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Opportunities and Challenges in Triboelectric Nanogenerator (TENG) based Sustainable Energy Generation Technologies: A Mini-Review

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A B S T R A C T

Almost ten years after the publication of the first triboelectric nanogenerator (TENG) paper in 2012, this review gives a brief overview of recent technological advances in applying TENG technology to key sustainable and renewable energy applications. The paper examines progress of TENG applications in four key areas such as wearables, wave, wind and transport. TENGs have advanced hugely since its inception and approaches to apply them to a host of freely available sources of kinetic energy have been developed. However, electrical output remains low (mostly less than 500 W/m^2) compared to some other forms of energy generation and the main challenges for the future appear to be further boosting output power and current, fabricating advanced TENGs economically and designing TENGs for lifetime survival in various practical environments. It concludes with a discussion of pressing challenges for realizing the full potential of TENGs in these application areas particularly from the perspective of materials and fabrication. It is noted that considerable research and development should be required to enable large-scale manufacture of TENG based devices. TENGs will be instrumental in the future evolution of the Internet of Things (IoTs), human-machine interfacing, machine learning applications and 'net-zero emission' technologies.

1. Introduction

The word 'Tribo' originated from the Greek word 'rubbing' and "Triboelectric" refers to the transfer of electrons from one surface to another through contact electrification and electrostatic induction. "Nanogenerator" refers to any device made from nanomaterials (typically less than 100 nm), which converts mechanical/thermal energy into electrical energy.

Contact is made between the two charge generating layers through mechanical force and electrons are exchanged between the two surfaces. When separated, electrons are abandoned leaving one surface electro negatively charged and the other electro positively charged. This transferred charge is then shunted during the next contact-separation cycle, through the charge trapping and collecting layers before it is passed to the charge storage layer where it is stored for later use [1]. There are four modes to categorize TENGs (Fig. 1). These are 1). Vertical Contact / Separation Mode, 2) Lateral Sliding Mode, 3) Single Electrode Mode and 4) Freestanding Triboelectric Layer Mode [2]. Each of these modes generate electricity in slightly differing ways but the general operation is the same.

TENGs in recent years have garnered massive attention within the field of renewable energy. First invented by Prof Zhong Lin Wang and his team in 2012, they used TENGs to successfully generate small amounts of electrical energy by coupling the triboelectric effect and electrostatic induction [1-5]. Since then, TENGs have come a long way in their development and TENG research has grown rapidly around the world. This new form of energy generation comes at a time where an energy revolution is under way, and massive steps are being taken to move away from fossil fuels. [4] It also coincides with an era where a plethora of devices and sensors are being developed with ever more advanced functionalities. In the past, the emphasis was on mainly device optimization, but the focus has now turned to the 'energy bottleneck' – *i.e.*, how to sustainably power all these devices (for example, all the portable computing devices and sensors used by people in their daily lives).

This short review paper aims to summarize and encapsulate the very recent advancements in the field of TENGs for energy generation, with particular emphasis on TENGs for wearables, wave, wind and transport applications. The paper concludes with a discussion of future prospects and challenges for TENGs.

2. TENG device advancements

As more applications of TENGs are realized, so does the number of different TENG devices. In this section, novel technologies designed to

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allow TENGs to extract energy from various freely available sources of kinetic energy are reviewed. The various sources of energy are illustrated schematically in Fig. 2.

2.1. Wearable Textile TENGs

In recent years, great effort has been put into the development of textile TENGs (or tTENGs) which are TENGs developed to be easily incorporated into clothing to harness the energy available during human motion. Although the harnessing of human body motion was conceptualized back in 2012, a textile TENG had not yet materialized in practice. Shortly afterwards in 2014, the first paper implementing a textile version of the TENG appeared. Zhou et al [11], successfully created a woven-structured TENG, (W-TENG) which was capable of successfully harnessing human body motion and converting it into electrical energy. The W-TENG was created by weaving together two opposing triboelectric materials (nylon and polyester) and an Ag fabric to act as a conducting material. When the structure is subjected to stretching or compression, charge transfer between the fabrics is the driver for the generation of electrical energy. Since then, T-TENGs have attracted a lot of attention and more intricate and optimized T-TENG designs [12, 13, 14] have emerged.

Dong et al [15] in 2020, successfully integrated a tTENG into the knee joint of clothing. and was able to produce a maximum output of 60V. The tTENG itself consisted of triboelectric materials woven around conducting fabric. These yarns were then knitted together into a patch on the knee joint of a pair of pants. Interestingly, in the same paper, it was noted that the output produced by the tTENG increased after washing. This output, though, is low when compared to the output reported by Wang et al [16] who reported an output of 135V from a single-electrode mode tTENG.

However, a few recent reports show that the output has been improving. For example, Xu et al [17] reported that a tTENG capable of generating an output of 232V had been created and used to successfully power small electronic devices (Fig. 3). This tTENG consisted of two pre-existing fabric materials being knitted onto an Ag fabric. The device was then fitted with a power management module which can convert the AC output of the TENG to DC as well as stabilize the high voltage and low current of the tTENG to successfully power small electronic devices. Work by Xia et al [18], also demonstrated a tTENG which was able to generate a high output of 328 V and 36.15μA. This trend of a steadily increasing output is a *proof of concept* that research into tTENGs is moving in the right direction and in the near future it will be more intrinsically adapted to our power needs.

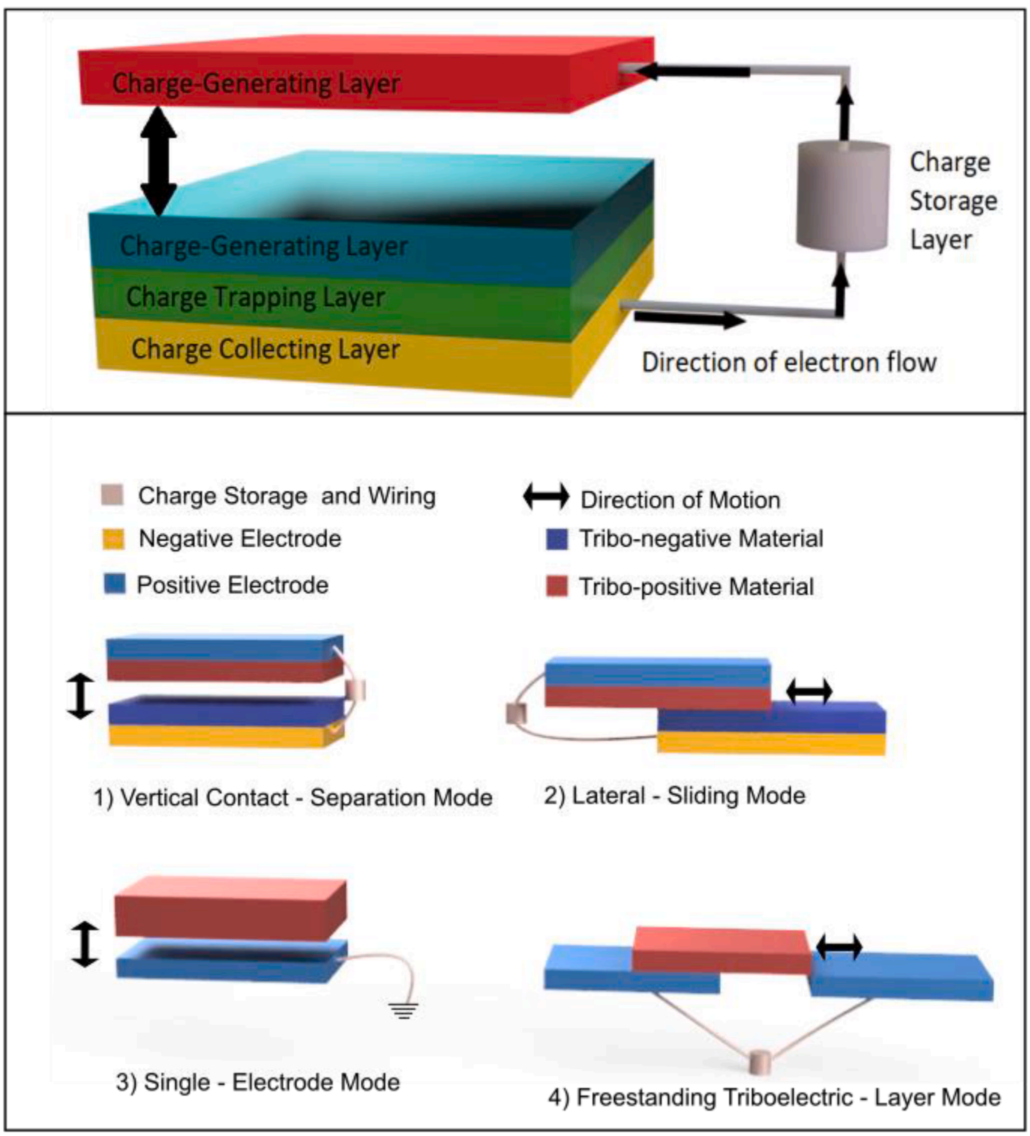

Fig. 1. Basic TENG design by operating layer and the four basic TENG design modes. Adapted from Z. L. Wang [3].

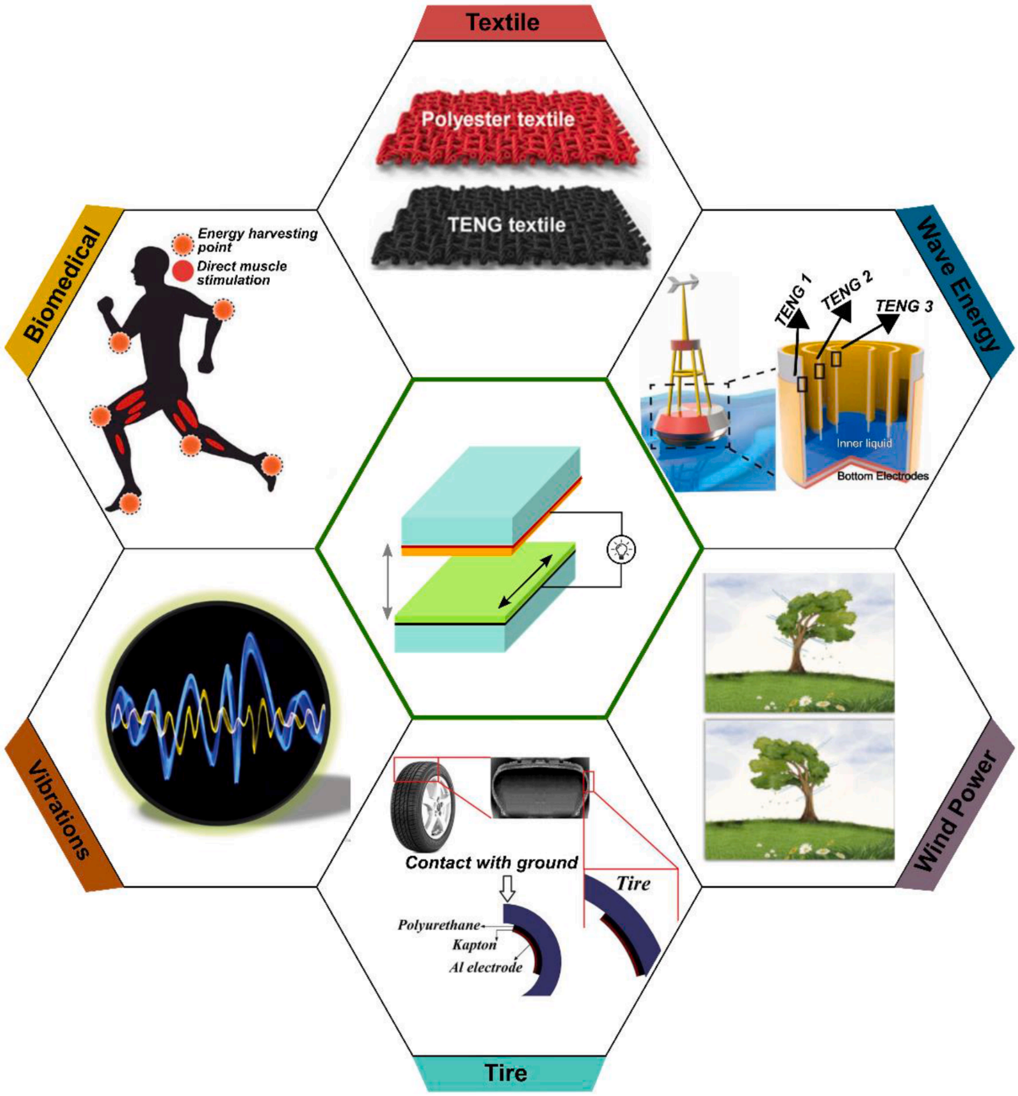

Fig. 2. Schematic diagram showing different application areas of TENG devices. From Aksari et al. [5], Wang et al. [6], Yu et al. 2017 [7], Zeng et al. [8], Chen et al. [9], Li et al. [10]. All copyrights obtained.

Fig. 3. Self-powered smart electronics powered by textile TENGs. Copyright obtained from Elsevier. Xu et al [17].

2.2. *Wave Energy TENGs*

The wave energy from the ocean is abundant and shows a tremendous potential to harness sustainable energy. [11,12] However, it is less developed than other renewable energy sources. For many centuries, waterways have served as an important transportation route serving numerous marine devices requiring a continuous power supply. TENGs could be a source of clean energy to power these devices, independently or in conjunction with traditional power generators. Over the last couple of years, significant progress has been made to utilise TENG operating principles to harness electrical power from dynamic blue energy (ocean or river waves) [19, 20, 21, 22, 23] (Fig 4).

Chen et al. [23] demonstrated a TENG network design to harvest electrical energy from large-scale water wave energy. In this TENG device, high-force and random oscillatory motions were utilised to form contact and separation (See table 1). Their floating TENG systems are lightweight and anticorrosion to the marine environment, which is a major issue to tackle. Recent work by Wu et al. [24] presented a small, versatile, and high-performance water-tube-based TENG device to operate under low-frequency and irregular motions. This TENG device was fabricated by wrapping two copper tapes outside of a fluorinated ethylene-propylene tube with encapsulated deionized water. A single tube-based TENG (about a finger-sized) gives maximum output voltage and charge of 223 V and 73 nC. This power output could be multiplied by a simple integration of individual devices. Zhang et al. [19] reported a new multi-grated TENG model based on freestanding triboelectric-layer for low-frequency ocean wave energy harvesting. This TENG system delivers continuous and smooth power outputs (open-circuit voltage: 140 V and short-circuit current: 60 μA), unlike other TENG models with vertical contact-separation mode. This makes it an appropriate candidate for low-frequency ocean waves.

Similarly, work by Xia et al [25], presented a water-balloon TENG which is also capable of harnessing energy form low-frequency oceans waves with efficiency that is 28 times that of traditional double stacked TENGs. Work by Wang et al. [22] constructed a ship-shaped hybrid generator to exploit the random low-frequency water wave energy. This hybrid TENG operates through the rolling of a magnetic cylinder which is propelled by water motion [22] (See table 1). In the direction of developing hybrid TENG systems, Xin et al. [21] fabricated a chaotic pendulum triboelectric-electromagnetic hybridized nanogenerator to efficiently scavenge mechanical vibrations from the marine environment and proposed a TENG based self-powered wireless sensing nodes system (See table 1). Wang et al. [26] presented a new TENG approach

Table 1
Table summarizing the reported output of recently developed TENG devices in the fields of Textile, Wave, Wind and Tire. V_{oc}, I_{sc} and NR mean open circuit voltage, short circuit current and not recorded respectively.

No.	TENG Category	Effective Area (cm^2)	V_{oc} (V)	I_{sc} (μA)	Power Density (mW/cm^2)	Reference
1	Textile	8 × 8	60	60 nA	NR	[15]
2	Textile	2 × 4	135	20.9	NR	[16]
3	Textile	4 × 8.5	232	2.03	66.12mW/ cm^2	[17]
4	Textile	1 × 1	328	36.15	NR	[18]
5	Wave	7 (diameter)	90	0.8	NR	[23]
6	Wave	10 × 1.2	223	0.3	NR	[24]
7	Wave	NR	140	60	NR	[19]
8	Wave	NR	95	2.8	9	[22]
9	Wave	3 × 1	197	3	1.23	[21]
10	Wave	0.7 × 0.7	NR	130	2.16	[26]
11	Wave	10 × 10	1221	147	NR	[25]
12	Wind	3 × 8 × 2	175	43	2.5	[30]
13	Wind	2.5 × 2.5 × 22	100	1.6	1.6	[32]
14	Wind	NR	1000	60	NR	[31]
15	Wind	2.5 × 2.5	1150	670	NR	[34]
16	Tire	0.7 × 0.6	190	7.5	NR	[38]
17	Tire	3 × 3	150	21	NR	[39]
18	Tire	5 × 3	225	42	0.5	[40]

based on the shuttling of charges corralled in conduction domains. This device delivered a high charge density (1.85 mC m^{-2}) and was effectively used to harvest wave energy. With a demonstrated promising output in recent years, TENG operation with wave energy could potentially provide a green, autonomous, and efficient energy source in running numerous marine devices such as maritime surveillance devices, buoy, metocean monitoring, and floating boats, *etc*. An interesting

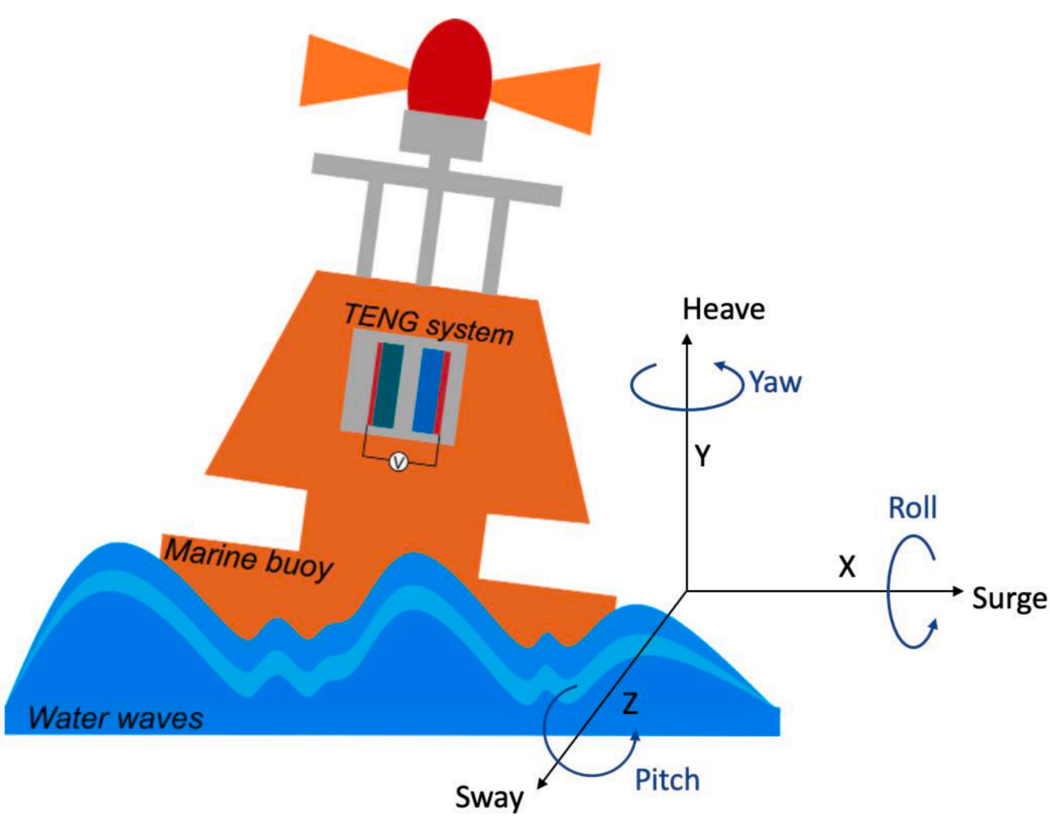

Fig. 4. Schematic representation of a floating ocean buoy where mechanical motions can be utilised in TENG devices to generate electrical power. Adapted from Rodrigues et al. [20].

paper by Jiang et al [27] emphasised the importance of mechanical design in wave TENG systems. They found that, by adding springs of appropriate stiffness, the effective frequency of the wave TENG device could be increased from the low level dictated by the water waves – they refer to this as the 'spring-assisted TENG'. This led to a boosting of the accumulated charge by 113% and an improvement in the translated electrical energy or efficiency of 150%.

2.3. Wind Energy TENGs

Extraction of electrical power from wind energy has been gaining interest from the scientific community as a clean, and high-performance energy source [28]. In 2018, wind energy produced more than 5% of worldwide electricity [29]. Traditionally, electromagnetic generator based wind turbines are used to generate electricity from wind. In recent years, researchers have successfully attempted to apply the new TENG technology to harvest power from wind or air-flow energy [4, 30, 31, 32, 33](Fig 5). Chen and co-workers [30] developed a Bernoulli effect-based TENG device, comprising two contacting triboelectric laminated films with four flapping modes, that works at low wind speed with high efficiency (See table 1). This TENG device is highly sensitive and can produce electricity even from a light breeze or a person's swinging arm [30].

Yang et al. [32] proposed a dual purpose TENG generator to harvest wind energy and to detect wind speed and direction. Innovatively, this TENG system consists of a fluorinated ethylene–propylene film between two aluminum foils and utilizes wind-induced resonance vibration to deliver output (output voltage: 100 V and output current: 1.6 μA). Feng et al. [31] developed a simple and cost-effective biodegradable plant leave-based TENG system and TENG tree to harvest wind energy. Developed TENGs produced impressively high electrical output (voltage: 1000 V and short-circuit current: 60 μA), which could run an electrical watch [31]. In a recent work by Zhang and co-workers [34], an unique windmill-like hybrid TENG generator is developed to harvest low-speed wind energy (See table 1). Their design utilizes the rotational motion (triggered by airflow) to execute the contact-separation mode of the TENG device. Finally, future research might focus on large-scale electricity production utilizing wind based TENG systems, through either integration of TENG devices into pre-existing wind farms or the creation of TENG based wind farms on their own.

2.4. TENGs in Transport: the tire based TENG

A great example of the many ways in which TENGs can be used in modern life to harvest energy is their adapted use in vehicle tires. Evolved from previous designs, which used piezoelectric and electromagnetic methods of energy generation, these TENG devices are designed in such a way that allows for the successful energy conversion of centripetal/frictional energy into electricity. TENG powered self-activated tire sensors have also been created (Fig. 6) to advance the development of advanced driving assistance systems (ADAS) for autonomous driving. These sensors can monitor both the tire conditions, such as pressure, road contact, tire direction and rpm [35, 36].

In two papers by Askari et al [5, 37], a self-powered sensor for the monitoring of tire conditions was developed and powered by a TENG which generated a peak-to-peak voltage of 1.4V and was synthesized

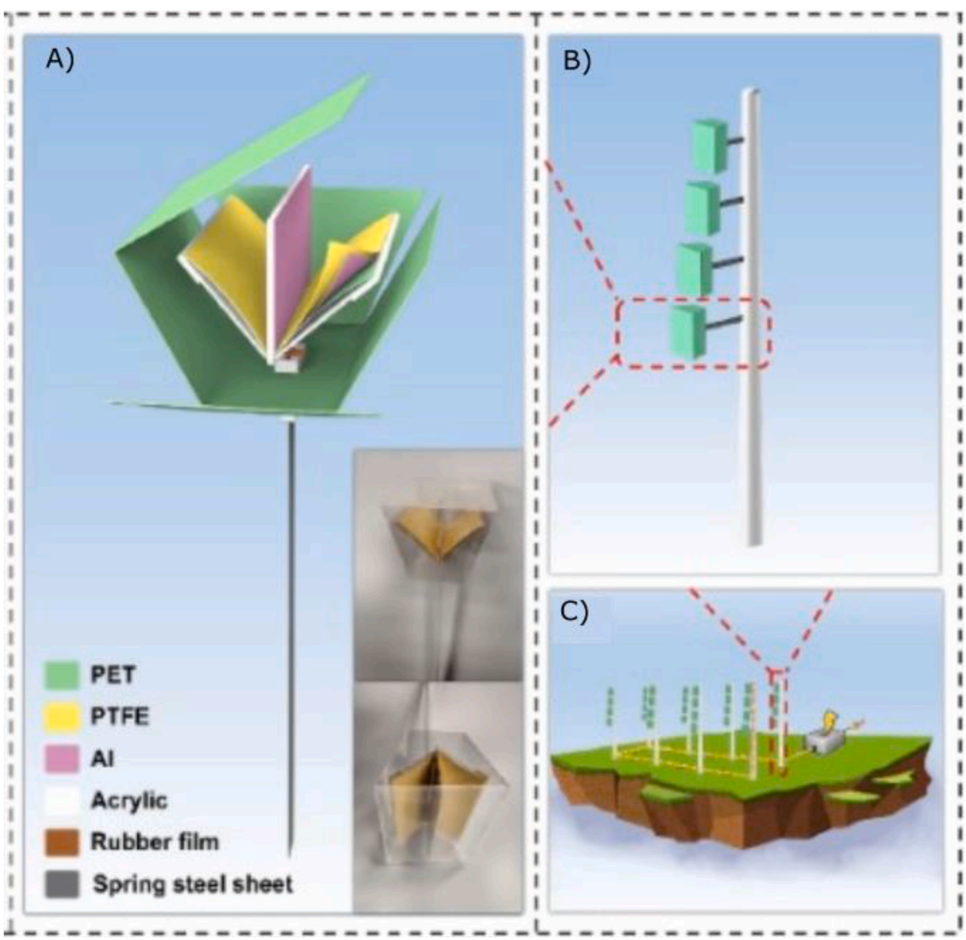

Fig. 5. Schematic of a contact mode TENG that utilizes movement induced by wind (mechanical energy) to harvest energy. Copyright obtained from Elsevier, Zeng et al. [8]

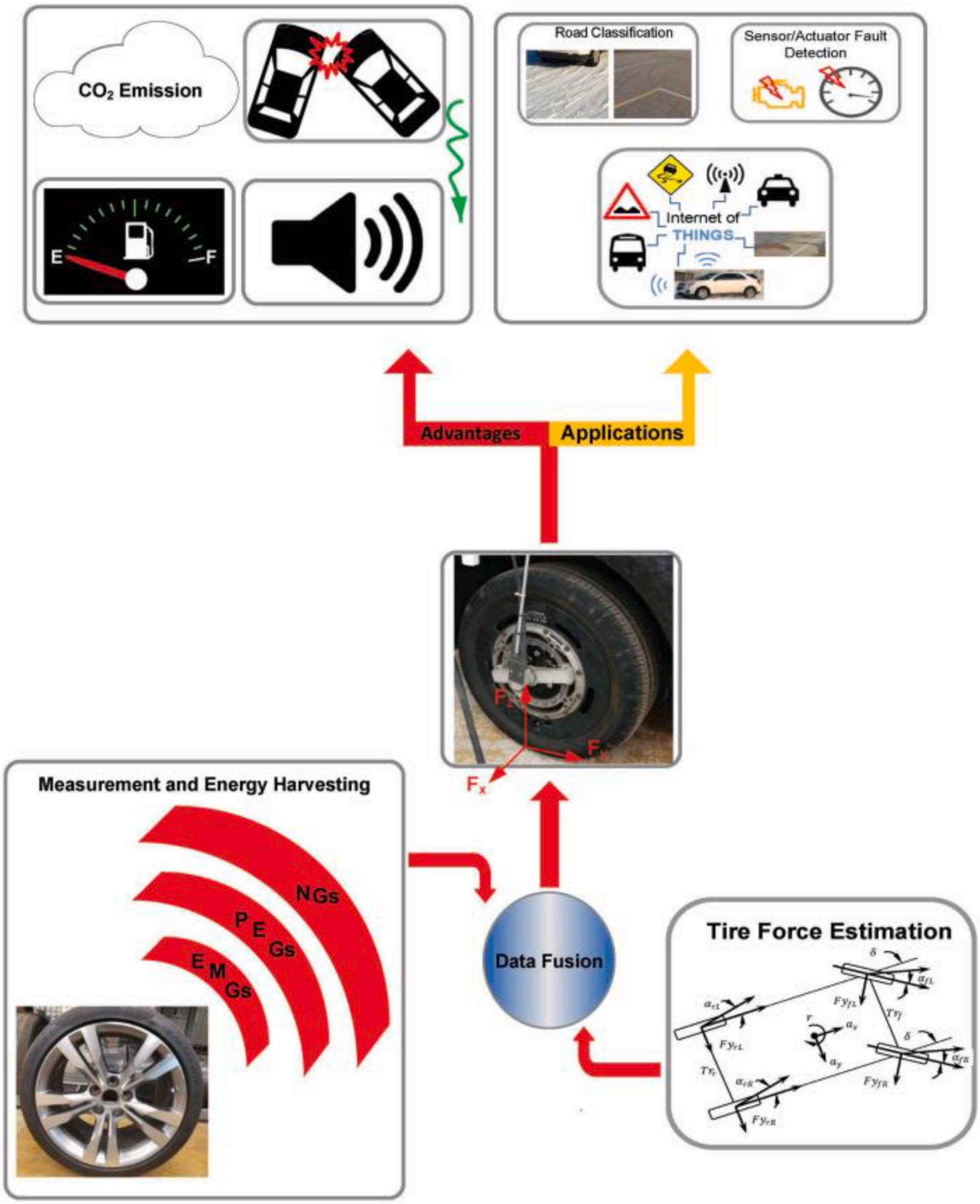

Fig. 6. Overview of tire evolution, advantages and predicted future aspects. Abbreviations for PEGs, EMGs and NGs are Piezoelectric Generators, Electromagnetic Generators and Nanogenerators respectively. Copyrights obtained from Wiley, Askari et al [37].

used Polyurethane, Kapton and Aluminum. By placing the TENG inside the tire, it would be subjected to the various cyclic forces a tire undergoes in a full rotation and would complete a TENG cycle, producing power. However, it is postulated, in a paper by Guo et al, that the output of a tire-TENG is still only governed by the weight and load imposed on it and is not affected by the speed of the rotation [38]. Wu et al [39], created a complete TENG tire by incorporating Silica threads into the tire rubber creating the friction layers within the tire. This was able to produce $V_{oc} = 150$V and $I_{sc} = 21\mu$A. Similarly, in a more recent paper by Seung et al [40], a TENG tire which utilized PDMS coated silver textiles and nylon was able to produce an average $V_{oc} = 225$ V and $I_{sc} = 42\mu$A.

3. Prospects and Challenges for Energy Harvesting TENGs

With the number of different TENG devices, as well as, efficiency and output continually increasing, TENG applications have also multiplied. However, there are four main areas which hinder the commercial use of TENGs for widespread and long-term energy generation and these are explored below (and illustrated in Fig. 7).

Electrical Output – Although output from TENGs has come a long way and increased significantly since their first inception, many still suffer from low electrical output and particularly, low AC current. This is especially so with textile TENGS [41]. A recent comprehensive literature comparison by Paosangthong et al. [13] found that output from textile TENGs fell between 22.5 nW/m^2 and 8.9 W/m^2 compared with up to 500 W/m^2 or more from conventional non-textile TENGs. The present authors hypothesize that the low output from textile devices may well be associated with extremely low levels of contact area. In fact, two recent papers by Xu et al [42]. and Min et al [43], have shown how TENG output scales with the amount of ‘real contact area’ developed. In turn,

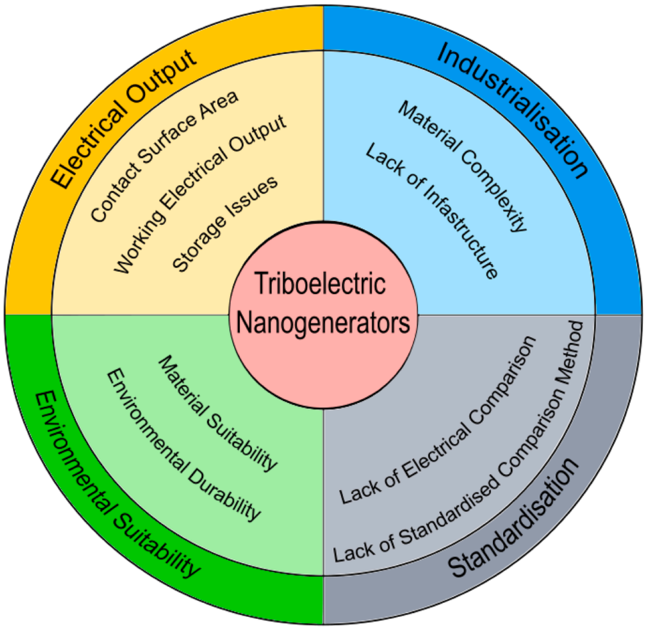

Fig. 7. Challenges which still impede TENG progression to widescale commercialization, illustrated and categorized.

the real contact area increases with the contact force. The problem for some TENG applications like wearables is that there is not much normal contact force available to press the surfaces together. For example, in Min et al [43], a contact pressure of 16 kPa produced only 0.25% contact even on a conventional (non-textile) Copper-on-PET interface and had to be up to 1.12 MPa to achieve 82% contact (i.e. % of the nominal device area). Other recent studies [44, 45, 46] have pointed out the crucial role of surface texturing (besides the physio-chemical properties) on interfacial surface phenomena. Further research should focus on developing a better understanding of the specific response to texture at a local scale and the resulting collective response of the global system. This understanding would help the development of optimized surface textures and structures optimising tribocharge density and boosting TENG performance. Recent developments in in-situ real contact visualization systems could offer important assistance to systematically explore this aspect [45]. Numerous methods of surface and sub-surface modification have been implemented in the drive to boost output such as plasma treatments [47, 48, 49], chemical treatments [50, 51, 52, 53, 54], micro/nano structuring of surface topography [13, 55], use of ferroelectric materials with appropriate nano fillers and introduction of low permittivity substrates [56]. Another important development was added by Wang et al [57] who showed that charge density could be significantly boosted by placing the TENG in a Vacuum to avoid the air breakdown limit dictated by Paschen's law. They achieved a record 1003 $\mu C/m^2$.

Many of the output boosting methods relating to materials and topography have produced increases in TENG output, but sometimes without the accompanying fundamental understanding of underlying mechanisms. We are now approaching a decade since the first TENG paper was published, and rapid progress has been made. However, further improvement is needed to make TENG output more viable. This will require continued effort on exploring the fundamental physics of triboelectrification. Improved understanding should guide the way to enhanced materials, surfaces and designs for use in next generation TENGs.

Manufacturing issues – With TENGs currently being fabricated manually for small scale testing, considerable progress would be required to enable large-scale production. If new infrastructure was to be put in place, it would have to be adaptable to keep up with new designs and research [58]. This issue also branches into the manufacturing of the materials in themselves. Materials which are used to make newer, more efficient TENGs are, very often, complex materials with multiple processing steps and this lowers the cost efficiency of some TENG solutions. There is also the added issue of marketing TENGs. Although they have already proven to be an up and coming reliable green energy alternative, for TENGs to be viable in the marketplace, they would have to be designed for a specific use while maintaining a high level of cost efficiency [59]. More broadly, one may also consider investigating advanced materials processing methods to re-use plastic material from waste to utilize in TENG devices.

Environmental Suitability – Although the issue of robustness and durability of TENG devices has been addressed in literature before, these studies have been conducted, for the most part, under research conditions with little research done into the robustness of TENG devices when subjected to extreme environmental conditions ranging from extreme temperatures to machine washing of fabric based TENGs. Materials selection has and will play an important role in this area as it is the materials which are critical in determining the life of a TENG device. TENGs which have been made from polymers like PDMS and PTFE have theoretically been proven to be stable to temperatures $\geq$300°C. However, in some cases these polymer materials would not be suited to the environment in which the TENG is to be used and other materials would have to be used. In addition, TENGs involve repeated contact or sliding of rather thin layers of relatively soft polymers and more work is needed to prolong the wear and fatigue life of devices for use in long-term energy generation applications. There is also the issue that the working output of TENGs could be a lot lower then recorded in the lab. When output is measured in the lab it is usually under optimized conditions of surface contact, frequency and amplitude [60, 61]. A TENG in a working environment would not have the luxury of these conditions. It might, for example, be subject to corrosion, wear and unpredictable actuation forces for example and, as such, output may be severely affected. A lot of work is required on assessing the lifetime response of TENGs in realistic environments.

Standardization – A complete method of measuring and comparing TENG output and efficiency has yet to be designed, proposed and accepted. Although open circuit voltage (V_{oc}), short circuit current (I_{sc}), and power density (mW/cm^2) are often used as comparative tools, it is usually only two of the three values reported, demonstrated in table 1, are the result of independent experimentation and parameters between testing can vary wildly from effective TENG size to pressure applied [58, 62]. Without a standardized way of comparing TENGs, progress is significantly more difficult. There has been some research into this area where in 2019, Zou et al [63, 64] proposed a method of quantifying the triboelectric series, although this method has yet to be accepted as a standard method.

Despite these issues, TENGs have a great adaptability meaning that they could be employed in incredibly large area applications [65]. TENGs have already been used as a power source for electrocatalytic systems [66], micro-welding [67], self-powered microsystems [68] and medical applications [69, 70, 71]. TENGs will also be instrumental in the future evolution of the Internet of Things [72, 73, 74], such as human-machine interfacing [75]. Energy generating TENGs could become the fourth main form of green energy alongside solar, wind and wave. The outlook for TENGs is massive and with the field developing rapidly, TENGs certainly have the potential to become one of the most diversely used energy generators. It should also be noted that the development of sustainable technologies such as TENGs will be vital for achieving the global target of 'net zero emissions' by 2050.

4. Conclusions

Coinciding with ten years since the publication of the first TENG paper, recent advances in the application of TENGs in key sustainable and renewable energy areas have been briefly reviewed. The paper has focused on four key areas: wearables, wave, wind and transport. A host of novel designs have emerged to adapt TENGs that can work for these applications. The key advantages of TENGs remain comparatively low cost, light weight and high efficiency at low frequencies typical of the low frequencies available in common sources of free energy such as water waves and human motion. However, electrical output remains low (mostly less than 500 W/m^2) compared to some other forms of energy generation and the main challenges for the future appear to be further boosting output power and current, fabricating advanced TENGs economically and designing TENGs for lifetime survival in various practical environments. Addressing some of the unresolved questions in triboelectrification and developing standardized approaches to assess and compared TENGs is also vital. Providing that these challenges are overcome though, TENG devices stand to become a major player in the field of renewable "green" energy alongside other sustainable technologies such as solar, wind and wave.

Declaration of Competing Interest

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

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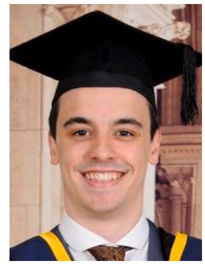

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