/adma.201504462
54. Quan Z, Han CB, Jiang T, Wang ZL. 2016. Robust thin films-based triboelectric nanogenerator arrays for harvesting bidirectional wind energy. *Adv Energy Mater* 6(5): 1501799. https://doi.org/10.1002/aenm.201501799
55. Zhao C, Zhang Q, Zhang W, Du X, Zhang Y, et al. 2019. Hybrid piezo/triboelectric nanogenerator for highly efficient and stable rotation energy harvesting. *Nano Energy* 57: 440-449. https://doi.org/10.1016/j.nanoen.2018.12.062
56. Wang Q, Zou HX, Zhao LC, Li M, Wei KX, et al. 2020. A synergetic hybrid mechanism of piezoelectric and triboelectric for galloping wind energy harvesting. *Appl Phy Lett* 117(4): 043902. https://doi.org/10.1063/5.0014484
57. Wang X, Wang S, Yang Y, Wang ZL. 2015. Hybridized electromagnetic–triboelectric nanogenerator for scavenging air-flow energy to sustainably power temperature sensors. *ACS Nano* 9(4): 4553-4562. https://doi.org/10.1021/acsnano.5b01187

58. Wang S, Wang X, Wang ZL, Yang Y. 2016. Efficient scavenging of solar and wind energies in a smart city. *ACS Nano* 10(6): 5696-5700. https://doi.org/10.1021/acsnano.6b02575
59. Park NG. 2020. Research direction toward scalable, stable, and high efficiency perovskite solar cells. *Adv Energy Mater* 10(13): 1903106. https://doi.org/10.1002/aenm.201903106
60. Jeon SB, Kim D, Yoon GW, Yoon JB, Choi YK. 2015. Self-cleaning hybrid energy harvester to generate power from raindrop and sunlight. *Nano Energy* 12: 636-645. https://doi.org/10.1016/j.nanoen.2015.01.039
61. Liu Y, Sun N, Liu J, Wen Z, Sun X, et al. 2018. Integrating a silicon solar cell with a triboelectric nanogenerator via a mutual electrode for harvesting energy from sunlight and raindrops. *ACS Nano* 12(3): 2893-2899. https://doi.org/10.1021/acsnano.8b00416
62. Fu Y, Liu Y, Ma K, Ji Z, Mai W, et al. 2020. Interfacial engineering to boost photoresponse performance and stability of V_2O_5/n-Si heterojunction photodetectors. *J Alloys Compd* 819: 153063. https://doi.org/10.1016/j.jallcom.2019.153063
63. Zhang Y, Peng M, Liu Y, Zhang T, Zhu Q, et al. 2020. Flexible self-powered real-time ultraviolet photodetector by coupling triboelectric and photoelectric effects. *ACS Appl Mater Interfaces* 12(17): 19384-19392. https://doi.org/10.1021/acsami.9b22572
64. Wang L, Wang Y, Wang H, Xu G, Döring A, et al. 2020. Carbon dot-based composite films for simultaneously harvesting raindrop energy and boosting solar energy conversion efficiency in hybrid cells. *ACS Nano* 14(8): 10359-10369. https://doi.org/10.1021/acsnano.0c03986
65. Liu X, Cheng K, Cui P, Qi H, Qin H, et al. 2019. Hybrid energy harvester with bi-functional nano-wrinkled anti-reflective PDMS film for enhancing energies conversion from sunlight and raindrops. *Nano Energy* 66: 104188. https://doi.org/10.1016/j.nanoen.2019.104188
66. Chi Y, Xia K, Zhu Z, Fu J, Zhang H, et al. 2019. Rice paper-based biodegradable triboelectric nanogenerator. *Microelectron Eng* 216: 111059. https://doi.org/10.1016/j.mee.2019.111059
67. Ghosh SK, Kim MP, Na S, Lee Y, Park J, et al. 2022. Ultra-stretchable yet tough, healable, and biodegradable triboelectric devices with microstructured and ionically crosslinked biogel. *Nano Energy* 100: 107438. https://doi.org/10.1016/j.nanoen.2022.107438
68. Wu C, Wang X, Lin L, Guo H, Wang ZL. 2016. Based triboelectric nanogenerators made of stretchable interlocking kirigami patterns. *ACS Nano* 10(4): 4652-4659. https://doi.org/10.1021/acsnano.6b00949
69. Khandelwal G, Minocha T, Yadav SK, Chandrasekhar A, Raj NP, et al. 2019. All edible materials derived biocompatible and biodegradable triboelectric nanogenerator. *Nano Energy* 65: 104016. https://doi.org/10.1016/j.nanoen.2019.104016
70. Sun Z, Yang L, Liu S, Zhao J, Hu Z, et al. 2020. A green triboelectric nano-generator composite of degradable cellulose, piezoelectric polymers of PVDF/PA_6, and nanoparticles of $BaTiO_3$. *Sensors* 20(2): 506. https://doi.org/10.3390/s20020506
71. Peng X, Dong K, Ye C, Jiang Y, Zhai S, et al. 2020. A breathable, biodegradable, antibacterial, and self-powered electronic skin based on all-nanofiber triboelectric nanogenerators. *Sci Adv* 6(26): eaba9624. https://doi.org/10.1126/sciadv.aba9624
72. Wang R, Mu L, Bao Y, Lin H, Ji T, et al. 2020. Holistically engineered polymer–polymer and polymer–ion interactions in biocompatible polyvinyl alcohol blends for high-performance triboelectric devices in self-powered wearable cardiovascular monitorings. *Adv Mater* 32(32): 2002878. https://doi.org/10.1002/adma.202002878
73. Zhang Y, Zhou Z, Fan Z, Zhang S, Zheng F, et al. 2018. Self-powered multifunctional transient bioelectronics. *Small* 14(35): 1802050. https://doi.org/10.1002/smll.201802050
74. Wang R, Ma J, Ma S, Zhang Q, Li N, et al. 2022. A biodegradable cellulose-based flame-retardant triboelectric nanogenerator for fire warning. *J Chem Eng* 450: 137985. https://doi.org/10.1016/j.cej.2022.137985
75. Hasan S, Kouzani AZ, Adams S, Long J, Mahmud MP. 2022. Comparative study on the contact-separation mode triboelectric nanogenerator. *J Electrostat* 116: 103685. https://doi.org/10.1016/j.elstat.2022.103685
76. Cui X, Zhang Y, Hu G, Zhang L, Zhang Y. 2020. Dynamical charge transfer model for high surface charge density triboelectric nanogenerators. *Nano Energy* 70: 104513. https://doi.org/10.1016/j.nanoen.2020.104513
77. Hu Y, Yue Q, Lu S, Yang D, Shi S, et al. 2018. An adaptable interface conditioning circuit based on triboelectric nanogenerators for self-powered sensors. *Micromachines* 9(3): 105. https://doi.org/10.3390/mi9030105
78. Niu S, Zhou YS, Wang S, Liu Y, Lin L, et al. 2014. Simulation method for optimizing the performance of an integrated triboelectric nanogenerator energy harvesting system. *Nano Energy* 8: 150-156. https://doi.org/10.1016/j.nanoen.2014.05.018
79. Huang S, Zuo W, Vrabie D, Xu R. 2021. Modelica-based system modeling for studying control-related faults in chiller plants and boiler plants serving large office buildings. *J Build Eng* 44: 102654. https://doi.org/10.1016/j.jobe.2021.102654