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TOPICAL REVIEW

Recent progress towards smart transportation systems using triboelectric nanogenerators

Minh Phuong Nguyen[1,5], Nghia Dinh Huynh[1,4,5], Thien Trung Luu[1] and Dukhyun Choi[1,2,3,*]

[1] School of Mechanical Engineering, Sungkyunkwan University, Suwon 16419, Republic of Korea
[2] Department of Future Energy Engineering, Sungkyunkwan University, Suwon 16419, Republic of Korea
[3] Institute of Energy Science & Technology (SIEST), Sungkyunkwan University, Suwon 16419, Republic of Korea
[4] James Watt School of Engineering, University of Glasgow, Glasgow G12 8LT, United Kingdom
[5] Minh Phuong Nguyen and Nghia Dinh Huynh contributed equally to this work.
[*] Author to whom any correspondence should be addressed.

E-mail: bred96@skku.edu

Keywords: smart transportation, self-powered sensor, triboelectric nanogenerators (TENGs), health monitoring system, infrastructure

Abstract

The field of transportation plays a crucial role in the development of society. It is vital to establish a smart transportation system to increase the convenience and security of human life. The incorporation of artificial intelligence and the internet of things into the traffic system has facilitated the emergence of innovative technologies like autonomous vehicles or unmanned aerial vehicles, which contribute to the reduction of traffic accidents and the liberation of human driving time. However, this improvement involves the use of multiple sensor devices that need external power sources. As a result, pollution occurs, as do increases in manufacturing costs. Therefore, the quest to develop sustainable energy remains a formidable obstacle. Triboelectric nanogenerators (TENGs) have emerged as a possible solution for addressing this problem owing to their exceptional performance and simple design. This article explores the use of TENG-based self-power sensors and their potential applications in the field of transportation. Furthermore, the data collected for this study might aid readers in enhancing their comprehension of the benefits linked to the use of these technologies to promote their creative ability.

1. Introduction

Mobilities transport goods and people from one area or country to another via road, sea, or air. Therefore, transport is among life's most critical aspects [1]. A system with advanced transportation and infrastructure will foster economic growth and enhance the quality of life [2]. Despite this progress, there are still many issues that need to be resolved, such as traffic accidents and pollution from vehicle emissions [3–5]. Traffic accidents are the 8th leading cause of mortality worldwide and will rise to 7th in 2030 if current trends continue, according to World Health Organization (WHO) estimates [6]. Consequently, the development of a smart transportation system (STS) is critical for the safety and convenience of human life [6–8]. Currently, the use of artificial intelligence and the internet of things (IoT) in transportation has brought significant advancements [9–11]. These are autonomous automobiles, unmanned aerial vehicles (UAVs), and monitoring systems that have decreased traffic accidents, boosted vehicle safety, and cut driving time [12–14]. This advancement has resulted in an increase in the number of IoT-related sensors exceeding 50 billion in quantity; projections indicate that this number will surpass 200 billion by 2025 [15, 16]. Despite their notable efficiency, wireless sensor systems still necessitate the supply of external power to operate [17, 18]. This leads to a capacity limit, inconvenient charging or replacement, and pollution of the environment [19, 20]. Consequently, the constraints of external power sources may be advantageously addressed by means of self-powered sensors.

The self-powered efficiency of triboelectrification nanogenerators (TENGs) has garnered considerable interest in recent years [21–23]. In 2012, Professor Zhonglin Wang's team developed TENGs by combining triboelectrification with electrostatic induction. When two materials with differing charge affinities contact and separate, the electrons transfer between the two electrodes via the external resistor, producing an alternating current (AC) [24–26]. This allows TENG to convert mechanical energy from its surroundings into electrical energy [27]. TENG has become the most efficient energy harvesting technology because of its simple method, low cost, and high conversion efficiency [28–30]. It has been shown to produce an output area power density of up to 500 W m^{-2} and a total energy conversion efficiency of up to 85% [31, 32]. TENG in STS can harvest energy from wheel rotation, vibration of moving equipment, wind energy, and so on to power sensors or function as a sensor [33, 34]. Furthermore, since TENG materials and designs are so varied, using TENG technology is still a potential chance for many future applications [35, 36]. This article outlines the advancements and successes of TENG for mobility in STS. Simultaneously, offer insights and obstacles regarding the advancement of TENG, including energy conversion efficiency and reliability.

2. TENG operating principles in mobility applications

Utilizing triboelectrification and electrostatic induction effects, TENGs operate in four different modes (figure 1):

- Vertical contact-separation mode (CS): CS has a layered structure with tribo-pair materials facing each other. When they make contact, electrons exchange, resulting in oppositely charged surfaces. When an external mechanical force separates them, a gap is formed between the two materials, and a potential difference is established. When two electrodes are connected to a load, free electrons from one electrode flow to the other to balance the voltage drop caused by triboelectricity. When the two tribo-material layers reestablish contact, the electron flow comes back, and the electric potential disappears. Repetition of this procedure generates AC output [37, 38]. Because CS are simple structures that are straightforward to construct, they are employed in a wide range of applications. CS tribo-pairs are frequently designed with an arch-shaped structure, spacer structure, or spring-assisted structure due to the requirement for space between their surfaces [39].
- Lateral sliding mode (LS): The electricity generation mechanism of LS is like that of CS; however, LS involves horizontal sliding between two materials [40]. Because of its large contact surface, LS has a high energy conversion efficiency. A plain-sliding structure, a linear-grating structure, or a case-encapsulated structure are common LS structures [41].
- Single-electrode mode (SE): For electrons to move through CS and LS, two electrodes must be connected to the load to create a closed circuit. This arrangement is unsuitable for converting energy from freely moving objects such as walking or running vehicles. This difficulty is solved by the SE structure, which has just one ground electrode. When the friction layer contacts the electrode, an induced current is produced. The current flows back to the ground when the friction material separates from the electrode [42].
- Free-standing triboelectric-layer mode (FS): A pair of symmetrical electrodes are positioned beneath the dielectric layer to construct the FS. A potential difference results from the movement of the dielectric layer across the two electrodes. To achieve potential equilibrium, electrons will move between the two electrodes [43]. This procedure results in the generation of an electric current. FS is well suited to free rotation energy collection applications such as wheel rotation and wind energy.

Different modes can be chosen based on the type of energy to be harvested and the goal of each application, which will be discussed in detail in the section below.

3. Key parameters and strategies for the efficiency of TENG devices

TENG is a breakthrough technological advancement that collects and transforms mechanical energy into electrical energy. The use of TENG technology in transportation has proven to be very beneficial, particularly in the implementation of self-powered sensor systems. Nevertheless, the reliability and energy conversion efficacy of TENG devices remain formidable challenges that need improvement.

3.1. Energy conversion efficiency of TENG devices

Since TENGs function as energy conversion devices, energy conversion efficiency is a significant determinant of the effectiveness of TENGs in practical applications. High energy conversion efficiency refers to the efficient transformation of mechanical energy into electrical energy. The four operational modes of TENG are all founded on the principles of contact electrification and electrostatic induction. Therefore, the intrinsic capacitance of TENG devices serves as a defining characteristic of their energy conversion efficiency. Capacitance denotes the capacity of the TENG device to retain electrical charge [44, 45]. Consequently, the conversion efficacy can be improved by increasing the charge density [46, 47].

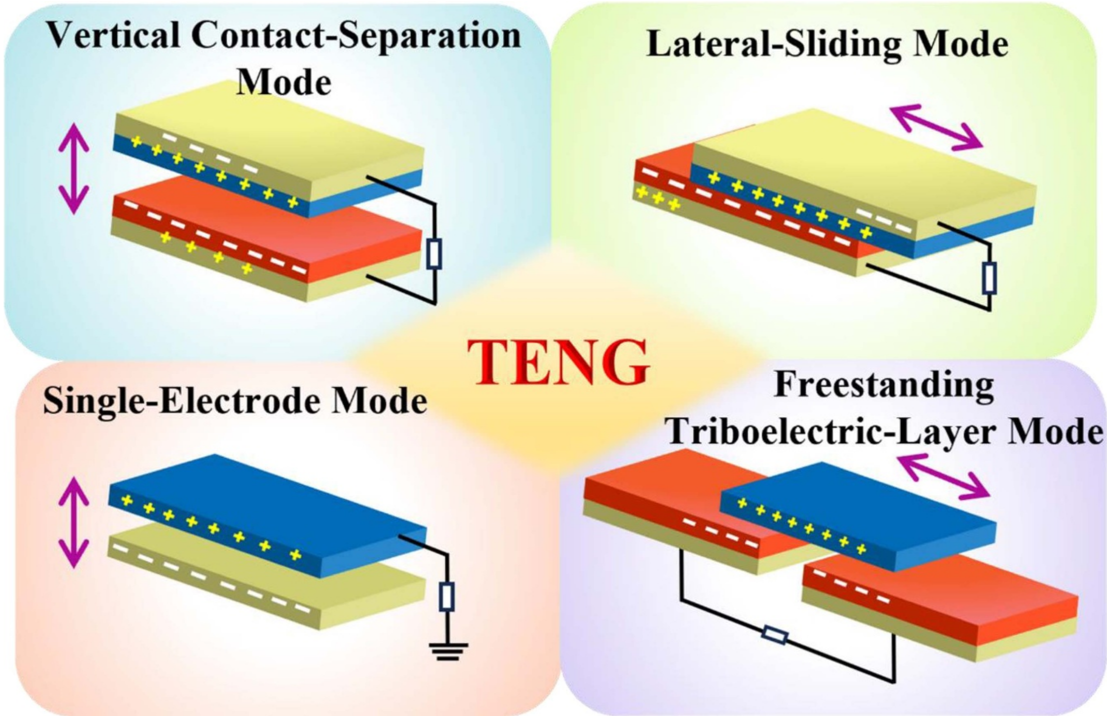

Figure 1. Illustration of four working modes of TENG.

Tribo-pairs are the primary component of all TENG devices; they have a direct impact on the TENG's output performance via the surface charge density characteristic [48]. The material's ability to gain and lose electrons determines this characteristic. Materials with a high electron affinity tend to gain electrons through friction, while strongly electropositive materials lose electrons [49]. Positive materials are those that donate electrons, while negative materials are those that receive electrons. For the tribo-pair of TENGs to produce a higher output, their polarization must differ significantly [50, 51]. Most negative friction materials are polymers, such as polytetrafluoroethylene (PTFE), polyvinylidene fluoride (PVDF), polydimethylsiloxane (PDMS) or fluorinated ethylene propylene (FEP) since fluorine is the most electronegative element in their chemical structure [52–57]. Additionally, certain materials will be described in the following section. Because of their ability to give electrons, metals such as aluminum (Al), copper (Cu), nickel (Ni), and palladium (Pd) are often selected as electropositive materials [58–60]. Additionally, nylon, polyurethane (PU), and polyvinyl alcohol (PVA) are often used due to their exceptional electro-positivity and resistance to abrasion [61, 62]. Currently, the commonly used materials are non-modified polymers, which have limited properties. Conversion efficiency is increased further by enhancing the material's intrinsic characteristics. Many recent studies have demonstrated that mixing polymers with nanoparticles increases permittivity and, thus, charge density [63, 64]. Another great method for improving charge transfer features is to graft functional groups to the polymer backbone that can gain or lose electrons by chemical modification (NH_2, OH, F, Cl, etc) [65, 66].

The contact area of the tribo-pair also improves the electrical output efficiency of TENGs devices [67, 68]. Typically, the output efficiency increases as the contact area increases. As a result, numerous studies have focused on increasing contact area, such as enhancing surface roughness by producing nanostructured surfaces using processes such as lithography, etching [69, 70], water-assisted oxidation [71, 72], or electrospinning nanofibers [73, 74]. Sandpaper with a naturally rough surface may also serve as a template for friction materials [75, 76]. In addition, the large surface area and high porosity of the porous structure, when applied to friction materials, aid in increasing charge accumulation abilities and contact area. There are several ways to produce porous materials, including the sacrificial template technique, electrostatic spinning, and aerogel [77–79]. Additionally, material thickness is a significant factor; typically, materials possessing a controlled thickness of microscales or less contribute to the establishment of reliable and consistent performance [80, 81].

In addition to enhancing charge density, minimizing charge loss also plays a crucial function. Electrodes are also one of the main structural components of TENG devices. Electrode materials must possess high conductivity; therefore, inexpensive, and low-resistance metals, including Al and Cu, are frequently selected for this purpose [82, 83]. Although gold (Au) and silver (Ag) are the most conductive metals, they are also expensive. Non-metals with excellent electrical conductivity, flexibility, and mechanical strength, such as carbon nanotubes and composite materials like carbon black-silicon rubber, are also employed [84]. Moreover, due to their AC output, TENG devices are not suitable for direct charging capacitors or sensor devices. A rectifier is used to convert AC to direct current (DC), which results in a charge loss. Hence, the development of DC-TENG devices represents a prospective approach to enhancing output performance [85, 86].

3.2. Reliability of TENG devices

For TENGs to be utilized effectively in practical applications, their reliability must be thoroughly evaluated. If TENG devices have high robustness and reliability, they will provide consistent output over long periods of time and in a variety of operating situations. Various factors, such as temperature, mechanical force, dust, humidity, contamination, and other variables, might impact the TENG equipment in the transport system, leading to a decrease in its durability. Furthermore, TENG devices operate based on the friction mechanism, necessitating the friction materials to endure lengthy and direct contact. Prolonged periods of use will lead to reduced durability and reliability, thereby diminishing the device's performance. How to enhance reliability and robustness is still a difficult topic that must be addressed. In general, this parameter may be improved by combining two factors: tribomaterial selection and TENG structure optimization.

Tribomaterial selection: Many studies use materials with good mechanical, high-flexibility, and aging-resistant properties, such as PTFE, FEP, nylon, rubber, and so on, to increase durability [52–57].

Optimizing TENG structure: The efficiency of the encapsulation method in safeguarding TENG against harsh environments has been demonstrated [87, 88]. In addition, the LS and FS modes of operation often exhibit high friction frequencies, leading to a decrease in durability. Therefore, there have been a lot of studies focused on enhancing durability in these two modes. Efficient approaches include automatic transitions between contact and noncontact working modes, lubrication, rolling structures, and soft contact structures.

- Automatic transition between contact and noncontact working modes: Static charges are produced on the tribomaterial and electrode layers upon contact because of triboelectrification. The charges can persist for an extended period on the surface of the friction layer. Hence, the TENG can effectively operate without physical friction for a certain duration. The absence of physical contact during operation greatly minimizes the wear on the material surface, hence improving the durability and stability of the TENG. However, these charges gradually diminish, necessitating their conversion to contact mode to generate supplementary friction charges. Hence, establishing an automated switching mechanism between contact and non-contact modes can significantly improve the reliability of TENG and provide steady performance [89, 90].
- Rolling structure: A group of rolling rods or rolling balls is inserted between two layers of friction material in this design. Consequently, the tribomaterials do not contact each other but rather the rolling materials. Compared with traditional constructions, durability is greatly enhanced because of the much lower rolling friction coefficient in contrast to the planar sliding friction coefficient [91, 92].
- Soft contact structure: Due to the significantly reduced physical frictional resistance between liquid and solid, surface wear is decreased, leading to enhanced material durability [93, 94].
- Adding lubrication: Most TENGs function in conditions of dry friction. This condition may cause scratches on the material's surface as well as crucial corrosion, reducing its durability. A lot of research has shown that adding a lubricant layer between two tribo-layers can significantly increase the durability and stability of the TENG. This phenomenon occurs due to the ability of the lubricating fluid to create a barrier between the surfaces of the two layers of friction material. Therefore, the two friction surfaces are not in direct contact with each other but rather only in contact with the lubricant. Consequently, there is a substantial enhancement in durability. On the other hand, the lubricant effectively inhibits air breakdown, leading to less charge loss and improved performance. Widely used lubricants include squalane, paraffin oil, ionic liquid, olive oil, PAO10, rapeseed oil, and others [95, 96].

4. TENGs for mobility

4.1. TENGs for non-motored mobility

4.1.1. Wheelchairs

According to WHO statistics, more than one billion people worldwide have impairments such as hearing, vision, speech, physical, and so on [97]. People with disabilities may face a range of hazards, challenges, and difficulties due to their health problems. Therefore, assistive devices for persons with disabilities are a practical support tool that helps individuals with impairments operate more easily in their daily activities. Among them, people with disabilities or weak legs frequently find it challenging to participate in traffic. Although electric wheelchairs are useful mobility aids, they encounter some limitations [98]. For instance, wheelchair users find it inconvenient to use public transportation because of the limited space and difficulty getting on and off the vehicle [99]. Furthermore, sitting in the wrong position or losing balance in a wheelchair for a long time can lead to health issues such as spine deformities, pressure sores, or other concerns when engaging in road traffic [100]. As a result, developing smart wheelchairs with embedded sensors that detect inappropriate sitting posture or warn of crashes to assist individuals with impairments in traveling small distances without relying on public transit is a viable alternative. However, these sensor systems necessitate external power for operation, hence increasing the size and cost of the wheelchair. Additionally, they must be frequently replaced or charged, resulting in inconvenience for the user. Hence, the development of self-sustaining electronic assistive devices for individuals with disabilities is an important task. TENG has advantages such as low cost, lightweight, and small size, allowing it to be used as a self-powered sensor system or a sensor power supply device [101, 102]. In 2022, Zhu's research team developed a portable and low-cost triboelectric nanogenerator (PL-TENG) that utilizes a TENG-based sensor to control the body balance of those with disabilities who use wheelchairs. They examined how well PL-TENG worked for wheelchair table tennis, a sport where body balance is crucial [101]. In this study, due to their flexibility and heat resistance, PU sheets and Kapton sheets were chosen as friction materials, thereby rendering PL-TENG resistant to sweat and body temperature. PL-TENG also had foam glue between the two tribo-layers and copper foil as the conducting electrode (figure 2). With this structure, PL-TENG operated in CS mode to collect biomechanical signals and turn them into electric signals. PL-TENG could be easily installed on the left (PL-TENG-L) and right (PL-TENG-R) wheelchair seats using adhesive tape, as shown in figure 2. As the athlete's center of gravity changed in response to body movement, distinct electrical signals were produced under the pressure variation on each side. Therefore, the PL-TENG could transmit real-time data on an athlete's equilibrium and posture to assist them in maintaining excellent body balance. The signals were wirelessly sent to a computer using an analog-to-digital acquisition module and a Bluetooth module. As a result, coaches can check the data on the computer and provide players with advice.

Similarly, Graham *et al* developed a triboelectric energy harvester and sensor (TEHS) installed on wheelchair seats and backrests to harvest energy from body movements and transform it into electrical signals for a people movement monitoring system [102]. The unique part of this study is the friction material pair, which is made up of PVA and polycaprolactone (PCL) (both biocompatible polymers). In addition, these polymers were electrospun microfibers, which increased the ratio of surface area to volume, thereby enhancing electrical performance. TEHS was coated with an arch-shaped polyethylene terephthalate (PET) substrate and worked in CS mode. Different electrical signals were created and recorded as the volunteers sat, leaned, or moved. Indeed, TEHS served as a self-powered sensor to monitor the postures of wheelchair users. The energy conversion abilities and durability of PL-TENG and TEHS are also shown in table 1. These investigations demonstrated that TENGs, with their simple design, small size, and effectiveness, hold great potential as a wheelchair support device for individuals with impairments. It may significantly enhance their safety in daily activities.

4.1.2. Bicycles

In recent years, many countries around the world have encouraged people to ride bicycles in urban traffic for short distances [137]. Bicycles have been considered a means that can effectively address societal issues such as reducing traffic congestion, protecting the environment, and promoting public health. Particularly since the COVID-19 outbreak, the tendency to take public transportation has shifted, and the usage of personal vehicles has expanded dramatically [138]. Bicycles are frequently utilized in several aspects of life due to their compact size, lack of requirement for large parking spaces, and safety. However, there are still many problems that need to be overcome. For example, cycling at night has numerous disadvantages, such as reduced visibility, increased risk of collision with other vehicles, or difficulty detecting insufficient tire pressure. This has stimulated interest in enhancing bicycle safety. Technological advancements that convert conventional bicycles into smart vehicles are among those that attract attention. Especially, using TENG devices to increase the safety of bicycles in traffic is a practical solution. The TENG devices can collect bicycle rotation energy and convert it to electricity. This electrical energy can be used to power light-emitting diodes (LEDs), serve as a warning signal to keep people safe while riding in the dark, or serve as a self-powered speedometer or tire pressure sensor [103–107]. For example, Yang *et al* created a three-dimensional TENG (3D-TENG) in 2014 to harvest the rotational energy of bicycle wheels [103]. The friction material layers (FLs) in this design were PTFE film and aluminum thin film. An electrochemical method was used to modify the aluminum surface to a nanopore surface, which improved output performance. The 3D structure of the external frame consisted of a circular acrylic substrate serving as a support and an iron block anchored to the substrate with three identical spring wires, creating a 120° angle. This structure permitted 3D-TENG to operate in both CS and

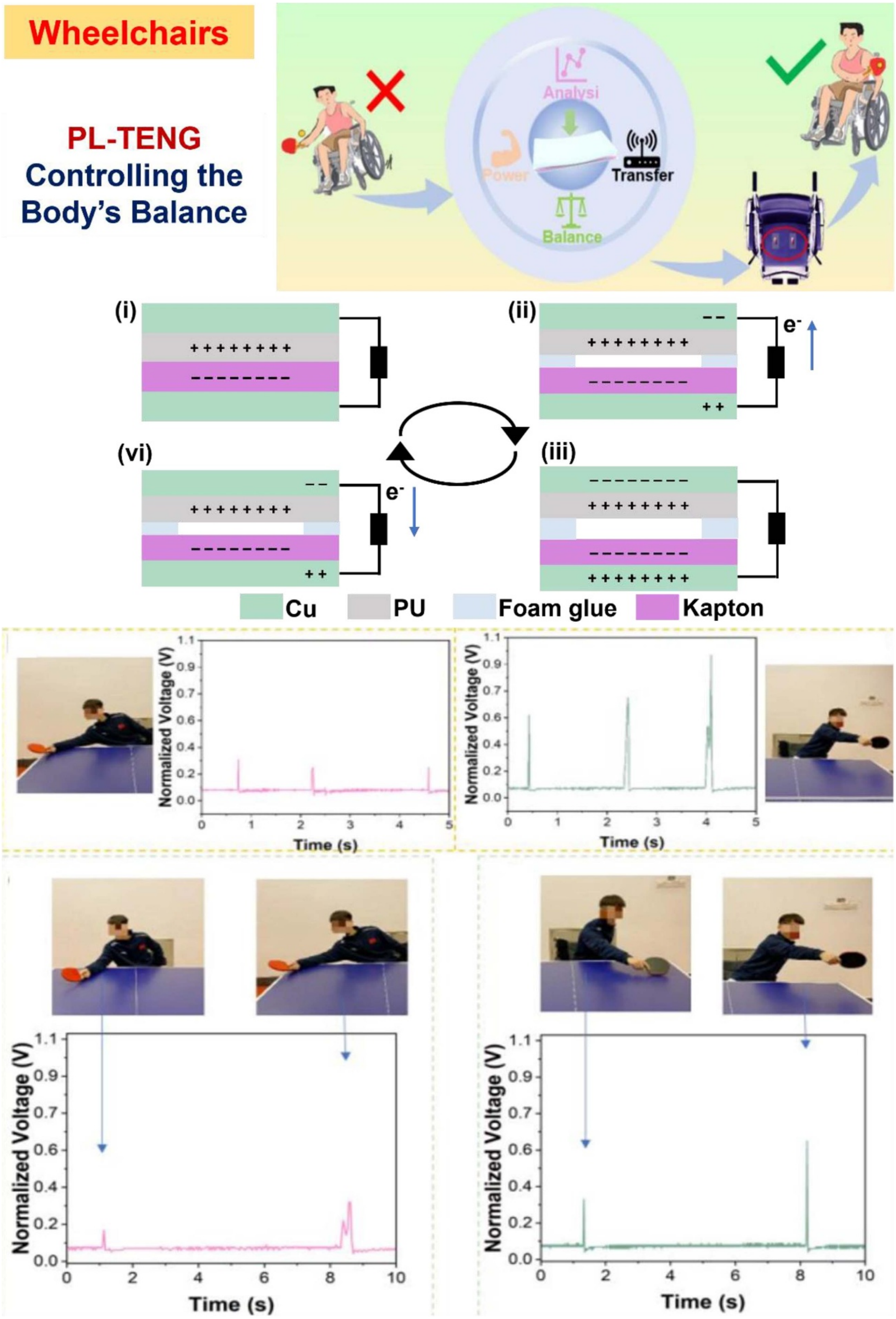

Figure 2. Demonstration of TENGs for wheelchairs. Structure, working mechanism, and application of PL-TENG for controlling the body's balance. Reproduced from [101]. CC BY 4.0.

LS modes. When 3D-TENG was connected to bicycle wheels, the rotational energy of the wheels drove the vibration of the 3D-TENG and converted it to electricity, which was then used to power 30 LEDs.

In 2015, Chen research group developed an automated TENG converter (AT-TENG) with excellent output efficiency [104]. AT-TENG's structure consisted of a functioning part and a rotating part. The functional part was protected by an acrylic substrate containing two friction materials: an Al nanoporous film that operated as both a positive friction layer and an electrode, and a negative friction layer of PTFE nanowire arrays film with a thickness of 25 μm, which was deposited with a copper electrode on one side.

Table 1. Summary of various TENG techniques for transportation.

References/strucrure/applications	Materials			Mode	Maximum open-voltage (V)	Maximum short-current	Transferred charges/charge density	Power/power density	Durability test
	Positive	Negative	Electrode						
PL-TENG (2022) [101] Monitoring wheelchair table tennis	PU	Kapton	Cu	CS	1.41	—	—	—	700 s
TEHS (2022) [102] Arch-shaped Monitoring wheelchairs	Microfiber-based tribofilm PVA	Microfiber-based tribofilm PCL	Al	CS	8	2.6 μA	15 μC	5 mW m^{-2} (60 MΩ)	9000 cycles (3 N)
3D-TENG (2014) [103] Spring structure Harvesting vibration energy from wheel bicycles Self-powered sensing system	Al	PTFE	Cu	CS FL	123 143	30 mA m^{-2} 32 mA m^{-2}	0.11 μC (0.03 s) 0.13 μC (0.03 s)	1.35 W m^{-2} 1.45 W m^{-2}	—
AT-TENG (2015) [104] Stator/rotor (Rotated by magnetism) Harvesting motion energy from bicycles Self-powered speedometer	Nanoporous Al	Nanowire arrays PTFE	Cu	CS Non-CS	~540 ~133	~257 μA ~62.5 μA	— —	1 W m^{-2} (1 MΩ)	300 000 cycles
DMR-TENG (2021) [105] Stator/Rotor Harvesting kinetic energy on bicycle disc brake to power warning signal Self-powered speedometer	Steel plate	PTFE	Cu	Braking mode/riding mode	150	28 μA	Riding: 2.5 μC cm^{-2} Braking: 8 μC m^{-2}	—	10 milion cycles
HNG (2021) [106] Stator/Rotor Harvesting bicycle rotation energy Self-powered sources portable electronics	Al	$NaNbO_3$/PDMS porous, thin film	Al	CS	180	6 μA	45 μC m^{-2}	3.75 W m^{-2} (100 MΩ)	90 000 cycles/9 N and 5 Hz
TBT (2021) [107] Self-powered bicycle safety light and pressure sensor	Al	PTFE	Al	SE	34.3	4.7 μA	—	—	120 000 cycles (160 rpm)

(Continued.)

Table 1. (Continued.)

References/strucrure/applications	Materials			Mode	Maximum open-voltage (V)	Maximum short-current	Transferred charges/charge density	Power/power density	Durability test
	Positive	Negative	Electrode						
heTENG (2018) [108] Rolling structure Self-powered vibration sensing Self-powered smart braking system for automobiles	Cu/metal balls	PTFE circular grid	Cu/Q235 Steel	FS/SE	221	27.9 μA cm^{-2}	33.4 μC cm^{-2}	—	—
Gas-TENG (2018) [109] Spring structure Self-powered gas sensor	Al	PTFE	Al	CS	75	10 μA	—	—	5 cycles (100 s and 100 ppm NO_2)
S-TENG (2018) [110] Helical structure Self-powered vibration sensing for automobiles	Conductive elastomer	Silicone rubber	Conductive elastomer	CS-vertical CS-horizontal	85 30	5 μA 1 μA	35 nC 10 nC	240 mW m^{-2} (10 MΩ)	30 000 cycles/16 Hz
DSA-TENG (2022) [111] Stator/rotor Self-powered sensor for smart automobiles	Cu	FEP	Cu	FS	—	~35 nA (30 mm s^{-1})	—	—	500 000 cycles
EMG-TENG (2019) [112] Cylinder-based hybrid TENG/EMG Stator/rotor Harvesting rotation energy from wheel cars Self-powered source for tire pressure sensor, counter, timer	Al	PTFE	Al	SE	16	0.1 mA	—	1.8 mW (20 KΩ)	—
BS-TENG (2021) [113] Stator/Rotor Harvesting rotational mechanical energy Self-powered sensor under high rotational speed	Cu	FTFE	Cu	FS	80	76 μA	85 nC	7.62 W m^{-3}	>10 000 cycles/900 rpm

(Continued.)

Table 1. (Continued.)

References/strucrure/applications	Materials			Mode	Maximum open-voltage (V)	Maximum short-current	Transferred charges/charge density	Power/power density	Durability test
	Positive	Negative	Electrode						
RSW-TENG (2022) [114] Stator/Rotor Harvesting rotation energy from wheel cars Self-powered road slope sensing and wheel speed sensing in monitoring systems	Water	PTFE	Cu	FS	1.78	0.91 μA	—	—	—
Hybrid BB-TENG and MG-EMG (2023) [115] Hybrid TENG/EMG Stator/rotor Self-powered flow sensing for automobiles	11 glass balls	POM outer ring	Interdigital electrodes	FS	374 (BB-TENG and MG-EMG)	31 mA (BB-TENG and MG-EMG)	—	65 mW (6.8 KΩ)	7 h (600 l min^{-1})
PP-TENG (2023) [116] Shock absorber sensor	NaCl-PEO film	Tea-PDMS film	Cu foil	CS	18.52	190.71 nA	—	1.46 μW cm^{-2} (50 MΩ)	5000 cycles
Smart green tire-TENG (2019) [117] Tire pressure and road condition sensor Using silica-filled tire can decrease CO_2 emissions	Metal	Rubber	Rubber/ Cu film	CS	150	21 μA	0.1304 μC	—	—
TEVA (2017) [139] Spring structure Self-power the accelerometer or the wireless sensor network nodes	Al	Kapton	Al	CS	88 (10 Hz)	—	—	—	—
ER-TENG (2021) [118] Stator/Rotor Harvesting wind energy Self-powered traffic light Self-powered sensing devices	Cu	PTFE	Cu	FS	600	120 μA	0.9 μC	29.1 mW (50 MΩ)	250 000 cycles

(Continued.)

Table 1. (Continued.)

References/strucrure/applications	Materials			Mode	Maximum open-voltage (V)	Maximum short-current	Transferred charges/charge density	Power/power density	Durability test
	Positive	Negative	Electrode						
FF-TENG (2021) [119] Stator/Rotor Self-powered wheel temperature and speed monitoring system for trains	PU	PTFE	Cu	FS	500	55 μA	235 nC	15.68 mW	—
MPNG (2017) [120] Harvesting vibration energy of trains Self-powered smart sensor (temperature, humidity)	Al	PTFE	Al	CS	TENG:43.8 EMG: 7.7	TENG: 1.39 μA EMG: 4.1 mA	—	TENG: 0.34 mW g^{-1} (50 MΩ) EMG: 0.12 mW g^{-1} (700 Ω)	—
HVS (2021) [121] Acrylic cover structure Vibration moniroring system for rail track fracture detection	Graphite layer/Ag particles	PTFE particles	Graphite layer	CS	600 mV (track safe)	—	Frequency solution of 0.01 kHz	—	—
S-TENG (2021) [139] Spong support structure Self-powered sensors for status of the railway system	Nylon	PTFE	Cu	CS	6 (10 MΩ, 2 mm, 1 Hz)	1.75 μA (10 MΩ, 2 mm, 4 Hz)	—	4.52 μW (2 mm, 2 Hz, 200 MΩ)	40 000 loading cycles
LS TENG (2018) [122] Liquid–solid Self-powered wireless SOS system for ocean emergencies	Water	PTFE	Ag	CS	300	290 μA	16 725 nC	—	—
DE-TENG (2023) [123] Liquid–solid Self-power signals potlights, the digital thermometer and the water quality detector	Water/PP	Water/FEP	Cu	CS	60	60 μA	—	5.38 Wm^{-3}	300 s
HW-NG (2021) [124] Hybrid TENG/EMG and Pendulum Self-powered source route avoidance warning system for ocean navigation	Cu	FEP	Cu	CS	580	28 μA	—	0.3 W m^{-2} (2 KΩ)	130 000 cycles

(Continued.)

Table 1. (Continued.)

References/strucrure/applications	Materials			Mode	Maximum open-voltage (V)	Maximum short-current	Transferred charges/charge density	Power/power density	Durability test
	Positive	Negative	Electrode						
MBB-TENG (2023) [125] Pendulum Illuminating 86 LEDs and charging capacitor	PU foam	PDMS	Cu	CS	145	8.9 μA	—	1.1 W m^{-2}	1200 cycles
I-TENG and S-TENG (2020) [126] Hybrid TENG/EMG and Pendulum Charging Lithium battery and powering temperature sensor	Al	FEP	Al	FS	63.6/124.2	—	—	95.4 mW (100 Ω)	—
SS-TENG (2020) [127] Swing structure Self-powered environment monitoring system	Acrylic	PTFE	Cu	FS	572	6.3 μA	195 nC	4.56 mW (300 MΩ)	400 000 cycles
SSF-TENG (2021) [128] Swing structure Self-powered marine environment monitoring system	Cu	PTFE	Cu	FS	1160	12.6 μA	239.6 nC	6.2 mW	—
AR-TENG (2022) [129] Eco-friendly materials Power a buoy-type ocean monitoring system and an intelligent life jacket	Pd	PMMA	Pd	CS	360	22 μA	—	1.547 W m^{-2}	1000 000 cycles
SD-TENG (2020) [130] Eco-friendly materials Harvesting water wave energy	Cu	Seawater degradable polymer (SDP)	Cu	CS	26	108 nA	10 nC	260 mW m^{-2}	—
SLC-TENG (2022) [131] Harvesting wind and ocean energy Self-powered sensor	Super-light lay	Kapton	Al	CS	81	2.9 μA	—	0.33 W m^{-2} (50 MΩ)	—
h-TENG (2021) [132] Honey-comb structure Real time self-powered sensor for UAVs	AgNW	FEB	AgNW	CS	1207	68.5 μA	—	0.275 mW cm^{-3}	75 000 cycles

(Continued.)

Table 1. (Continued.)

References/strucrure/applications	Materials			Mode	Maximum open-voltage (V)	Maximum short-current	Transferred charges/charge density	Power/power density	Durability test
	Positive	Negative	Electrode						
FRD-TENG (2021) [133] Stator/rotor Self-powered gyroscope angler sensor for the flight control system of UAV	Cu	PTFE	Cu	FS	108	15.1 μA	80 nC	—	—
AW-TENG (2022) [140] Arc-shaped structure Wind speed sensor (UAV)	Cu	PTFE	Cu	CS	55	28 μA	—	—	—
EMG/TENG (2016) [134] Stator/Rotor Harvesting wind energy from running vehicles through the tunnel	Al	PTFE	Al	SE	240	10 μA	—	55.7 W m^{-3} (700 Ω)	500 000 cycles
AG-TENG (2023) [135] Stator/rotor Harvesting wind energy on highways Anti-glare, power to LED lights, signal lights, and low-power IoT devices	Polyester fur	PTFE	Cu	FS	2.4 kV	60 μA	295 nC	0.2 W m^{-2}	1440 000 times
TENG-SE (2021) [136] Packed structure Self-powered and self-sensing in civil infrastructure	PLA with carbon black	PU	PLA with carbon black	CS	750 mV	—	—	—	—
CS-TENG (2022) [141] Arch-shape Self-powered bridge health monitoring system	Cu	PTFE	Cu	CS	30.3	97.6 nA	—	—	—
Hybrid TENG/EMG (MS-HNG) (2022) [142] Soft-contact Self-powered source for sustainable tunnel lighting system	Fur	PTFE	Al foil	FS	TENG: 800 (25 mm, 0.5 Hz) EMG: 6.5	TENG: 80 μA EMG: 17 mA	TENG: 300 nC	108 mW (400 Ω)	10 000 cycles
A-TENG (2023) [143] Cylindrical structure Real-time quantitative acceleration monitoring for bridge cable vibration	Al	PTFE	Al	Contact/non-contact FS	—	45 nA (9 Hz)	—	—	30 000 cycles

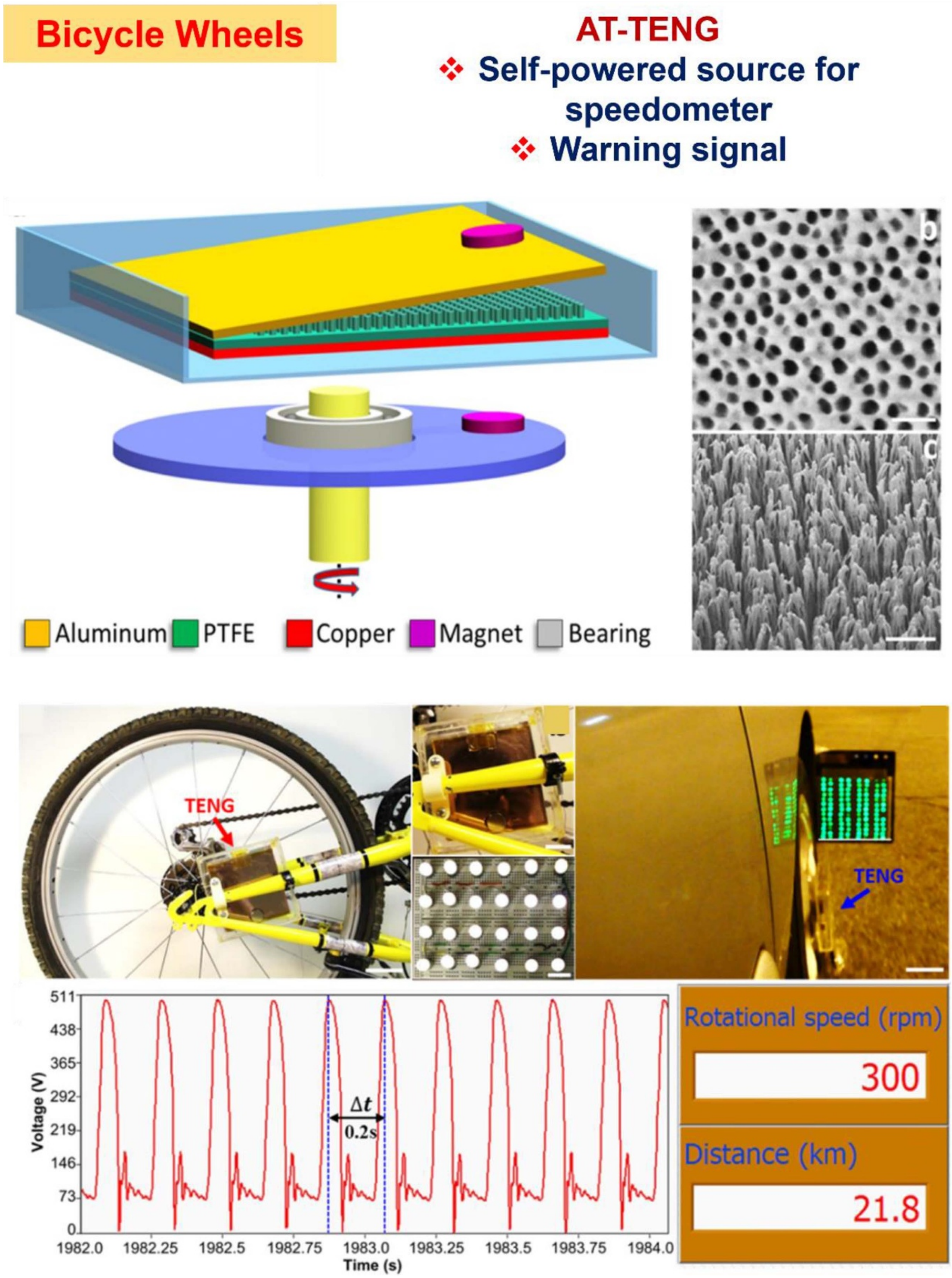

Figure 3. Demonstration of TENGs for collecting rotation energy from bicycle wheels. Design of AT-TENG for self-powered source speedometer and warning signal. Reprinted with permission from [104]. Copyright (2015) American Chemical Society.

The PTFE membrane was attached to the substrate's bottom, while the aluminum membrane was on top. As seen in figure 3, one end of the friction layer was fixed while the other was free. The rotation part was located below the function part. A fascinating feature of this configuration is the utilization of a dual-poled magnet assembly fixed to the upper section of both the operational component and the rotating component. Due to the complete substrate coverage and the rotating part's use of magnets, AT-TENG was able to operate in harsh conditions, which made it superior to conventional TENG. Furthermore, AT-TENG worked in two modes with this structure. When rotating at normal speed, the AT-TENG had a CS mechanism based on the push of the pair magnet; however, when rotating at high speed, the Al layer vibrated around its equilibrium position at the frequency of the rotation, changing the mechanism of the AT-TENG to a noncontact

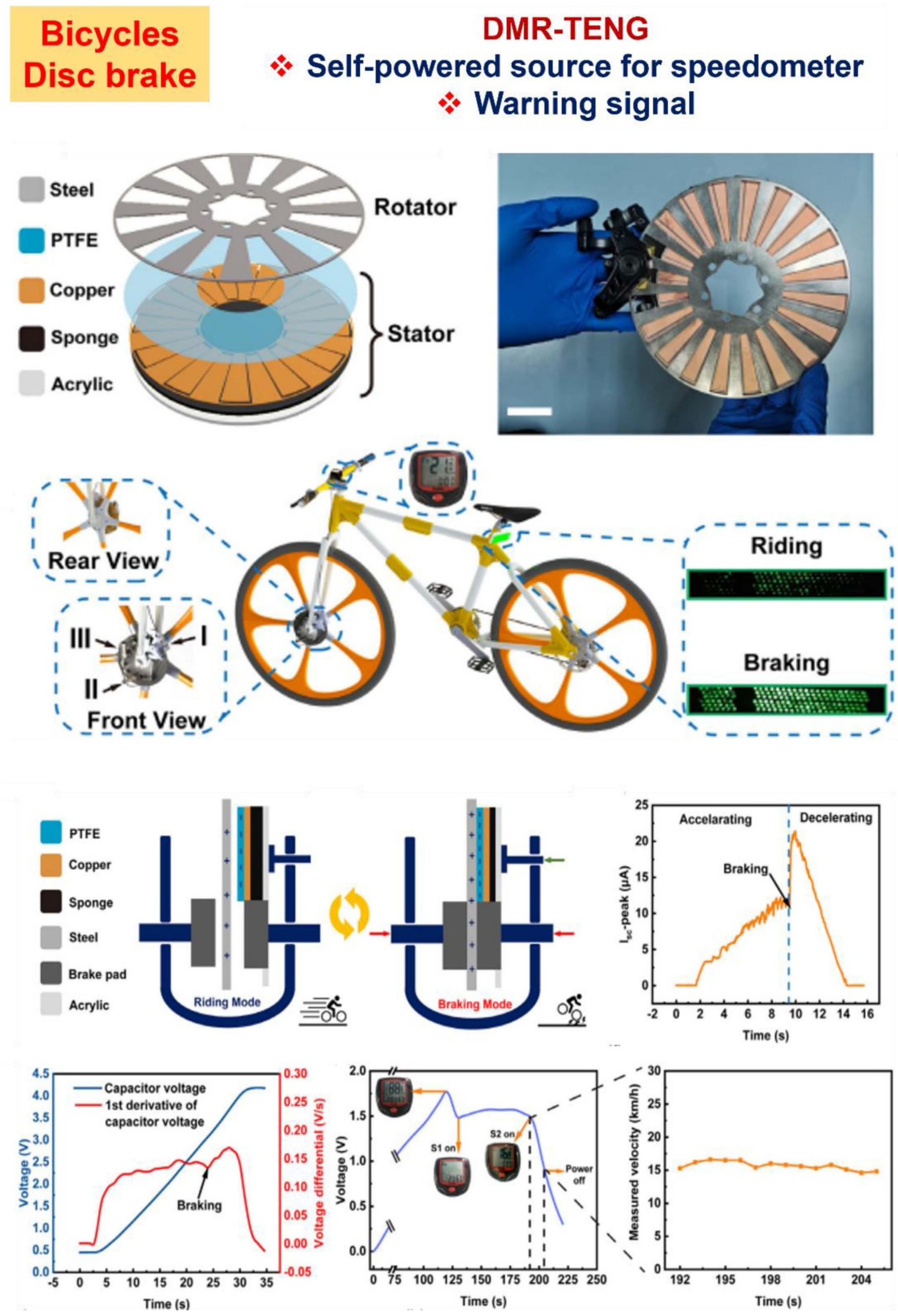

Figure 4. Demonstration of TENGs for bicycle disc brakes. Design of DMR-TENG for harvesting kinetic energy of disc brake. Reproduced from [105].

free-standing mode due to the joining effect of centrifugal force and gravitation. When AT-TENG was integrated into the bicycle wheel, the rotor rotated according to the rotation of the wheel; thus, AT-TENG harvested rotational energy and converted it into electricity to light 104 LEDs.

In addition, another research group employed a dual-mode rotary TENG (DMR-TENG) to collect the kinetic energy generated during the operation of bicycle disc brakes, both during riding and braking maneuvers (Zhou *et al* 2021) [105]. Figure 4 depicts the DMR-TENG construction, which consists of a rotator and a stator. The rotator was a steel plate with a brake disc structure; it was both a positive tribo-material and a brake disc. The stator part had PTFE film as a negative tribo-material, a copper radial electrode, a sponge layer, and an acrylic layer (figure 4). Because steel is the original material of the brake disc, it can maintain the original braking performance and mechanical characteristics. The sponge and acrylic functioned as protective layers; the sponge also brought the flexible PTFE closer to the steel. DMR-TENG's construction allowed it to be simply mounted to a bicycle disc brake, collect kinetic energy, and convert it to electricity. The DMR-TENG was capable of lighting 156 LEDs and acting as a power source for charging a 300 μF capacitor in a speedometer. Son's research team successfully created a triboelectric bicycle tire (TBT) in 2022. An aluminum film (50 mm $\times$ 25 mm) was put between the tire thread and the inner tube, separated from the inner tube by a PTFE layer (70 mm $\times$ 50 mm) [107]. TBT was operated in SE or FS mode, depending on the PTFE and Al layer designs. As the wheel turned, electrons were transferred between the electrode layer and the tire thread, creating an electric current. This current could power nine LEDs through a rectifier circuit when the bike was ridden on asphalt or concrete roads. Furthermore, different tire pressures result in varying contact areas between tire threads and the road surface, resulting in different electrical outputs. This phenomenon enabled the TBT to function as a self-powered bicycle tire pressure sensor. Specifically, using commercial bicycle components, the TBT system had a fully packed construction and could create exceptionally stable electrical output for 120 000 cycles. The application of TENG on bicycles is still being explored by many research groups, as shown in table 1. The investigations demonstrate that TENG has practical utility in smart bicycle devices.

4.2. TENGs for motored mobility

4.2.1. Cars

Because of their speed, comfort, and convenience, automobiles have become the predominant means of urban transportation. In addition, after the COVID-19 pandemic, private automobiles became more popular than public ones [144]. This results in apprehensions regarding the escalation of issues including traffic congestion, environmental pollution, and auto accidents. Car accidents are frequently the result of vehicle damage and negligent driving, and according to statistics, they are among the primary causes of mortality in the United States [3]. Consequently, there has been a strong emphasis on enhancing safety. Thanks to the application of IoT and AI, a series of sensor systems have been strategically installed in many locations on the car to increase safety, such as navigation systems, driver behavior monitoring sensors, detection sensors for damage to the vehicle, and many other sensors [145, 146]. Notably, the development of autonomous vehicles represents a technological breakthrough in IoT and AI, with the potential to usher in numerous remarkable developments in the field of transportation. Self-driving vehicles release driving time and decrease human-caused mishaps, including distracted driving, drinking before driving, and exhaustion, which are among the top causes of traffic accidents. Through the integration of sensors and Wi-Fi systems, autonomous vehicles can establish real-time connections to detect potential risks, automatically modify their speed and distance from other vehicles to prevent accidents, and simultaneously choose the most efficient and secure route [147–149]. The advantages demonstrate that autonomous cars are a very efficient solution for enhancing the safety of the traffic system. Studies have predicted that autonomous vehicles have the potential to decrease road fatalities by as much as 90% [150]. In addition, this technology also solves traffic congestion and is environmentally friendly since it reduces fuel usage, thereby decreasing harmful carbon dioxide emissions. Conversely, self-driving vehicle systems are also humane since they may provide convenient mobility for those with disabilities. Despite the notable efficiency of these technologies, the task of finding sustainable energy sources for sensor devices continues to be formidable. TENG technology has demonstrated its revolutionary potential in the field of energy harvesting, particularly in the development of self-powered sensor systems for automotive applications. This technology possesses distinct benefits and unique properties that make it highly suitable for this purpose. There has been a growing proliferation of research groups proposing the utilization of TENG in the development of autonomous sensing systems capable of harnessing energy for application in automobiles [108–117].

The TENGs can convert the mechanical energy generated by the car into electrical energy. As an illustration, the operation of automobiles on roadways generates oscillations within the engine. Numerous research groups have studied the use of vibration energy, leading to the development of TENG devices made specifically for harvesting vibration energy [108–110]. For example, Wen's research team created a harsh environment TENG (heTENG) that could operate as a self-powered smart braking (SP-SB) device in 2018 [108]. The distinctive structure of the heTENG consists of an Al-ball-filled PTFE circular grid frame (rolling structure). When vibrated, the Al balls may collide straight up and down between the two PTFE membranes. The Cu electrode was utilized on one side of the heTENG, while Q235 steel was used on the other, as seen in figure 5. A hybridizing micro-nanocomposite material was employed as the substrate to encapsulate heTENG to increase wear resistance and endure high temperatures. The heTENG comprised two

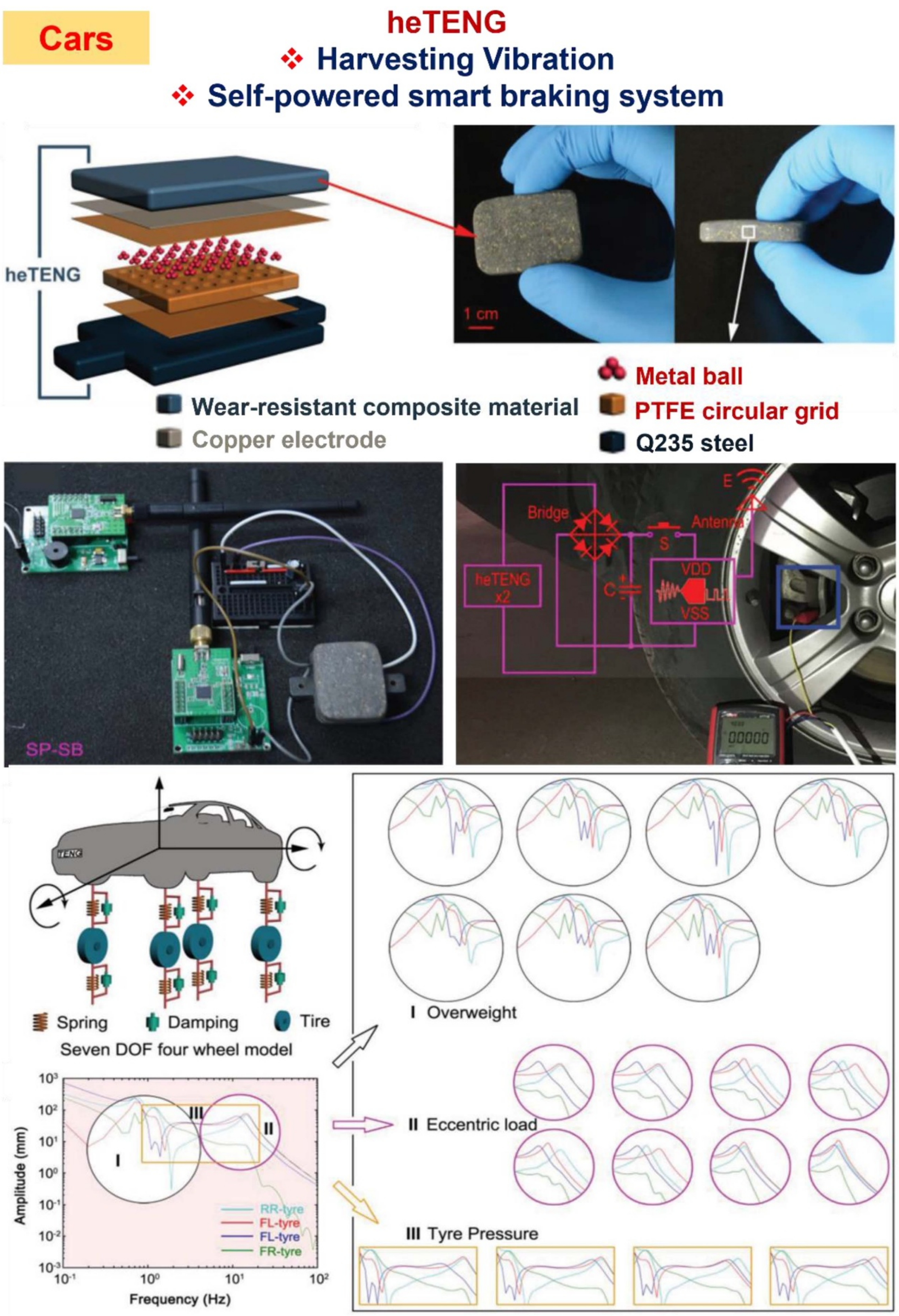

Figure 5. Demonstration of TENGs for harvesting vibration energy from moving cars. Design of heTENG for self-powered smart braking system [108]. John Wiley & Sons. © 2018 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim.

fundamental components: the heTENG-I, which functioned in FS mode, and the heTENG-II, which operated in SE mode with a grounded electrode on the lower portion. The heTENG converted both slide and vibration energy, achieving a high output performance of 221 V, 27.9 A μcm^{-2}, and 33.4 μC cm^{-2} at a high engine speed of 4000 rpm and a frequency of roughly 1 Hz. The heTENG also had strong wear resistance (dynamic friction coefficient around 0.69 μm at low friction around 8.1 N at room temperature), excellent high-temperature tolerance (from −30 °C to 550 °C), and high hardness. Wen *et al* created a SP-SB device from heTENG to show how it works. With the SP-SB device's designed structure (illustrated in figure 5), it was possible to detect when the brake pads required replacement without the need for an engineering expert. The SP-SB worked as a driving safety early warning system for cars, detecting overweight, eccentric load, and tire pressure.

Based on the combined triboelectric and chemical resistive effects, Shen *et al* developed TENG as a self-powered source for the emission detector of a vehicle in 2018 [109]. The device was made up of three independent parts: the TENG was the vibration energy harvester, the exhaust detector was a resistive kind of gas sensor, and the warning signal was a commercial LED. The TENG was made up of an Al foil that served as the positive triboelectric material and electrode, and a PTFE film that served as the negative triboelectric material. PTFE nanowires (diameter 100 nm and length 1 μm) were manufactured in addition to the core TENG component to increase roughness and surface charge density. Two acrylic substrates with four springs protected the device (figure 6). Finally, a heavy iron block was put on top of the TENG to ensure that the upper and lower parts of the system are in direct contact, and the bottom was an insulating plate for working at high temperatures. The NO_2 sensor included WO_3 nanorods that connected in parallel to two electrodes of the TENG and many commercial LEDs. This device could be easily installed on an automobile engine to collect lost vibration energy. The TENGs device operated in CS mode based on mobile vibration and NO_2 gas flow, and the sensor detected NO_2 concentration to send out a warning signal. By adjusting the number of LEDs illuminated by the TENG, the concentration sensitivity of NO_2 gas could be modified.

Xu's research team also suggested a TENG (S-TENG) based on a soft and powerful spring for collecting vibration energy [110]. S-TENG possessed a distinctive spiral structure along the spring wire. The spring wire coating was an elastic electrode composed of silicon rubber and carbon nanofibers with diameters ranging from 100 to 200 nm. This layer was resistant to deformation up to 133%. An extra layer of silicon rubber covered the bottom electrode. The top part of the S-TENG was free to move, while the bottom part was fixed to the base. As a result, S-TENG vibrated vertically and horizontally and worked in the CS mode of the elastic electrode layer and silicon rubber layer. When mounted on the top of a model automobile, the TENG collected the shaker energy and powered over 20 LED lights, or it charged a temperature and humidity sensor capacitor in 300 s. By adjusting the spring's hardness and the thickness of the silicon rubber layer, this design permitted the device to be utilized at various resonant frequencies.

The utilization of the motion energy of the car steering wheel has also been harnessed. In 2022, Li's research team created a self-powered dual-type pulse signal angle sensor (DSA-TENG) that directly converted motion variables into AC and DC electrical signals in various directions of motion [111]. DSA-TENG had a stator/rotor structure, as shown in figure 7. The rotor consisted of a FL, which was a FEP film layer with a thickness of 150 μm, and a periodic grading structure that was created using a laser cutting machine. This FEP layer was adhered to a foam (thickness of 0.5 mm) and circular acrylic substrate. The friction efficiency of the two contact layers was improved by this substrate layer. The stator was a thin copper foil (thickness of 30 μm) connected to the base of a circular substrate with a fan-shaped interspace structure (the angle between the fan blades was 45°); the copper foil worked as a friction electrode (FE). Two identical copper foils were additionally bonded to both sides of a fan-shaped hole, with one side grounded to act as a DC filtering electrode (DCFE) and the other as a charge-collecting electrode (CCE). The activity of DSA-TENG was a combination of the operations of each DS-TENG unit in the DSA-TENG structure (as indicated in the picture). When the rotor part rotated clockwise (the FE is in front of the CCE), the triboelectrification effect occurred first, followed by air breakdown, which generated the DC current. When the rotor part turned counterclockwise (the CCE is in front of the FE), it generated AC signals without a DCFE via triboelectrification and electrostatic induction. DSA-TENG was installed on the automobile steering wheel in an innovative design to operate as a real-time monitoring sensor in rotation angle and direction. The DSA-TENG sensor signal was sent to the computer for analysis, with the pulse peak type (DC or AC) representing rotation direction, the pulse peak number representing rotation angle, and the pulse peak width representing rotation speed. As a result, the DSA-TENG sensor provided real-time monitoring and steering wheel information feedback. This could be applied to automated vehicle systems that track the trajectory of the vehicle in real time to ensure driving safety.

The spinning wheel also generates robust steady energy. The capability of TENG to effectively gather and convert rotational energy into electrical energy has been demonstrated [112–114]. In the year 2019, the research team of He successfully designed and created a hybrid electromagnetic generator TENG (EMG-TENG) device with the purpose of collecting rotational energy [112]. The device was comprised of a cylindrical framework made of acrylic material, referred to as the stator component, and a central shaft that was connected to four acrylic blades capable of rotational movement around the shaft, known as the rotator component. The rotator was affixed with a layer of PTFE film, which acted as a negative friction layer, and was accompanied by sponge padding. On the other hand, the stator component was embedded with an Al foil electrode (figure 8). The structure of the EMG consisted of four pairs of cylindrical magnets and cores

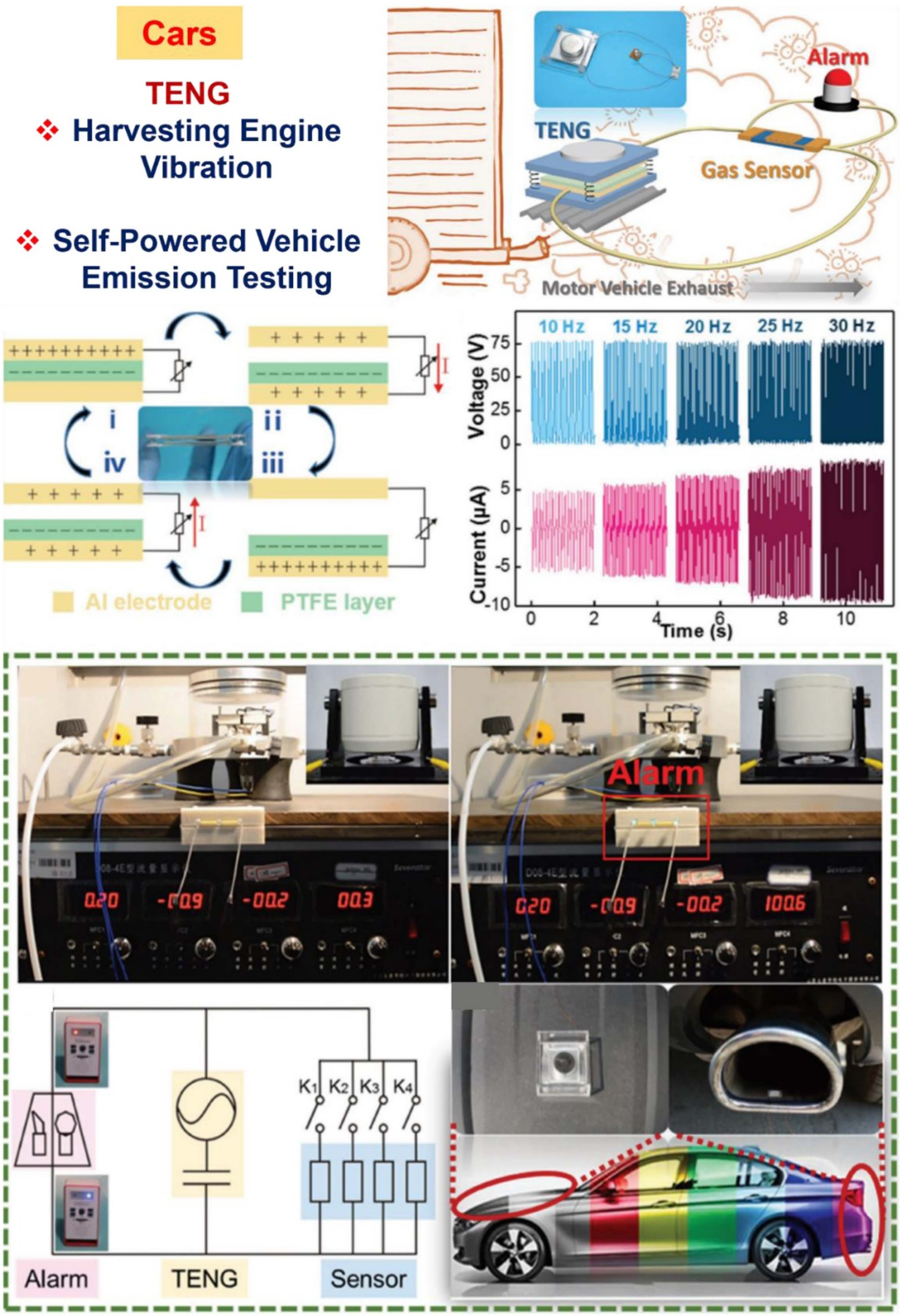

Figure 6. Demonstration of TENGs for harvesting vibration energy from moving cars. Design of TENG for self-powered vehicle emission testing [109]. John Wiley & Sons. © 2017 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim.

that were uniformly installed on an acrylic substrate. When this design was incorporated into the wheel, the rotor exhibited rotational movement in alignment with the wheel's revolution, thereby generating an electric current. This hybrid device had the capability to provide electricity to several sorts of sensors, including tire pressure sensors, self-powered counters, and timers for potential speed detection. Furthermore, numerous accomplishments are gathered from other reports, as depicted in table 1.

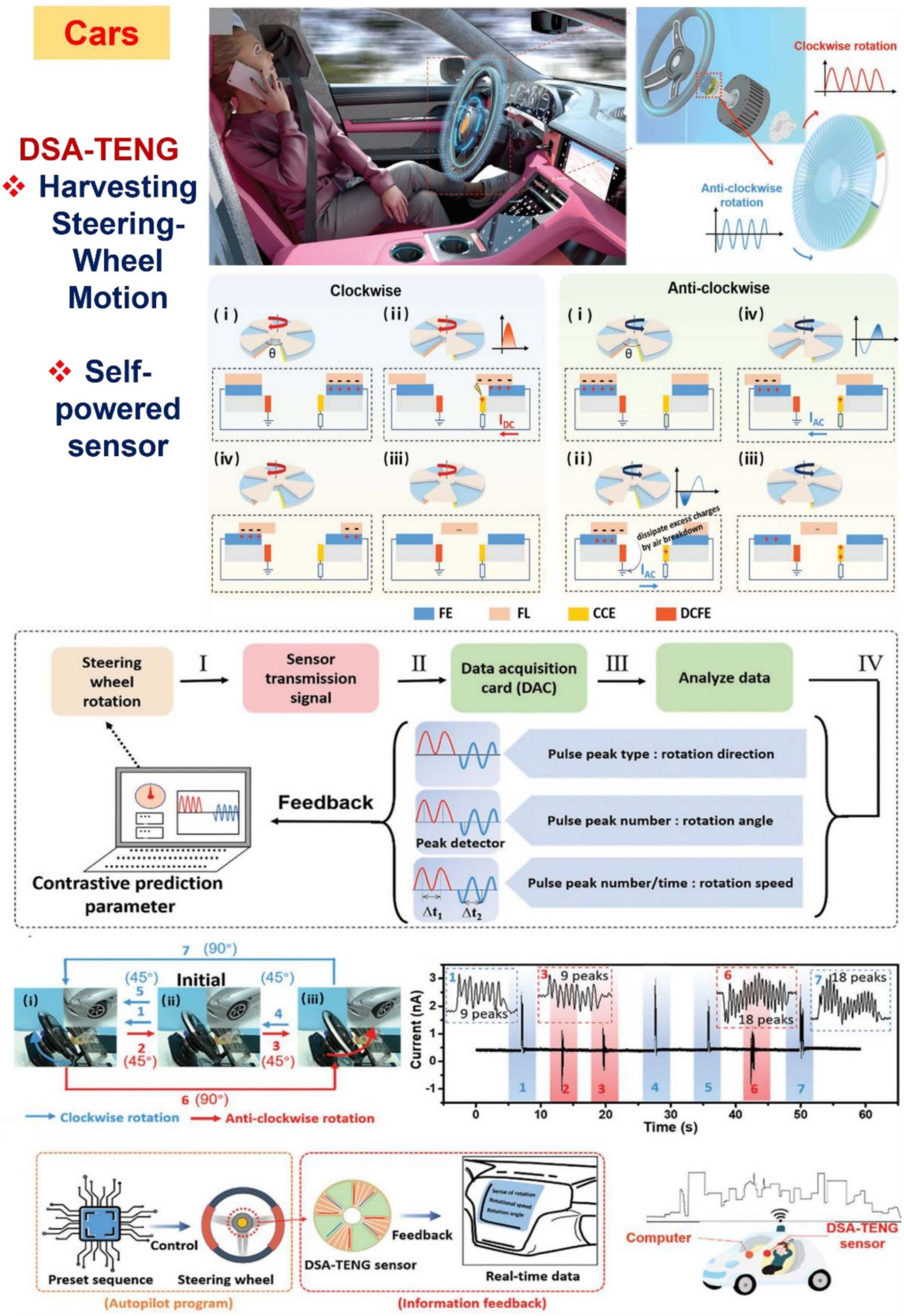

Figure 7. Demonstration of TENGs for harvesting rotation energy of car steering wheel. Design and working mechanism of DSA-TENG for self-powered sensor on car steering-wheel [111]. John Wiley & Sons. © 2022 Wiley-VCH GmbH.

4.2.2. Trains

The utilization and popularity of high-speed rail networks are increasing because of enhanced convenience, improved time management, and economic benefits. As a result, monitoring the railway to guarantee safety is a crucial objective. Currently, the sensors used in the railway system remain operational. Nevertheless, the power supply capabilities of these sensor systems remain limited. Self-powering devices that harvest and convert a variety of energy sources into electricity have been growing in recent years. For instance, solar cells

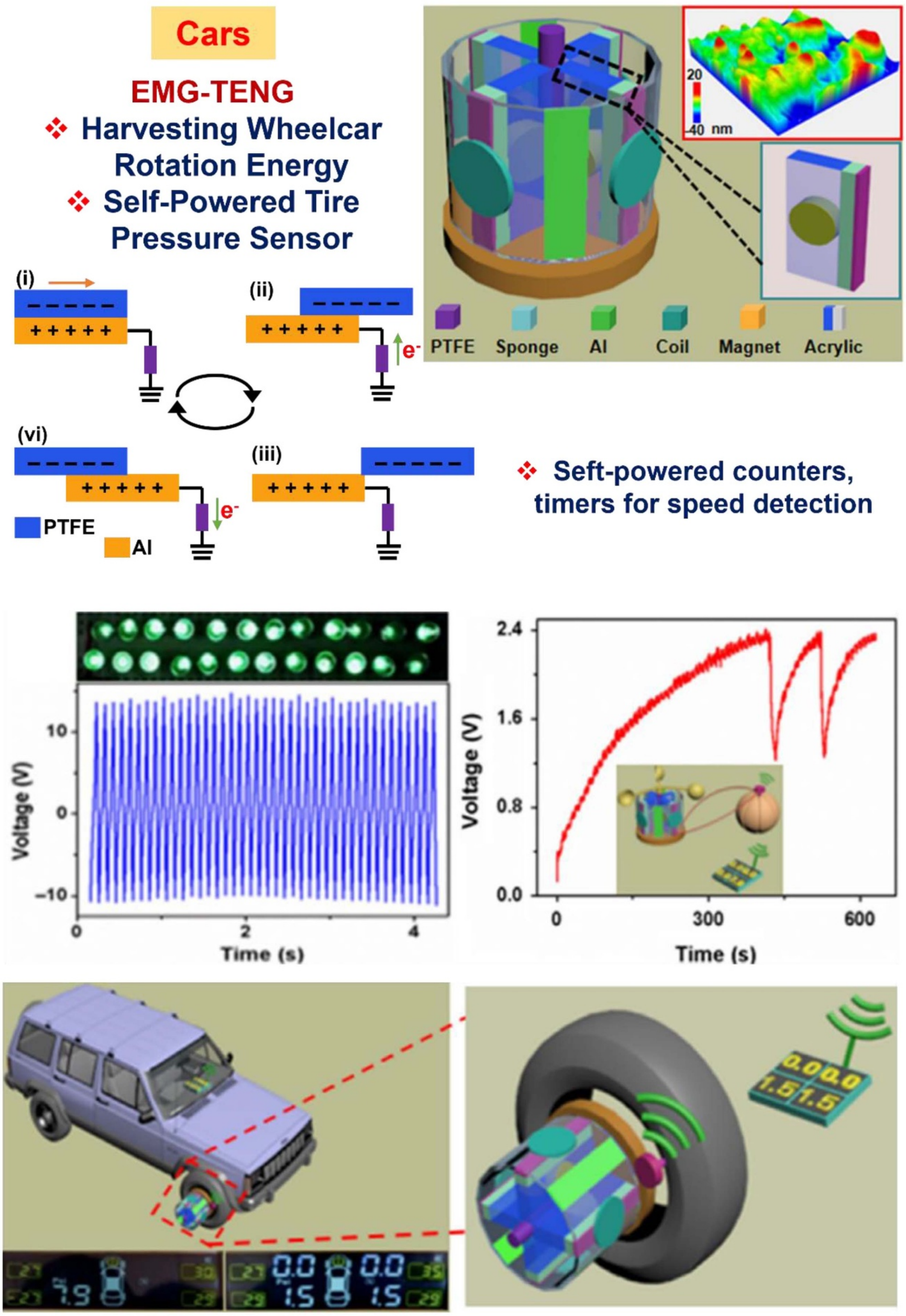

Figure 8. Demonstration of TENGs for harvesting rotation energy of wheel cars. Design and working mechanism of hybrid TENG/EMG for self-powered sensor on car steering-wheel. Reproduced from [112]. CC BY 4.0. © 2019 The Authors. Energy Science & Engineering published by the Society of Chemical Industry and John Wiley & Sons Ltd.

harvest solar energy, whereas wind turbines capture wind energy and convert it into electrical power. However, these devices are weather-dependent and costly [151, 152]. Recent research has demonstrated that vibrational energy possesses numerous advantages. Vibrations generated by the train's interaction with the rails are harnessed and transformed into electrical energy. This electricity is suitable for sensor network systems that operate wirelessly [153, 154]. The present vibration energy harvesting techniques that are widely used include electromagnetic, piezoelectric, triboelectric, and hydraulic [155–158]. Vibration energy harvesting has frequently employed electromagnetic techniques due to their numerous benefits, including high output power, high energy density, and compactness. Piezoelectric technology is popular for collecting vibration energy because of its tiny and light construction, high sensitivity, and stability. However, the railway system's vibration energies are discontinuous, low-frequency, and of small amplitude. Consequently, the effectiveness of these energy-harvesting technologies is limited. According to many studies, TENG technology has been shown to be extremely sensitive to vibrations at frequencies of a few hertz [158, 159]. TENGs could be used to collect energy from vibrations in railways. Various types of TENGs have been developed for integration with train systems [118–121, 139, 160].

Trains possess heavy cargo loads and operate at high velocities, resulting in the generation of significant levels of vibrational energy during their traversal along the railway. TENG devices are capable of harnessing and transforming this vibrational energy into electrical energy. In 2017, Zhao *et al* developed a self-powered triboelectric nano vibration accelerometer known as TEVA [160]. This device was specifically designed for application in rail tracks, with the aim of harnessing the low-frequency vibration energy generated by the passing of high-speed trains (below 10 Hz). The TEVA device had a simple spring structure (provided the device recovery force), and a poly (methyl methacrylate) (PMMA) substrate covered it. PMMA provided device protection due to its notable attributes such as high hardness, lightweight, convenient processability, and cost-effectiveness. The tribo-pair consisted of an Al nanolayer film and a Kapton nanostructure, with thin Al film serving as the electrode. The TEVA exhibited sensitivity to vibration acceleration ranging from 1.07 m s^{-2} to 1.25 m s^{-2}. This sensitivity enabled the generation of electric current to charge a lithium battery (1.5 V to 3.1 V) and self-power the accelerometer or the wireless sensor network nodes. Therefore, the self-powered TEVA presents a solution to the issue of powering the accelerometer, and the accelerometer location will not be limited. On the other hand, the timely collection of the vibration signal from equipment on trains facilitates a seamless execution of the diagnostic process. Table 1 demonstrates that this energy source is also utilized by different other research groups.

High-speed trains produce a substantial quantity of wind energy that is often dispersed. TENG can capture and transform the energy that is now wasted into useful electrical energy. In 2021, Zhang *et al* created elastic rotation TENGs (ER-TENGs) that had less friction and more output to collect wind energy from high-speed rail vehicles [118]. As seen in figure 9, ER-TENG had a dual stator/rotor construction. The rotator included a circular acrylic board with 12 negative tribo-membranes of PTFE arranged in a fan shape, connected to one side, and an additional 12 PTFE membranes attached to the other side. An inner layer of Kapton was added to the PTFE layer to improve mechanical contact and decrease the driving force. The stator component included two grooved copper panels attached to both sides of the rotor, functioning as positive layers and electrodes. An acrylic covering protected the ER-TENG, ensuring its durability even in harsh conditions. The ER-TENG was strategically installed at intervals along both sides of the railway track to collect the wind energy generated by a high-speed train passing over a railway and power the traffic lights and sensor networks. As a result, the ER-TENG is a self-powered system that significantly reduces high-speed train operating costs.

The high-speed train wheels' rotational energy may serve as a potential source for TENGs. In 2021, Jin *et al* developed a free-fixed TENG (FF-TENG) for monitoring the wheel train [119]. The FF-TENG had a stator/rotor structure and functioned in FS mode. The key idea of this design was to use magnets to attach the stator to the bogie. As a result, the stator did not make direct contact with the bogie, reducing the damage to the wheel. In addition to stabilizing the stator, the magnetic force increased the stator-rotor contact area, which increased the output. The stator consisted of a blade-shaped PU (electropositive layer) linked to one side of a circular acrylic sheet and two sets of magnets attached to the other side. Similarly, two more sets of magnets are attached to the bogie to help stabilize the stator section. The rotator had a PTFE electronegative layer, a Cu-blade-shaped electrode, and an acrylic cylindrical shell, as shown in figure 10. The rotation of the rotator induced friction between the PU and PTFE, which generated energy. The FF-TENG triggered 140 commercial LEDs and provided electricity to a wheel monitoring system. The energy conversion efficiency and reliability of the investigations, as well as several additional studies, are summarized in table 1. According to the research, TENG can be utilized in the construction of a modern and safe rail system.

4.3. TENGs for ships-blue energy

Wireless sensor systems are very handy and easy to install in road systems. However, there are still several issues when installing in large oceanic areas because of limited energy resources. Although there have been a variety of wireless warning systems used, such as radio navigation aids, they frequently run on standard batteries, which have a short lifespan and pose environmental risks. Therefore, the quest for clean and sustainable energy sources has garnered global attention. Ocean energy, also referred to as blue energy, has garnered considerable interest in recent times. The ocean, which comprises 70% of the earth's surface, is a

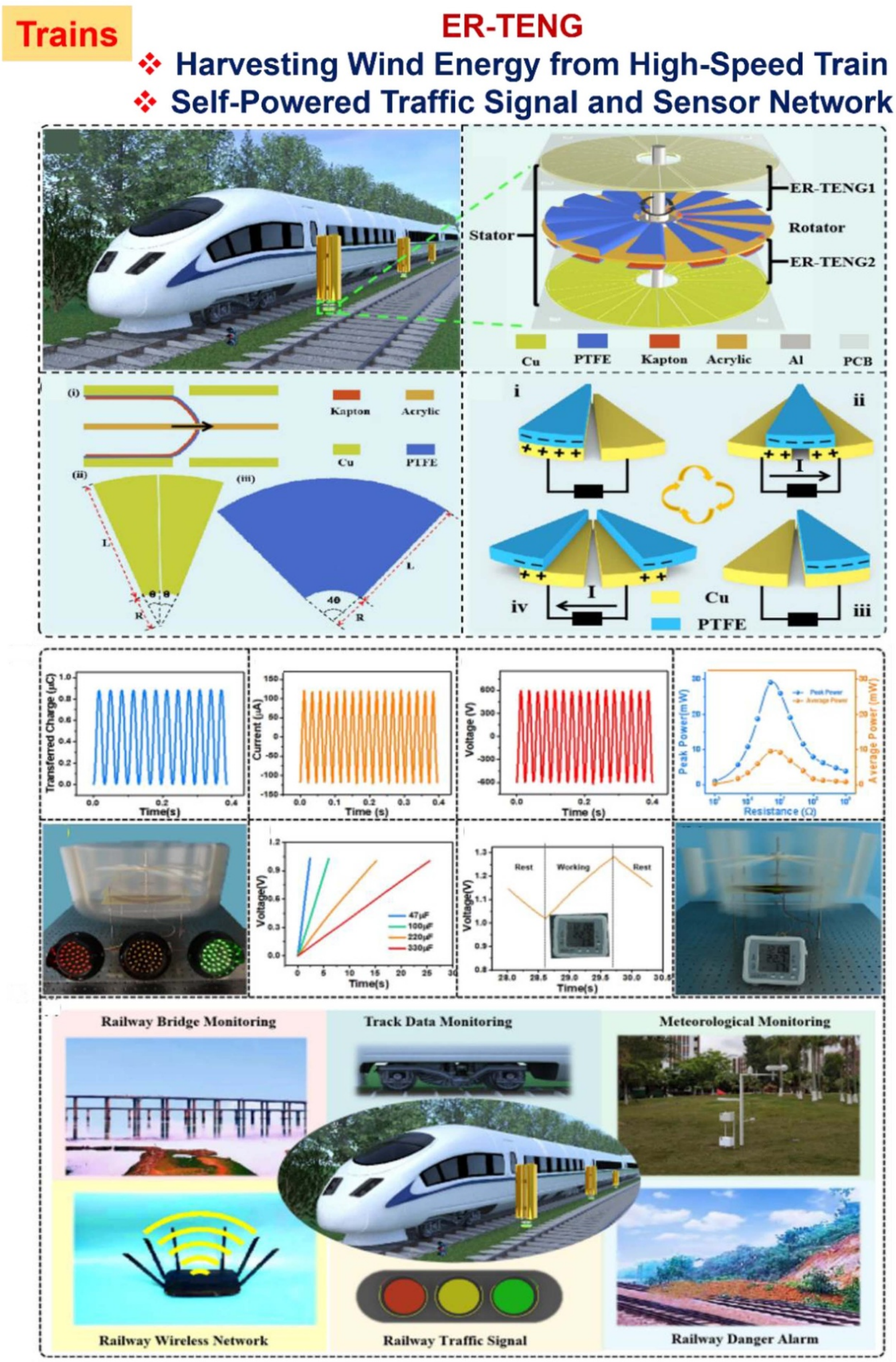

Figure 9. Demonstration of TENGs for harvesting wind energy from high-speed train. Design and working mechanism of ER-TENG for self-powered traffic signal and sensor network. Reprinted with permission from [118]. Copyright (2021) American Chemical Society.

boundless source of energy, particularly wave energy [161–163]. Due to its high density, widespread distribution, and environmental friendliness, wave energy can be collected and converted into useful electrical energy. However, since ocean waves often move at random and low frequencies, developing highly efficient exploitation technology remains difficult. TENG has emerged as a promising technology due to its cost-effectiveness, simplicity, and ability to harness irregular and low-frequency mechanical energy. Several

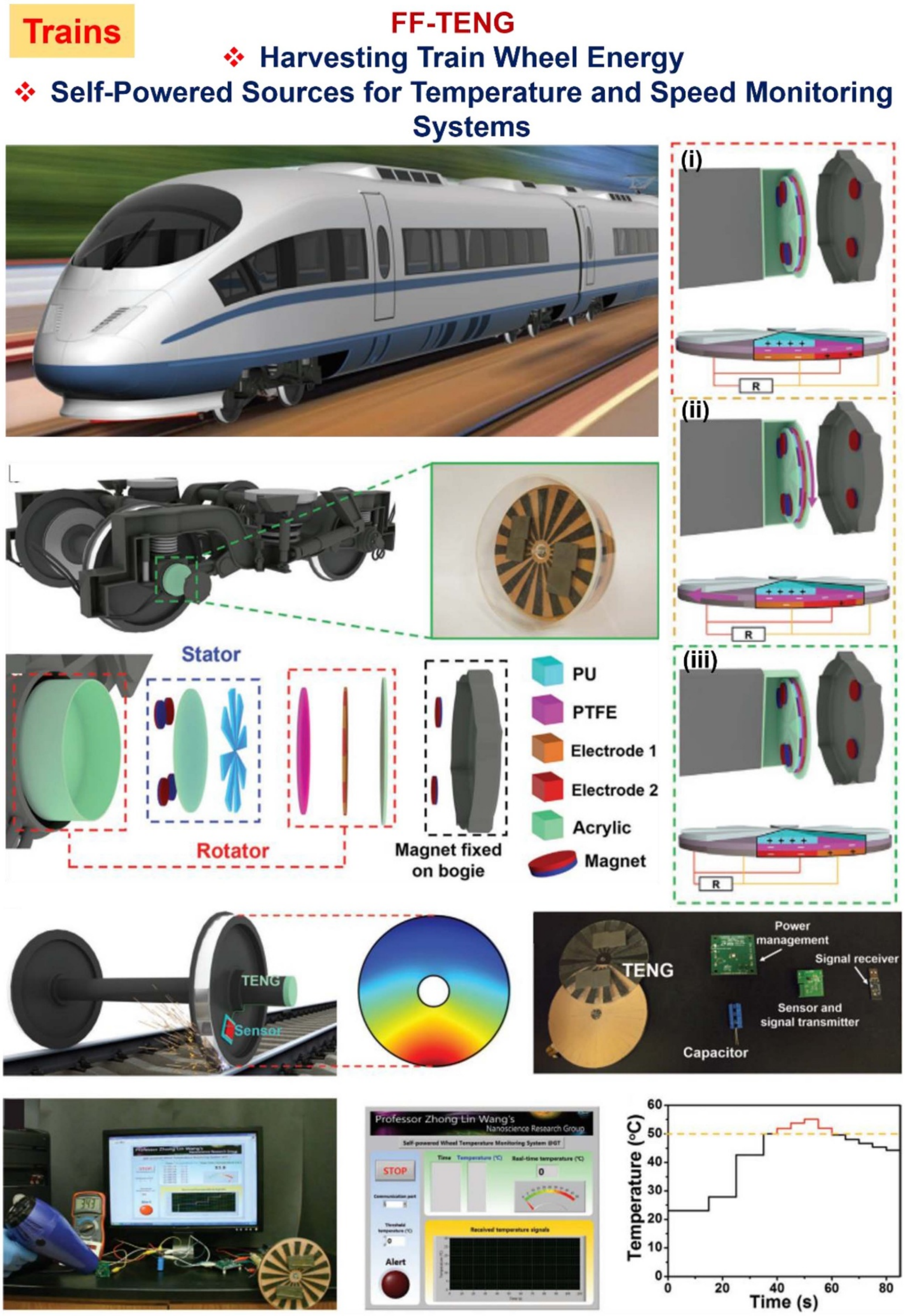

Figure 10. Demonstration of TENGs for harvesting energy from train wheel. Design and working mechanism of FF-TENG for self-powered source [119]. John Wiley & Sons. © 2021 Wiley-VCH GmbH.

TENG structures, including rolling structures, liquid–solid structures, and rotary disks, have been suggested for wave energy harvesting [122–125].

Using a liquid–solid structure, Li *et al* established a network of high-performance TENGs based on liquid–solid interface contact electrification (LS TENG) in 2018 [122]. Herein, the buoy-like LS-TENG can collect low-frequency blue energy from the ocean. TENG is a liquid–solid-contact buoy with three concentric cylinders of varying diameters (4 cm, 7.7 cm, and 11 cm). The cylinders were composed of many layers, with

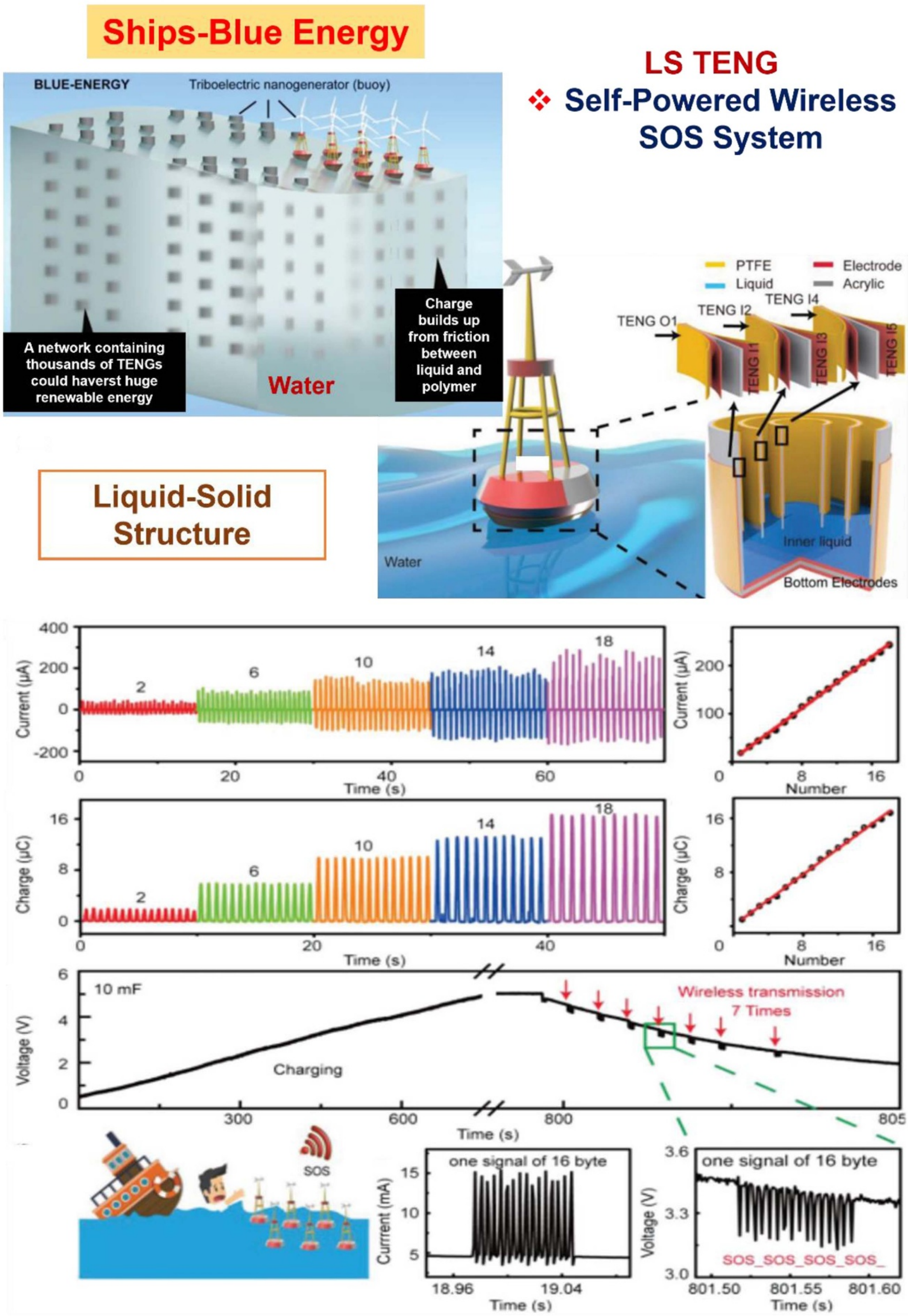

Figure 11. Demonstration of TENGs for harvesting low-frequency energy from ocean. Design of LS TENG for self-powered wireless SOS system [122]. John Wiley & Sons. © 2018 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim.

an acrylic substrate layer as the innermost layer, a middle electrode layer (Cu, Ag, and Al) on both sides of the acrylic layer, and a polymer negative friction layer on the outermost layer, as shown in figure 11 (PTFE, FEP, FET, and PDMS). The LS-TENG was completed when the water and bottom electrodes were inserted within the concentric cylinder. When the buoy LS-TENG shook, the water touched the polymer within, generating an output current. The LS-TENG captured energy from several movements, including vertical oscillation, shaking, and rotation. Additionally, the energy generated by a liquid–solid contact LS-TENG was shown to be 48.7 times higher than that of a solid–solid contact TENG, demonstrating a substantial increase in friction. The group of 18 LS-TENGs successfully charged a capacitor (10 mF) in a wireless SOS system from 0 to 5 V in around 13 min. By combining several LS TENGs, a substantial amount of blue energy can be collected from the ocean. Furthermore, it is anticipated that LS-TENG will exhibit stability for 10 years. In 2023, Liang's research group also created an asymmetric liquid–solid TENG (DE-TENG) [123]. DE-TENG was composed of two rectangular acrylic panels (70 mm $\times$ 65 mm $\times$ 2 mm) aligned with a 2 mm gap. The package included two identical PP and FEP films (64 mm $\times$ 64 mm $\times$ 100 μm). Magneton sputtering was used to create Cu electrode layers (60 mm $\times$ 60 mm) on these film surfaces. PP is more electropositive than water, but FEP is more electronegative than water; hence, DE-TENG has an asymmetric structure. When immersed in water, the water waves fill the gap between the two membrane surfaces, forming two electroactive layers facing each other and converting the kinetic energy of the water into electricity. One thousand DE-TENGs can be interconnected to harvest the energy of ocean waves. DE-TENG arrays provided electricity to signal lights, digital thermometers, and water quality indicators.

Hybrid TENG/EMG and pendulum structures have also been effectively designed by many groups [124–131]. Ren *et al* showed a self-powered route avoidance warning system for ocean navigation (HW-NG) in 2021 using hybrid TENG/EMG and pendulum structures [124]. The TENG had a multilayer structure with six pairs of CS-mode TENGs connected by springs, as indicated in figure 12. Polyimide was selected as the TENG's backbone because of its high mechanical strength and flexibility. The Cu film acted as the positive friction layer and an electrode on the frame, while the FEP with a nanostructured surface worked as the negative friction layer. A foam base was sandwiched between the layers. EMG is made up of a wobbling magnet block and four Cu coils arranged in an arc on a PMMA substrate. EMG and TENG could communicate through the pendulum bar. TENG and EMG were both protected by a cubic-shaped PMMA shell. As a result, the HW-NG successfully collected wave energy via pendulum bar vibration and operated as a power source for long-distance (1.5 km) wireless transmission. Thus, connecting hundreds of thousands of HW-NG nodes in seas near islands or coral reefs would result in a self-powered navigational warning system that provides vessel safety in all-weather situations. Table 1 summarizes the presentations of this structure by the research groups of Liu *et al* [126] and Demircioglu *et al* [125].

Swing structure has also been exploited effectively in some studies [127, 128]. Typically, Jiang *et al* fabricated a TENG with a powerful rotating structure in 2020 [127]. The cylindrical SS-TENG was made from a cylindrical acrylic shell that housed 6 copper electrodes and 4 PTFE (negative layer) stripes. The core of the cylinder had a spinning component comprised of three acrylic blocks affixed to a steel shaft using three bearings (figure 13). An arc-shaped acrylic strip (positive layer) was connected to the protruding sections of three acrylic blocks. A space existed between the copper electrode and the acrylic strips. In addition, several copper blocks are inserted at the bottom of the acrylic block to lower the center of gravity and facilitate the rotation process. Lubricant oil was also added to the connecting bearings to decrease friction. The SS-TENG device efficiently collected blue energy and transferred it to electricity, which powered environmental monitoring systems.

The emphasis has also been placed on using eco-friendly materials [129, 130]. Ahn *et al* developed an all-recyclable, mechanochemically robust TENG (AR-TENG) in 2022 to harvest wave energy as well [129]. AR-TENG has a straightforward design, with PMMA acting as the substrate or negative layer and noble metal (Pd) functioning as the positive layer and electrode (figure 14). PMMA was chosen for its formability, chemical resistance, weather resistance, UV resistance, abrasion resistance, high track and arc resistance, mechanical strength, and low cost, whereas Pd was chosen for its chemical stability and maximum triboelectric effect when combined with PMMA. Both PMMA and Pd contain nanohole pattern structures that improve AR-TENG's energy harvesting ability. PMMA and Pd are readily recycled in acetone, a green solvent. AR-TENG has spring structure and is protected by an acrylic base frame. AR-TENG can operate in contact-separation mode with this arrangement. AR-TENG has outstanding output power density and better mechanochemical stability following immersion in saltwater or 1000 000 cycling tests. This AR-TENG's practical applicability is proven by its usage to power a buoy-type ocean monitoring system and an intelligent life jacket.

The research achievements demonstrate that TENG is an innovative technology for harvesting blue energy. This offers potential for the development of sustainable energy sources that can power STS on land and at sea.

4.4. TENGs for unmanned aerial vehicles (UAVs)

UAVs are an excellent practical IoT application. UAVs have been employed in a variety of applications ranging from military to civilian, including detecting and tracking objects, exploring dangerous locations, transporting goods, and monitoring infrastructure [164, 165]. When UAVs are incorporated into road traffic monitoring systems, it attracts a lot of interest. UAVs can assist in automating this system by collecting road

Figure 12. Demonstration of TENGs for harvesting wave energy. Design of HW-NG for wireless ocean navigation [124]. John Wiley & Sons. © 2021 Wiley-VCH GmbH.

traffic conditions to minimize congestion, identifying vehicles with high speeds, and giving a good perspective on traffic incidents [166–169]. As a result, using a self-powered TENG on UAVs will help them become a potential tool for the future, opening many more practical applications [132, 133, 140].

Tao's research team created a TENG with a honeycomb form (h-TENG) in 2021 [132]. The h-TENG includes a negative friction thin film layer of FEP with nanostructured pillars, a transparent PET substrate layer with electrode silver nanowires (AgNWs) to support cycling pressing and releasing operations, and a

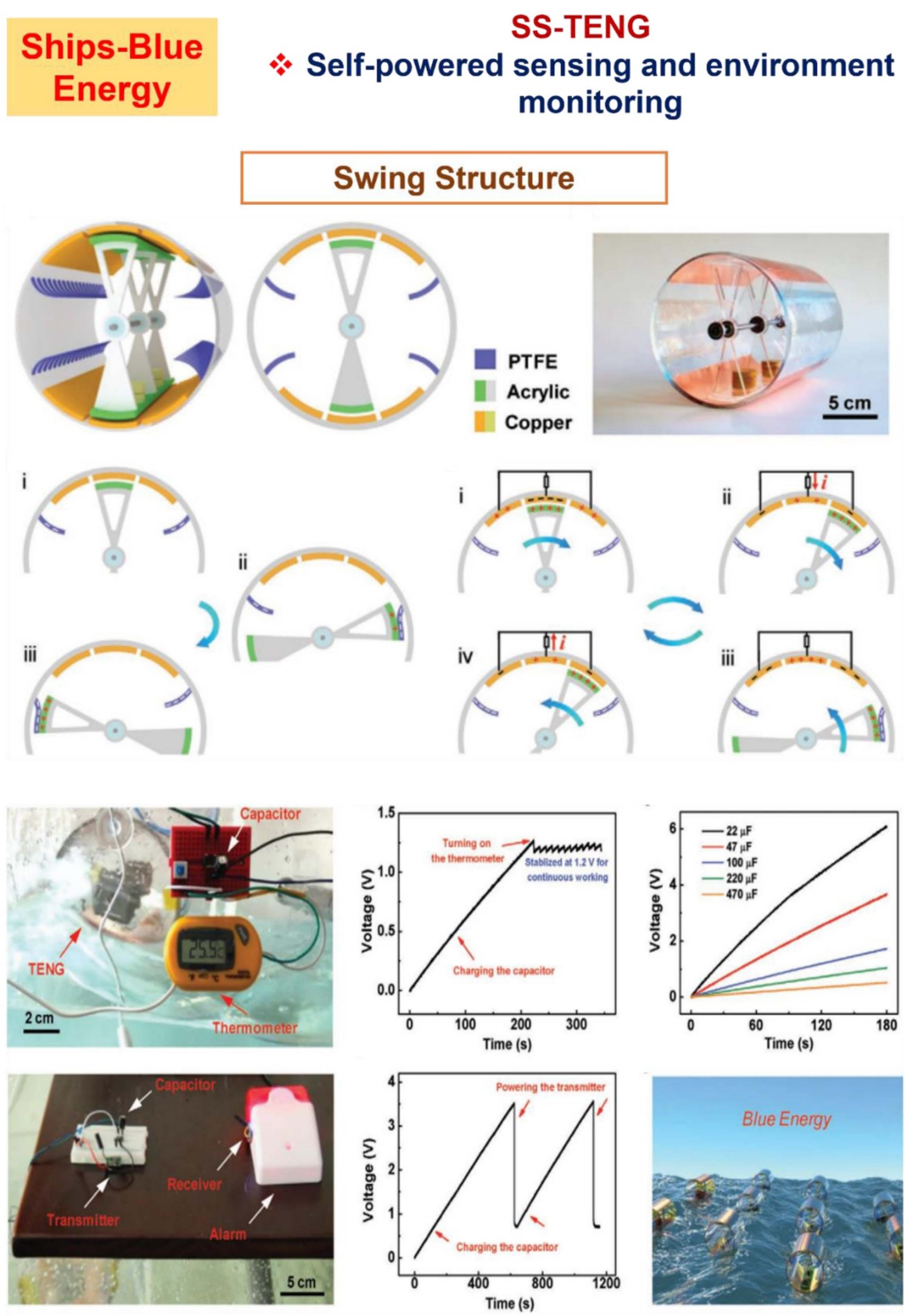

Figure 13. Demonstration of TENGs for harvesting wave energy. Design of SS-TENG for self-power environment monitoring system [127]. John Wiley & Sons. © 2020 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim.

transparent PET substrate layer with electrode AgNWs to sustain cycling pressing and releasing operations (figure 15). The considerable roughness of the AgNW and FEP surfaces assists in charge capture, improving h-TENG performance. The h-TENG is divided into a parallel-connected array of arch-shaped deformable capacitors by the porous honeycomb structure. Each unit will be capable of bending and compressing. As a result, overall capacitance changes are greatly magnified, making h-TENG very susceptible to external perturbations. The h-TENG can operate for 75 000 cycles under mechanical shaker. The h-TENG devices are

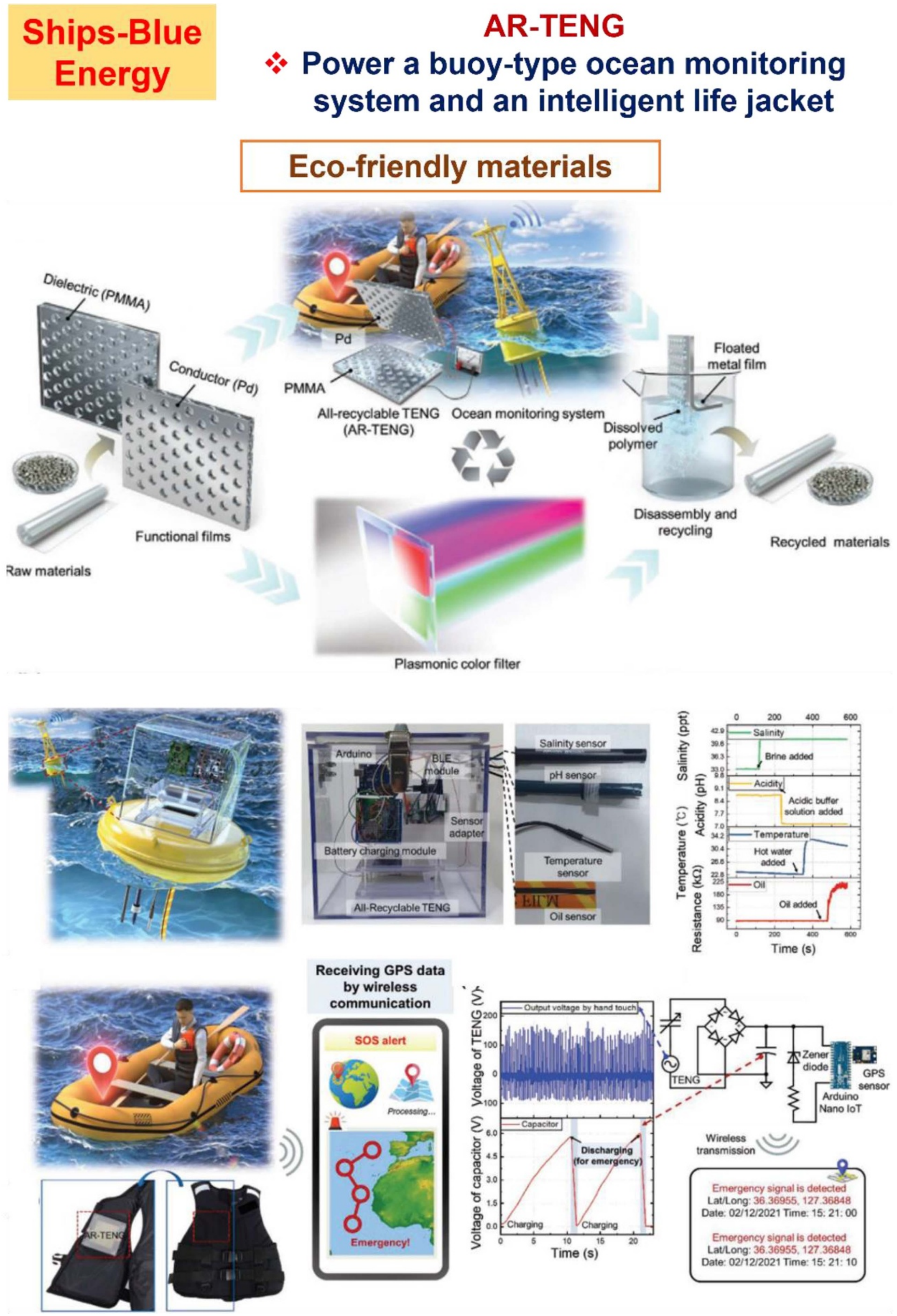

Figure 14. Demonstration of TENGs for harvesting wave energy. Design of AR-TENG for self-power environment monitoring system [129]. John Wiley & Sons. © 2022 Wiley-VCH GmbH.

small, flexible, transparent, and lightweight due to their outstanding resilience and self-rebounding qualities. With this unique characteristic, h-TENG may be incorporated into UAVs to collect and convert kinetic energy from morphing wing motions into electricity. As a result, h-TENG may be utilized as a self-powered source for UAVs.

Gyroscopes are now frequently used as sensors in applications that require the measurement of angle, tilt, and angular velocity, such as monitoring the flying posture of a UAV and taking photos. Gyroscopes,

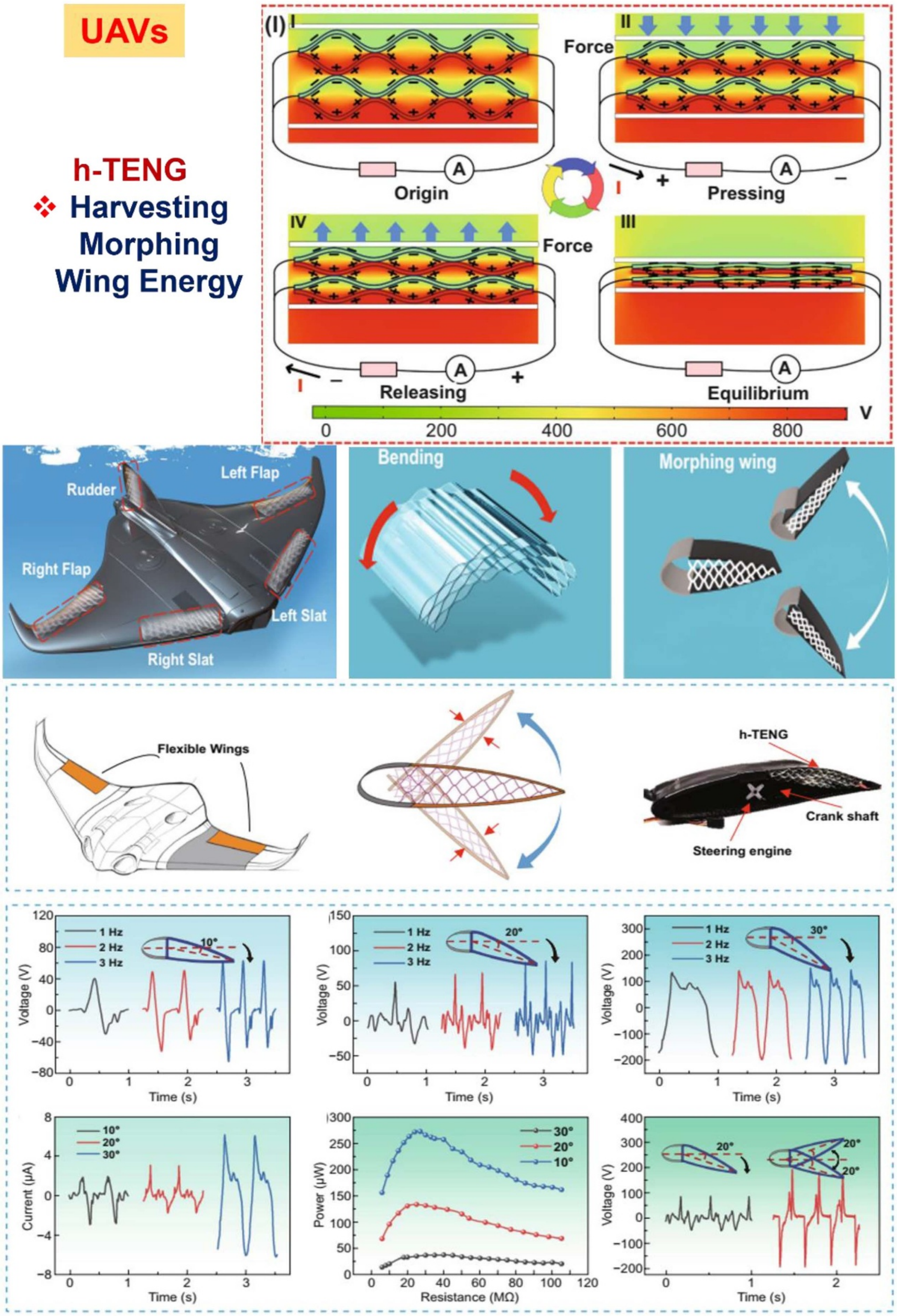

Figure 15. Demonstration of TENGs for harvesting morphing wing energy from UAVs. Design and working mechanism of h-TENG. Reproduced from [132].

although effective, still need an external power source. To address this issue, Xie *et al* developed a freestanding-mode rotary disc-shaped TENG (FRD-TENG) in 2021 for a self-powered gyroscope angle sensor (SGAS) [133]. FRD-TENG had a stator/rotor structure, as seen in figure 16. The rotor consisted of 30 radial copper electrodes (each at a 6° with the other), and the stator included two circular interdigital electrodes and negative tribolayer PTFE. The FRD-TENG has been connected in series with a resistive rotary potentiometer to form the SGAS. The results demonstrated that various electrical signals were received at

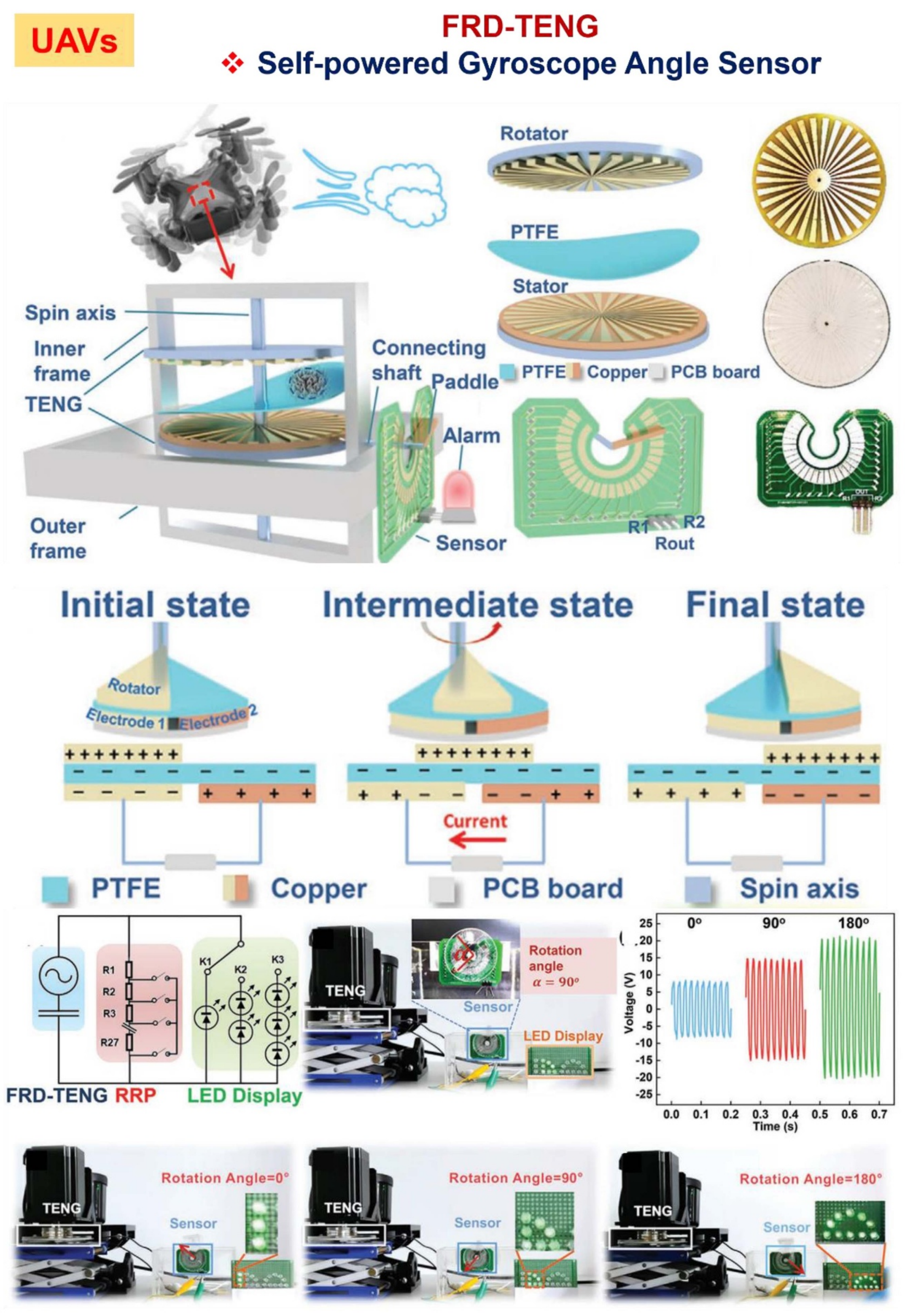

Figure 16. Demonstration of TENGs for UAVs. Design and working mechanism of FRD-TENG for self-powered SGAs sensor [133]. John Wiley & Sons. © 2021 Wiley-VCH GmbH.

different rotation angles, implying that SGAS might be employed as a very sensitive real-time rotation angle sensor. In addition, SAGS activated the LEDs of the alert system. As a result, Xie *et al* have effectively developed a self-powered rotation angle sensor system with broad applicability in areas such as UAV navigation or automatic driving.

In 2022, Yao *et al* created an arc-shaped TENG, known as AW-TENG, which serves as a wind speed sensor [140]. The AW-TENG structure included a negative tribolayer of PTFE, a copper electrode, and a 3D-printed

PLA arc-frame shell. The arc design of AW-TENG helped reduce air resistance. AW-TENG achieved a voltage frequency of 50–200 Hz within a wind speed range of 6–20 ms^{-1}. The sensitivity was 9.88 Hz ms^{-1}, and the goodness of fit R_2 was 0.998. When integrated into the UAV and operated in CS mode, AW-TENG gathered wind speed signals and communicated them wirelessly to the ground station, triggering a response from the UAV. Thus, AW-TENG can function as a self-powered wind speed monitoring system for UAVs.

Briefly, TENGs offer a renewable energy solution for sensor systems in UAVs, enhancing the safety and in-real-time precision of intelligent transportation systems.

4.5. TENGs for infrastructures

The presence of a synchronized and contemporary infrastructure system is indicative of a nation that has achieved a high level of development. This system plays a crucial role in guaranteeing the safety of traffic. As a result, most countries prioritize the building of modern infrastructure [170, 171]. Furthermore, the inescapable degradation of infrastructure systems resulting from prolonged operation in severe conditions and substantial vehicle loads is also a cause for concern [172]. The utilization of TENG in infrastructure systems has yielded several noteworthy accomplishments, encompassing the development of self-sustaining traffic light systems for roadways and tunnels, as well as self-powered monitoring systems for bridges and other civil infrastructure [118, 134–136, 141–143].

In this application, TENG devices have the capability to capture wind energy produced by moving vehicles. For instance, Zhang *et al* created a rotating disk-based hybridized nanogenerator of EMG and TENG in 2016 [134]. This study used the stator/rotor TENG structure with the above rotor of four intercrossing acrylic blades mounted on a circular shaft and grated negative tribolayer (PTFE) (a buffer PU layer was between PTFE and blades). The below stator was positive tribolayer of grated Al foil. These two tribolayers' surfaces featured a nanostructure to increase the contact area. The EMG included four magnets on one side (rotor) and four symmetrical coils on the other (stator), as shown in figure 17. The device has been installed in the tunnel for operational efficiency. The movement of vehicles generated airflow, resulting in the rotation of the rotor. This lead the EMG-TENG to generate electricity, which then powered wireless traffic volume sensors. Consequently, EMG-TENG is an efficient tool for real-time monitoring of traffic flow, which aids in the reduction of traffic accidents. Similarly, in 2023, Su *et al* also used the stator/rotor design (AG-TENG), but with structural upgrades to increase the power output [135]. The upper stator of the AG-TENG consisted of a copper foil with a grating structure with a gap of 4 mm, mounted on a PCB board serving as an electrode. Additionally, three polyester furs acted as a ternary dielectric material. The rotor was a grating structure composed of PTFE and nylon film, as shown in figure. When AG-TENG was in FE mode, PTFE first touched the polyester fur, receiving electrons from it, and then nylon contacted the fur, transferring electrons to it. Therefore, the fur could both donate its own electrons and receive more electrons from nylon to transfer them to PTFE. This technique enhanced the quantity of electrons transferred, hence enhancing the output (a single AT-TENG yielded a power density of 0.2 W m^{-2} at a wind speed of 3 ms^{-1}). In addition, AG-TENG enabled the transfer of electrons between opposite-polarity tribomaterials without contact. This feature reduced the wear and tear on the system. It was worth noting that AG-TENG can operate continuously for 80 h, performing 1440 000 cycles without any stability issues. Moreover, the traditional design of the stator/rotor, with the rotor positioned above the stator, presents some issues, such as electrostatic attraction and gravitational forces that result in the rotor being in closer proximity to the stator. This closeness leads to increased levels of friction and wear. To address this issue, AG-TENG can be employed by positioning the rotor beneath the stator and utilizing the gravitational force of the rotor to counterbalance the gravitational electromechanical force. AG-TENG also included an anti-glare panel system. When implemented in highway systems, the utilization of large-scale AG-TENG technology enabled the collection of wind energy from moving vehicles to supply power to LED lights, signal lights, and low-power IoT devices along the highways. Additionally, it served to reduce the likelihood of traffic accidents by obstructing the intense light that approaching cars emit.

The mechanical excitation of the infrastructure system may potentially be used as an energy source for the TENGs. Zhang's research team successfully incorporated TENG into the reinforcing steel bars (FRBs) that comprise the structural components of civil infrastructure systems (TENG-SEs) in 2021 [136]. The five layers of FRB are illustrated in figure 18. The innermost layer was composed of Nylon 66 with 10% carbon fiber reinforcement. The conductor layer was composed of PLA with carbon black. These two interconnected layers were commonly referred to as the 'core'. The dielectric PU layer and the PLA with carbon black layer were the next two layers, which were referred to as 'cloth' overall. The outermost layer was PU, as shown in figure 18. Due to the cloth layer's curved structure, there was a gap between the core and the cloth. This enabled the operation of TENG-SE in CS mode. With this design, the rebar worked as both a normal way to strengthen concrete structures and as a TENG that could capture mechanical excitations and detect problems in civil infrastructure systems.

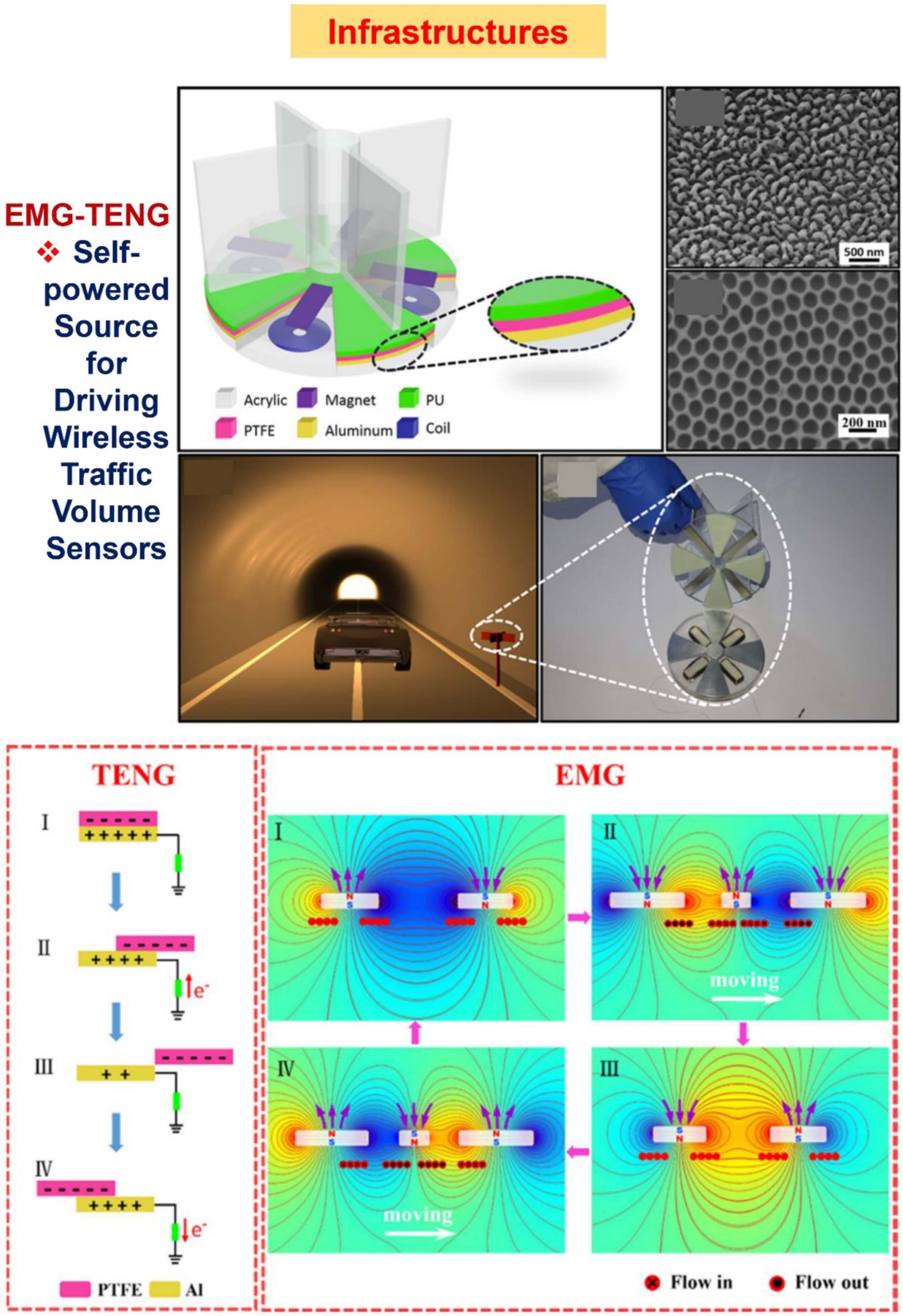

Figure 17. Demonstration of TENGs for harvesting wind energy at the tunnel. (a) Design and working mechanism of EMG-TENG for self-powered traffic signals. Reprinted with permission from [134]. Copyright (2016) American Chemical Society.

In 2022, Xu's research team implemented TENG into a self-powered health monitoring system (CS-TENG) based on the fundamental structure of CS mode [141]. In this design, a copper foil layer serves as the positive material and electrode (Copper 1), while a PTFE layer (240 μm) serves as the negative material layer and is attached to the copper foil electrode (Copper 2). Melting and heating PP straw creates a

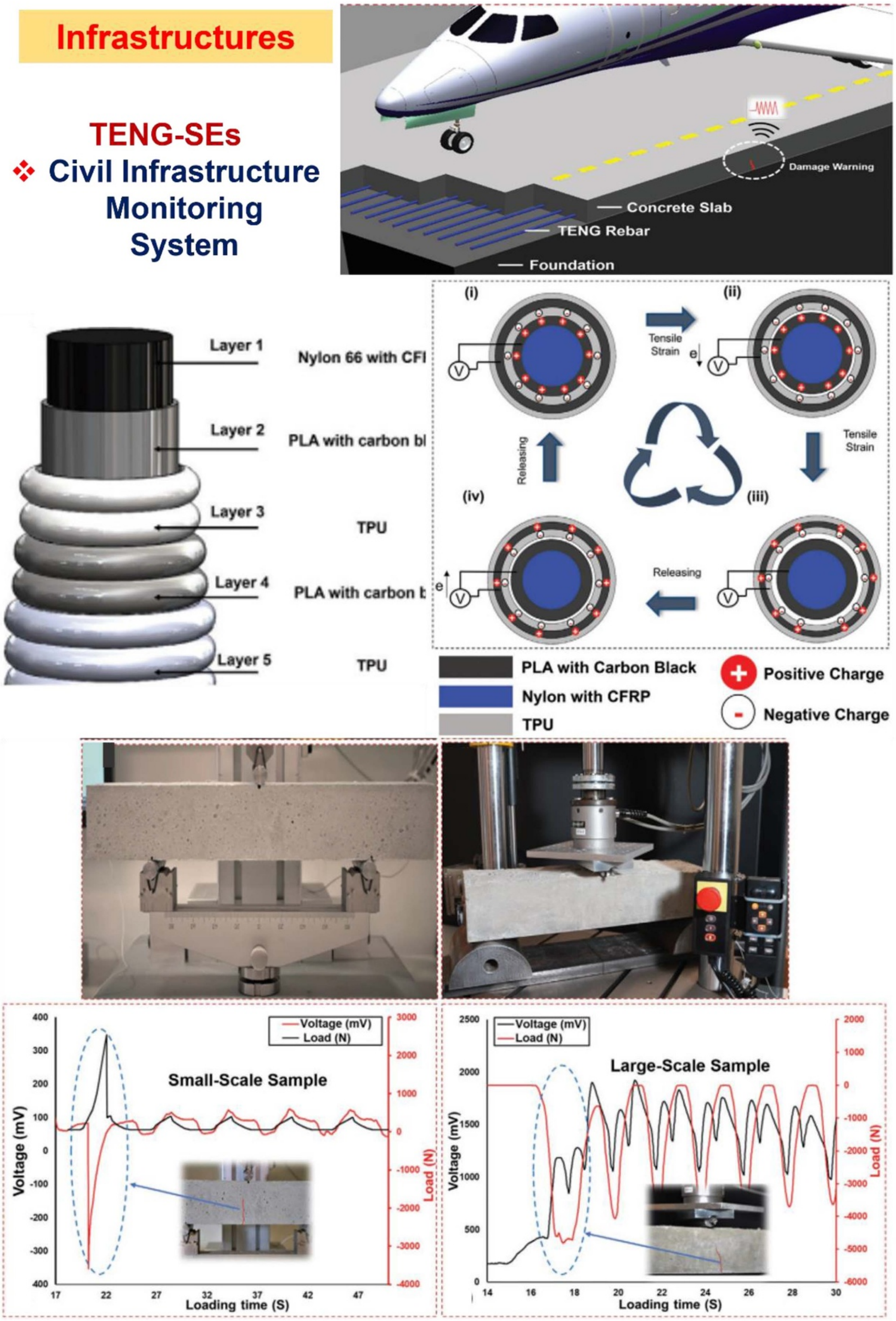

Figure 18. Demonstration of TENGs for civil infrastructure. Design and working mechanism of TENG-SEs for civil infrastructure monitoring system [136]. John Wiley & Sons. © 2021 Wiley-VCH GmbH.

cavity-like structure to cover the device (figure 19). CS-TENG's structure is simple but very effective; it has a 50 000 cycles operating life, is accurate to within 1 mm, and can detect pressure fluctuations of 0.86 V kPa^{-1} at ambient pressure. CS-TENG has the capability to effectively identify and monitor the structural problems associated with bridges and road infrastructure in real-time.

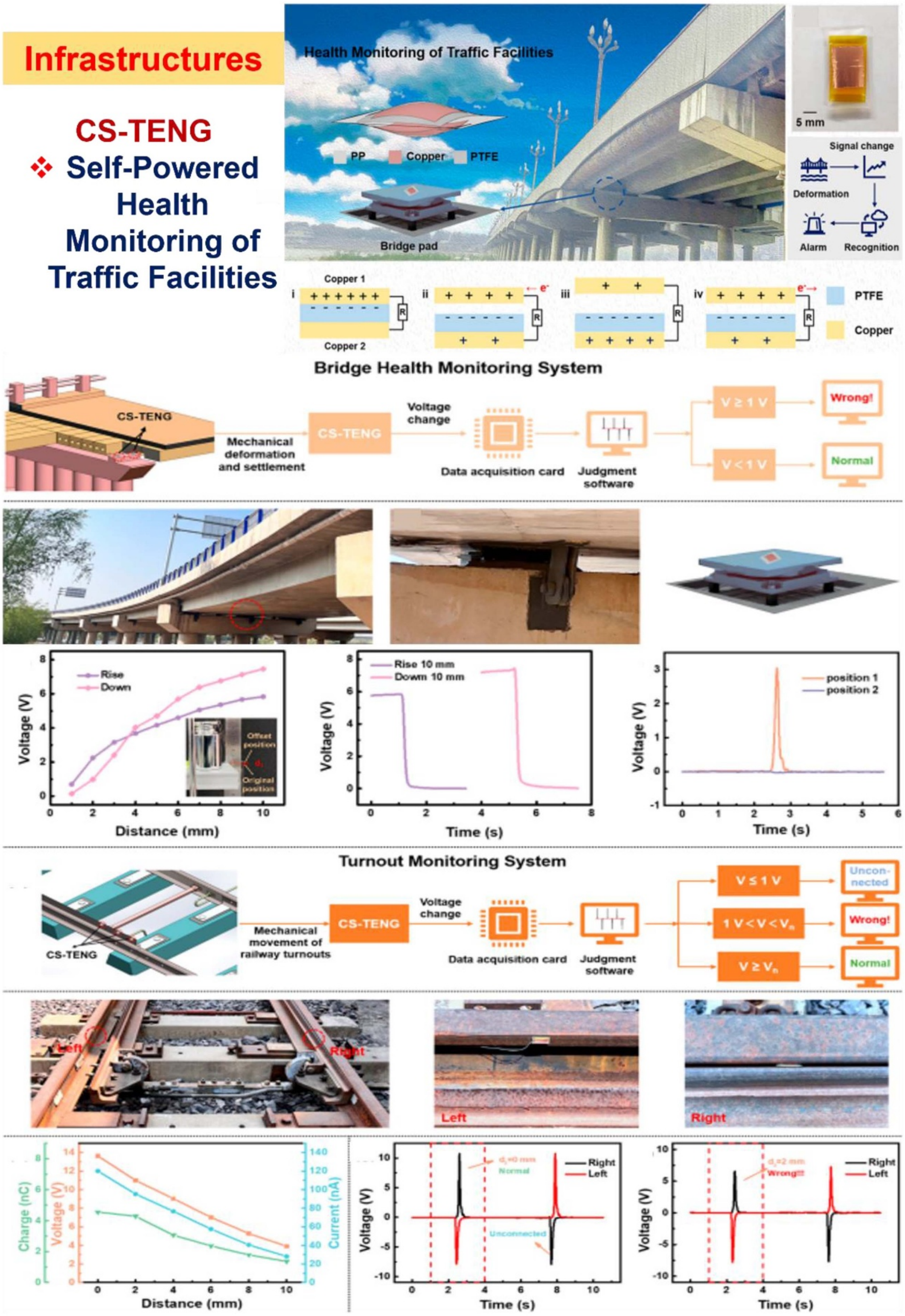

Figure 19. Demonstration of TENGs for traffic facilities. Design and working mechanism of CS-TENG for self-powered health monitoring of traffic facilities. Reprinted with permission from [141]. Copyright (2022) American Chemical Society.

5. Perspective and conclusion

The overview of TENG-based STS has been summarized from various ambient energy harvesting sources such as rotation, wind energy, and rotation of mechanical components, which provides huge benefits to our daily life applications. Besides, the rapid development of the IoT, AI, and 5G or 6G technologies brings us to the era of smart cities. In the past few years, the data collected in our daily lives for serving in safety transportation, weather forecasting, monitoring, and other services in the city has made huge progress. As a result of that, there is a relatively strong connection between STS, AI, IoT, and so on that can be developed toward safer monitoring and more rapid service for smart cities. To do this, the lower power consumption with high-sensitivity sensors and the light weight, eco-friendly material selection, flexibility, etc of TENG, resulting in the low cost and miniaturization of sensors for STS, a part of smart cities, are still a big challenge. Finally, the applications of TENG-based STS need to be realized in industrial production soon if current challenges and future perspectives are considered.

- Current challenges are about the wireless connection to the smart grid, the efficiency of TENG in STS, the durability of TENG due to the harsh environment, its integration to avert the safety effects on transportation vehicles, and the selection of materials for environmental friendliness. These factors are truly crucial to developing a sustainable TENG-based STS. In addition, due to the rapid development of STS powered by TENG, recycling materials and technology should be considered for long-term operation and an eco-friendly solution.
- Future perspectives in our view are about the automatic communication wirelessly among transportations (vehicles, ships, airplanes, UAVs, motorized and non-motorized mobility), infrastructure, and other electronic devices for real-time monitoring, data analysis and sharing, etc. Moreover, the combination with other energy harvesting technologies to establish a hybrid system for sufficient energy is also a need. These mentioned requirements really play an important role for emerging autonomous vehicles such as UAVs, unmanned vehicles and drones, self-driving cars, etc.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Acknowledgments

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ORCID iD

Dukhyun Choi https://orcid.org/0000-0002-4788-0215

References

[1] Oladimeji D, Gupta K, Kose N A, Gundogan K, Ge L and Liang F 2023 Smart transportation: an overview of technologies and applications *Sensors* **23** 3880
[2] Hybel J and Mulalic I 2022 Transportation and quality of life: evidence from Denmark *Transp. Res.* A **157** 107–25
[3] Ahmed S K, Mohammed M G, Abdulqudir S O, Abd El-Kader R G, El-Shall N A, Chandran D, Rehman M E U and Dhama K 2023 Road traffic accidental injuries and deaths: a neglected global health issue *Health Sci. Rep.* **6** e1240
[4] Zhang K and Batterman S 2013 Air pollution and health risks due to vehicle traffic *Sci. Total Environ.* **450–1** 307–16
[5] Alanazi F 2023 Electric vehicles: benefit, challenges, and potential solutions for widespread adoption *Appl. Sci.* **13** 6016
[6] Jain S and Jain S S 2021 Development of intelligent transportation system and its applications for an urban corridor during COVID-19 *J. Inst. Eng. India* B **102** 1191–200
[7] Astarita V, Haghshenas S S, Guido G and Vitale A 2023 Developing new hybrid grey wolf optimization-based artificial neura network for predicting road crash severity *Transp. Eng.* **12** 100164
[8] Guido G, Shaffiee Haghshenas S S, Haghshenas S S, Vitale A and Astarita V 2022 Application of feature selection approaches for prioritizing and evaluating the potential factors for safety management in transportation systems *Computers* **11** 145
[9] Nizectic S, Solic P Gonzalez-De D L and Patrono L 2020 Internet of things (IoT): opportunities, issues, and challenges towards a smart and sustainable future *J. Clean. Prod.* **274** 122877
[10] Iyer L S 2021 AI enabled applications towards intelligent transportation *Transp. Eng.* **5** 100083
[11] Alahi M E, Sukkuea A, Tina F W, Nag A, Kurdthongmee W, Suwannarat K and Mukhopadhyay S C 2023 Intergration of IoT-enabled technologies and artificial intelligence (AI) for smart city scenario: recent advancements and future trends *Sensors* **23** 5206
[12] Zhang Y, Carballo A, Yang H and Takeda K 2023 Perception and sensing for autonomous vehicles under adverse weather conditions: a survey *ISPRS J. Photogramm. Remote Sens.* **196** 146–77
[13] Mohsan S A H, Othman N Q H, Li Y, Alsharif M H and Khan M A 2023 Unmanned aerial vehicles (UAVs): practical aspects, applications, open challenges, security issues, and future trends *Intell. Serv. Robot.* **16** 109–37
[14] Josephinshermila P, Priya S S, Malarvizhi K, Hegde R, Pran S G and Veerasamy B 2023 Accident detection using automotive smart black box-based monitoring system *Meas. Sens.* **27** 100721

[15] Burhan M, Rehman R A, Khan B and Kim B S 2018 IoT elements, layered architectures and security issues: a comprehensive survey *Sensors* **18** 2796
[16] Kim W G, Kim D W, Tcho L W, Kim J K, Kim M S and Choi Y K 2021 Triboelectric nanogenerator: structure, mechanism, and applications *ACS Nano* **15** 258–87
[17] Leon R H, Urquizo J, Silva C E, Leon J S, Wu J, Singh P and Soriano G 2022 Powering nodes of wireless sensor networks with energy harvesters for intelligent buildings: a review *Energy Rep.* **8** 3809–26
[18] Duan Z, Yuan Z, Jiang Y, Zhao Q, Huang Q, Zhang Y, Liu B and Tai H 2022 Power generation humidity sensor based on primary battery structure *Chem. Eng. J.* **446** 136910
[19] He W, Fu X, Zhang D, Zhang Q, Zhuo K, Yuan Z and Ma R 2021 Recent progress of flexible/wearable self-charging power units based on triboelectric nanogenerators *Nano Energy* **84** 105880
[20] Wang N, Liu Y, Ye E, Li Z and Wang D 2023 Innovative technology for self-powered sensors: triboelectric nanogenerators *Adv. Sens. Res.* **2** 2200058
[21] Wang Z L 2013 Triboelectric nanogenerators as new energy technology for self-powered systems and as active mechanical and chemical sensors *ACS Nano* **7** 9533–57
[22] Jin L, Tao J, Bao R, Sun L and Pan C 2017 Self-powered real-time movement monitoring sensor using triboelectric nanogenerator technology *Sci. Rep.* **7** 10521
[23] Shi X, Han K, Pang Y, Mai W and Luo J 2023 Triboelectric nanogenerators as self-powered sensors for biometric authentication *Nanoscale* **15** 9635–51
[24] Zhang C, Zhao J, Zhang Z, Bu T, Liu G and Fu X 2023 Tribotronics: an emerging field by coupling triboelectricity and semiconductors *Int. J. Extrem. Manuf.* **5** 042002
[25] Wu C, Wang A C, Ding W, Guo H and Wang Z L 2018 Triboelectric nanogenerator: a foundation of the energy for the new era *Adv. Energy Mater.* **9** 1802906
[26] Choi D *et al* 2023 Recent advances in triboelectric nanogenerators: from technological progress to commercial applications *ACS Nano* **17** 11087–219
[27] Pang Y, Zhu X, Lee C and Liu S 2022 Triboelectric nanogenerator as next-generation self-powered sensor for cooperative vehicle-infrastructure system *Nano Energy* **97** 107219
[28] Wang Y, Yang Y and Wang Z L 2017 Triboelectric nanogenerators as flexible power sources *npj Flex. Electron.* **1** 10
[29] Xu S, Fu X, Liu G, Tong T, Bu T, Wang Z L and Zhang C 2021 Comparison of applied torque and energy conversion efficiency between rotational triboelectric nanogenerator and electromagnetic generator *iScience* **24** 102318
[30] Shi B *et al* 2023 Progress in recent research on the design and use of triboelectric nanogenerators for harvesting wind energy *Nano Energy* **116** 108789
[31] Luo J and Wang Z L 2020 Recent progress of triboelectric nanogenerators: from fundamental theory to practical applications *EcoMat* **2** e12059
[32] Pongampai S, Pakawanit P, Charoonsuk T and Vittayakorn N 2021 Low-cost fabrication of the highly efficient triboelectric nanogenerator by designing a 3D multi-layer origami structure combined with self-charged pumping module *Nano Energy* **90** 106629
[33] Walden R, Kumar C, Mulvihill D M and Pillai S C 2022 Opportunities and challenges in triboelectric nanogenerator (TENG) based sustainable energy generation technologies: a mini-review *Chem. Eng. J. Adv.* **9** 100237
[34] Thakur V N and Han J I 2023 Triboelectric nanogenerator for smart traffic monitoring and safety *J. Ind. Eng. Chem.* **124** 89–101
[35] Zhang R and Olin H 2020 Material choices for triboelectric nanogenerators: a critical review *Ecomat* **2** e12062
[36] Kim D W, Lee J H, Kim J K and Jeong U 2020 Material aspects of triboelectric energy generation and sensors *NPG Asia Mater.* **12** 6
[37] Zhou Y, Deng W, Xu J and Chen J 2020 Engineering materials at the nanoscale for triboelectric nanogenerators *Cell Rep. Phys. Sci.* **1** 100142
[38] Chu Y, Han R, Meng F, Cao Z, Wang S, Dong K, Yang S, Liu H, Ye X and Tang F 2021 Theoretical study on the output of contact-separation triboelectric nanogenerators with arbitrary charging and grounding conditions *Nano Energy* **89** 106383
[39] Ma Z, Cao X and Wang N 2023 Biophysical sensors based on triboelectric nanogenerators *Biosensor* **13** 423
[40] Wang Z L, Lin L, Chen J, Niu S and Zi Y 2016 Triboelectric nanogenerators *Green Energy and Technology* (Springer International Publishing) pp 91–107
[41] Akram W, Chen Q, Xia G and Fang J 2023 A review of single electrode triboelectric nanogenerators *Nano Energy* **106** 108043
[42] Niu S, Liu Y, Chen X, Wang S, Zhou Y S, Lin L, Xie Y and Wang Z L 2015 Theory of freestanding triboelectric-layer-based nanogenerators *Nano Energy* **12** 760–74
[43] Zou H *et al* 2019 Quantifying the triboelectric series *Nat. Commun.* **10** 1427
[44] Niu S and Wang Z L 2015 Theoretical systems of triboelectric nanogenerators *Nano Energy* **14** 161–92
[45] Dai K, Wang X, Niu S, Yi F, Yin Y, Chen L, Zhang Y and You Z 2017 Simulation and structure optimization of triboelectric nanogenerators considering the effects of parasitic capacitance *Nano Res.* **10** 157–71
[46] Zargari S, Rezania A, Koozehkanani Z D, Veladi H, Sobhi J and Rosendahl L 2022 Effect of the inherent capacitance optimization on the output performance of triboelectric nanogenerators *Nano Energy* **92** 106740
[47] Yoon H-J, Kwak S S, Kim S M and Kim S-W 2020 Aim high energy conversion efficiency in triboelectric nanogenerators *Sci. Technol. Adv. Mater.* **21** 683–8
[48] Pace G, Ansaldo A, Serri M, Lauciello S and Bonaccorso F 2020 Electrode selection rules for enhancing the performance of triboelectric nanogenerators and the role of few-layers graphene *Nano Energy* **76** 104989
[49] Dharmasena R D I G and Wijayantha K G U 2021 Theoretical and experimental investigation into the esymmetric external charging of triboelectric nanogenerators *Nano Energy* **90** 10651
[50] Zhao J and Shi Y 2023 Boosting the durability of triboelectric nanogenerators: a critical review and prospect *Adv. Funct. Mater.* **33** 2213407
[51] Qian J, Kim D S and Lee D W 2018 On-vehicle triboelectric nanogenerator enabled self-powered sensor for tire pressure monitoring *Nano Energy* **49** 126–36
[52] Chen A, Zhang C, Zhu G and Wang Z L 2020 Polymer materials for high-performance triboelectric nanogenerators *Adv. Sci.* **7** 2000186
[53] Hernández E A E, Hernández J H, León A D, Vega C G, Alvarado E D, Huerta F L and May A L H 2024 Green energy harvesting to power electronic devices using portable triboelectric nanogenerator based on waste corn husk and recycle polystyrene *Energy Rep.* **11** 276–86

[54] Yang Y, Zhang H, Liu R, Wen X, Hou T C and Wang Z L 2013 Fullu enclosed triboelectric nanogenerators for applications in water and harsh environments *Adv. Energy Mater.* **3** 1563–8

[55] Dhanumalayan E and Joshi G M 2018 Performance properties and applications of polytetrafluoroethylene (PTFE)-a review *Adv. Compos. Hybrid Mater.* **1** 247–68

[56] Zhang Z and Cai J 2021 High output triboelectric nanogenerator based on PTFE and cotton for energy harvester and human motion sensor *Curr. Appl. Phys.* **22** 1–5

[57] Xic Y, Wang S, Lin L, Jing Q, Lin Z H, Niu S, Wu Z and Wang Z L 2013 Rotary triboelectric nanogenerator based on a hybridized mechanism for harvesting wind energy *ACS Nano* **7** 7119–25

[58] Zhu G, Chen J, Liu Y, Bai P, Zhou Y S, Jing Q, Pan C and Wang Z L 2013 Linear-grating triboelectric generator based on sliding electrification *Nano Lett.* **13** 2282–9

[59] Lin Z, Chen J, Li X, Zhou Z, Meng K, Wei W, Yang J and Wang Z L 2017 Triboelectric nanogenerator enabled body sensor network for self-powered human heart-rate monitoring *ACS Nano* **11** 8830–7

[60] Li G-Z *et al* 2022 Performance enhancement of transparent and flexible triboelectric nanogenerator based on one-dimensionally hybridized copper/polydimethylsiloxane film *Nano Energy* **99** 107423

[61] Choi Y S and Narayan S K 2020 Nylon-11 nanowires for triboelectric energy harvesting *EcoMat* **2** e12063

[62] Babu A, Aazem I, Walden R, Bairagi S, Mulvihill D M and Pillai S C 2023 Electrospun nanofiber based TENGs for wearable electronics and self-powered sensing *Chem. Eng. J.* **452** 139060

[63] Hajra S, Panda S, Song S, Pannigrahi B K, Pakawanit P, Jeong S M and Kim H J 2023 Flexible composite material for self-powered applications via triboelectricity and mechanoluminescence: PDMS/ZnS:Cu composites *Nano Energy* **114** 108668

[64] Mohan V, Mariappan V K, Pazhamalai P, Krishnamoorthy K and Kim S J 2023 Unravelling the impact of carbon allotropes in flexible polydimethylsiloxane film toward self-powered triboelectric humidity sensor *Carbon* **205** 328–35

[65] Liu Y, Fu Q, Mo J, Lu Y, Cai C, Luo B and Nie S 2021 Chemically tailored molecular surface modification of cellulose nanofibrils for manipulating the charge density of triboelectric nanogenerators *Nano Energy* **89** 106369

[66] Wen R, Zhao B, Fan L, Guo J and Zhai J 2023 Controlling the output performance of triboelectric nanogenerator through filling isostructural metal-organic frameworks with varying functional groups *Adv. Mater. Technol.* **8** 2201330

[67] Trinh V L and Chung C K 2023 Renewable energy: working mechanism, tribo-surface structure, energy storage-collection system, and applications *Processes* **11** 2796

[68] Ke K H and Chung C K 2020 High-performance Al/PDMS TENG with novel complex morphology of two-height microneedles array for high-sensitivity force-sensor and self-powered application *Small* **16** 2001209

[69] Zou Y, Xu J, Chen K and Chen J 2021 Advances in nanostructures for high-performance triboelectric nanogenerators *Adv. Mater. Technol.* **6** 2000916

[70] Shang W, Gu G Q, Yang F, Zhao L, Cheng G, Du Z L and Wang Z L 2017 A sliding-mode triboelectric nanogenerator with chemical group grated structure by shadow mask reactive ion etching *ACS Nano* **11** 8796–803

[71] Park S J, Seol M L, Kim D, Jeon S B and Choi Y K 2016 Triboelectric nanogenerator with nanostructured metal surface using water-assisted oxidation *Nano Energy* **21** 258–64

[72] Jo S, Kim I, Jayababu N and Kim D 2020 Performance-enhanced triboelectric nanogenerator based on the double-layered electrode effect *Polymer* **12** 2854

[73] Li Y, Xiao S, Luo Y, Tian S, Tang J, Zhang X and Xiong J 2022 Advances in electrospun nanofibers for triboelectric nanogenerators *Nano Energy* **104** 107884

[74] Ye B U, Kim B J, Ryu J, Lee J Y, Bail J M and Hong K 2015 Electrospun ion gel nanofibers for flexible triboelectric nanogenerator: electrochemical effect on output power *Nanoscale* **7** 16189–94

[75] Kim D, Lee H M and Choi Y K 2017 Large-sized sandpaper coated with solution-processed aluminum for a triboelectric nanogenerator with reliable durability *RSC Adv.* **7** 137–44

[76] Zhang X W, Li G Z, Wang G G, Tian J L, Liu Y L, Ye D M, Liu Z, Zhang H Y and Han J C 2018 High-performance triboelectric nanogenerator with double-surface shape-complementary microstructures prepared by using simple sandpaper templates *ACS Sustain. Chem. Eng.* **6** 2283–91

[77] Liu H, Feng Y, Shao J, Chen Y, Wang Z L, Li H, Chen X and Bian Z 2020 Self-cleaning triboelectric nanogenerator based on TiO_2 photocatalysis *Nano Energy* **70** 104499

[78] Kim Y, Wu X and Oh J H 2020 Fabrication of triboelectric nanogenerators based on electrospun polyimide nanofibers membrane *Sci. Rep.* **10** 2742

[79] Qian Z, Li R, Guo J, Wang Z, Li X, Li C, Zhao N and Xu J 2019 Triboelectric nanogenerators made of polybenzazole aerogels as fire-resistant negative tribo-materials *Nano Energy* **64** 103900

[80] Zhou Q, Takita R and Ikuno T 2023 Improving the performance of triboelectric nanogenerator by using an asymmetric TiO_2/PDMS composite layer *Nanomaterials* **13** 832

[81] Wang M, Zhang N, Tang Y, Zhang H, Ning C, Tian L, Li W, Zhang J, Mao Y and Liang E 2017 Single-electrode triboelectric nanogenerators based on sponge-like porous PTFE thin films for mechanical energy harvesting and self-powered electronics *J. Mater. Chem.* A **5** 12252–7

[82] Aazem I, Mathew D T, Radhakrishnan S, Vijoy K V, John H, Mulvihill D M and Pillai S C 2022 Electrode materials for stretchable triboelectric nanogenerator in wearable electronics *RSC Adv.* **12** 10545–72

[83] Zhang W, Liu Q, Chao S, Liu R, Cui X, Sun Y, Ouyang H and Li Z 2021 Ultrathin stretchable triboelectric nanogenerators improved by postcharging electrode material *ACS Appl. Mater. Interfaces* **13** 42966–76

[84] Kim H S *et al* 2019 Microwave-welded single-walled carbon nanotubes as suitable electrode for triboelectric energy harvesting from biomaterials and bioproducts *Nano Energy* **56** 338–46

[85] Mariappan V K, Krishnamoorthy K, Pazhamalai P, Manoharan S and Kim S J 2022 Decoupling contact and rotary triboelectrification vs materials property: toward understanding the origin of direct-current generation in TENG *ACS Appl. Mater. Interfaces* **14** 34593–602

[86] Fu S, He W, Wu H, Shan C, Du Y, Li G, Wang P, Guo H, Chen J and Hu C 2022 High output performance and ultra-durable DC output for triboelectric nanogenerator inspired by primary cell *Nano-Micro. Lett.* **14** 155

[87] Long L, Li W, Wang Z, He W, Li G, Tang Q, Guo H, Pu X, Liu Y and Hu C 2021 High performance floating self-excited sliding triboelectric nanogenerator for micro mechanical energy harvesting *Nat. Commun.* **12** 4689

[88] Jiang T, Yao Y, Xu L, Zhang L, Xiao T and Wang Z L 2017 Spring-assisted triboelectric nanogenerator for efficiently harvesting water wave energy *Nano Energy* **31** 560–7

[89] Li S, Wang S, Zi Y, Wen Z, Lin L, Zhang G and Wang Z L 2015 Largely improving the robustness and lifetime of triboelectric nanogenerators through automatic transition between contact and noncontact working states *ACS Nano* **9** 7479–87

[90] Xu W, Wong M C and Hao J 2019 Strategies and progress on improving robustness and reliability of triboelectric nanogenerators *Nano Energy* **55** 203–15

[91] Qin Q, Cao X and Wang N 2023 Ball-mill-inspired durable triboelectric nanogenerator for wind energy collecting and speed monitoring *Nanomaterials* **13** 939

[92] Lin L, Xie Y, Niu S, Wang S, Yang P K and Wang Z L 2015 Robust triboelectric nanogenerator based on rolling electrification and electrostatic induction at an instantaneous energy conversion efficiency of ∼55% *ACS Nano* **9** 922–30

[93] Sun M, Lu Q, Wang Z L and Huang B 2021 Understanding contact electrification at liquid-solid interfaces from surface electronic structure *Nat. Commun.* **12** 1752

[94] Sun B, Xu D, Wang Z, Zhan Y and Zhang K 2022 Interfacial structure design for triboelectric nanogenerators *Battery Energy* **1** 20220001

[95] Zhang X *et al* 2023 Highly durable bidirectional rotary triboelectric nanogenerator with a self-lubricating texture and self-adapting contact synergy for wearable applications *Small* **19** 2300890

[96] Wu J, Xi Y and Shi Y 2020 Toward wear-resistive, highly durable and high performance triboelectric nanogenerator through interface liquid lubrication *Nano Energy* **72** 104659

[97] Qu X, Liu Y, Liu Z and Li Z 2021 Assistive devices for the people with disabilities enabled by triboelectric nanogenerators *J. Phys. Mater.* **4** 034015

[98] Riener R 2016 The Cybathlon promotes the development of assistive technology for people with physical disabilities *J. Neuroeng. Rehabil.* **13** 1–4

[99] Velho R 2019 Transport accessibility for wheelchair users: a qualitative analysis of inclusion and health *Int. J. Transp. Sci. Technol.* **8** 103–15

[100] Fogelberg D, Atkins M, Blanche E I, Carlson M and Clark F 2009 Decisions and delemmas in everyday life: daily use of wheelchairs by individuals with spinal cord injury and the impact on pressure ulcer risk *Top. Spinal Cord Inj. Rehabil.* **15** 16–32

[101] Zhu X, Zhang M, Wang X, Jia C and Zhang Y 2022 A portable and low-cost triboelectric nanogenerator for wheelchair table tennis monitoring *Electronics* **11** 4189

[102] Graham S A, Patnam H, Manchi P, Paranjape M V, Kurakula A and Yu J S 2022 Biocompatible electrospun fibers-based triboelectric nanogenerators for energy harvesting and healthcare monitoring *Nano Energy* **100** 107455

[103] Yang J, Chen J, Yang Y, Zhang H, Yang W, Bai P, Su Y and Wang Z L 2014 Broadband vibrational energy harvesting based on a triboelectric nanogenerator *Adv. Energy Mater.* **4** 1301322

[104] Chen J, Yang J, Guo H, Li Z, Zheng L, Su Y, Wen Z, Fan X and Wang Z L 2015 Automatic mode transition enabled robust triboelectric nanogenerators *ACS Nano* **9** 12334–43

[105] Zhou H, Liu G, Gao Y, Wang Z, Qin Y, Wang Y, Lin Y, Xie Y, Chen Y and Zhang C 2021 Dual mode rotary triboelectric nanogenerator for collecting kinetic energy from bicycle brake *Adv. Energy Sustain. Res.* **2** 2000113

[106] Paranjape M V, Graham S A, Patnam H, Manchi P and Yu J S 2021 3D printed bidirectional rotatory hybrid nanogenerator for mechanical energy harvesting *Nano Energy* **88** 106250

[107] Son J *et al* 2021 Highly reliable triboelectric bicycle tire as self-powered bicycle safety light and pressure sensor *Nano Energy* **93** 106797

[108] Wen J *et al* 2018 Harsh-environmental-resistant triboelectric nanogenerator and its application in autodrive safety warning *Adv. Energy Mater.* **8** 1801898

[109] Shen Q, Xie X, Peng M, Sun N, Shao H, Zheng H, Wen Z and Sun X 2018 Self-powered vehicle emissions testing system based on coupling of triboelectric and chemoresistive effects *Adv. Funct. Mater.* **28** 1703420

[110] Xu M, Wang P, Wang Y-C, Zhang S L, Wang A C, Zhang C, Wang Z, Pan X and Wang Z L 2018 A soft and robust spring based triboelectric nanogenerator for harvesting arbitrary directional vibration energy and self-powered vibration sensing *Adv. Energy Mater.* **8** 1702432

[111] Li S, Zhao Z, Liu D, An J, Gao Y, Zhou L, Li Y, Cui S, Wang J and Wang Z L 2022 A self-powered dual-type signal vector sensor for smart robotics and automatic vehicles *Adv. Mater.* **34** 2110363

[112] He J, Cao S and Zhang H 2019 Cylinder-based hybrid rotary nanogenerator for harvesting rotational energy from axles and self-powered tire pressure monitoring *Energy Sci. Eng.* **8** 291–9

[113] Yang J, Sun Y, Zhang J, Chen B and Wang Z L 2021 3D-printed bearing structural triboelectric nanogenerator for intelligent vehicle monitoring *Cell Rep. Phys. Sci.* **2** 100666

[114] Le C-D, Nguyen T-H, Vu D-L, Vo C-P and Ahn K K 2022 A rotational switched-mode water-based triboelectric nanogenerator for mechanical energy harvesting and vehicle monitoring *Mater. Today Sustain.* **19** 100158

[115] Zhu D, Guo X, Li H, Yuan Z, Zhang X and Cheng T 2023 Self-powered flow sensing for automobile based on triboelectric nanogenerator with magnetic field modulation mechanism *Nano Energy* **108** 108233

[116] Luo F, Chen B, Ran X, Ouyang W and Shang L 2023 PEO-PDMS-based triboelectric nanogenerators as self-powered sensors for driver status monitoring *Chem. Eng. J.* **451** 138961

[117] Wu W, Cao X, Zou J, Ma Y, Wu X, Sun C, Li M, Wang N, Wang Z and Zhang L 2019 Triboelectric nanogenerator boosts smart green tires *Adv. Funct. Mater.* **29** 1806331

[118] Zhang C, Liu Y, Zhang B, Yang O, Yuan W, He L, Wei X, Wang J and Wang Z L 2021 Harvesting wind energy by a triboelectric nanogenerator for an intelligent high-speed train system *ACS Energy Lett.* **6** 1490–9

[119] Jin L, Zhang S L, Xu S, Guo H, Yang W and Wang Z L 2021 Free-fixed rotational triboelectric nanogenerator for self-powered real-time wheel monitoring *Adv. Mater. Technol.* **6** 2000918

[120] Jin L *et al* 2017 Self-powered wireless smart sensor based on maglev porous nanogenerator for train monitoring system *Nano Energy* **38** 185–92

[121] Lin Z, Sun C, Liu W, Fan E, Zhang G, Tan X, Shen Z, Qiu J and Yang J 2021 A self-powered and high-frequency vibration sensor with layer-powder-layer structure for structural health monitoring *Nano Energy* **90** 106366

[122] Li X, Tao J, Wang X, Zhu J, Pan C and Wang Z L 2018 Networks of high perormance triboelectric nanogeneratos based on liquid-solid interface contact electrification for harvesting low-frequency blue energy *Adv. Energy Mater.* **8** 1800705

[123] Liang X, Liu S, Lin S, Yang H, Jiang T and Wang Z L 2023 Liquid-solid triboelectric nanogenerator arrays based on dynamic electric-double-layer for harvesting water wave energy *Adv. Energy Mater.* **13** 2300571

[124] Ren Z, Liang X, Liu D, Li X, Ping J, Wang Z and Wang Z L 2021 Water-wave driven route avoidance warning system for wireless ocean navigation *Adv. Energy Mater.* **11** 2101116

[125] Demircioglu O, Cicek M O, Doganay D, Gazaloglu G, Baykal C, Cinar S and Unalan H E 2023 Triboelectric nanogenerators for blue energy harvesting in simulated wave conditions *Nano Energy* **107** 108157
[126] Liu L, Shi Q and Lee C 2020 A novel hybridized blue energy harvesting aiming at all-weather IoT applications *Nano Energy* **76** 105052
[127] Jiang T, Pang H, An J, Lu P, Feng Y, Liang X, Zhong W and Wang Z L 2020 Robust swing-structured triboelectric nanogenerator for efficient blue energy harvesting *Adv. Energy Mater.* **10** 2000064
[128] Pang H, Feng Y, An J, Chen P, Han J, Jiang T and Wang Z L 2021 Segmented swing-structured fur-based triboelectric nanogenerator for harvesting blue energy toward marine environmental applications *Adv. Funct. Mater.* **31** 2106398
[129] Ahn J *et al* 2022 All-recyclable triboelectric nanogenerator for sustainable ocean monitoring systems *Adv. Energy Mater.* **12** 2201341
[130] Chen G, Xu L, Zhang P, Chen B, Wang G, Ji J, Pu X and Wang Z L 2020 Seawater degradable triboelectric nanogenerators for blue energy *Adv. Mater. Technol.* **5** 2000455
[131] Wang K, Zhang Y, Luo X, Zhu L and Wang Z L 2022 Active deformable and flexible triboelectric nanogenerator based on super-light clay *ACS Appl. Electron. Matter* **4** 4764–71
[132] Tao K *et al* 2021 Hierarchical honeycomb-structured electret/triboelectric nanogenerator for biomechanical and morphing wing energy harvesting *Nano-Micro Lett.* **13** 123
[133] Xie X *et al* 2021 Self-powered gyroscope angle sensor based on resistive matching effect of triboelectric nanogenerator *Adv. Mater. Technol.* **6** 2100797
[134] Zhang B, Chen J, Jin L, Deng W, Zhang L, Zhang H, Zhu M, Yang W and Wang Z L 2016 Rotating-disk-based hybridized electromagnetic-triboelectric nanogenerator for sustainably powering wireless traffic volume sensors *ACS Nano* **10** 6241–7
[135] Su E, Li H, Zhang J, Xu Z, Chen B, Cao L N Y and Wang Z L 2023 Rationally designed anti-glare panel arrays as highway wind energy harvester *Adv. Funct. Mater.* **23** 2214934
[136] Zhang Q, Barri K, Kari S R, Wang Z L and Alavi A H 2021 Multifunctional triboelectric nanogenerator-enabled structural elements for next generation civil infrastructure monitoring systems *Adv. Funct. Mater.* **31** 2105825
[137] González L A, Pans M, Devís J D and González L-M 2023 Cycling in urban environments: quantitative text analysis *J. Transp. Health* **32** 101651
[138] Kraus S and Koch N 2021 Provisional COVID-19 infrastructure induces large, rapid increases in cycling *Proc. Natl Acad. Sci.* **118** e2024399118
[139] Zhang H, Su X, Quan L, Jiang J, Dong B and Wei G 2021 Sponge-supported triboelectric nanogenerator for energy harvesting from rail vibration *J. Energy Eng.* **147** 04021006
[140] Yao Y, Zhou Z, Wang K, Liu Y, Lu X and Cheng T 2022 Arc-shaped flutter-driven wind speed sensor based on triboelectric nanogenerator for unmmaned aerial vehicle *Nano Energy* **104** 107871
[141] Xu J, Wei X, Li R, Kong S, Wu Z and Wang Z L 2022 A capsule-shaped triboelectric nanogenerator for self-powered health monitoring of traffic facilities *ACS Mater. Lett.* **4** 1630–7
[142] Zhang B *et al* 2022 Sustainable tunnel lighting system based on mechanical-regulated and soft-contact hybridized nanogenerator *Nano Energy* **104** 107868
[143] Huan K, Zhou Y, Zhang Z, Zhang H, Lü C, Luo J and Shen L 2023 A real-time quantitative acceleration monitoring method based on triboelectric nanogenerator for bridge cable vibration *Nano Energy* **118** 108960
[144] Kim Y, Kim E-J, Jang S and Kim D-K 2021 A comparative analysis of the users of private cars and public transportation for intermodal options under mobility-as-a-service in Seoul *Travel Behav. Soc.* **24** 68–80
[145] Ignatious H A, Sayed H-E and Khan M 2022 An overview of sensors in autonomous vehicles *Proc. Comput. Sci.* **198** 736–41
[146] Mohankumar P, Ajayan J, Yasodharan R, Devendran P and Sambasivam R 2019 A review of micromachined sensors for automotive applications *Measurement* **140** 305–22
[147] Biswas A and Wang H-C 2023 Autonomous vehicles enabled by the integration of IoT, edge intelligence, 5G, and blockchain *Sensors* **23** 1963
[148] Lin F, Wang K, Zhao Y and Wang S 2020 Intergrated avoid collision control of autonomous vehicle based on trajectory re-planning and V2V information interaction *Sensors* **20** 1079
[149] Kheder M Q and Mohammed A A 2023 Real-time traffic monitoring system using IoT-aided robotics and deep learning techniques *Kuwait J. Sci.* **51** 100153
[150] Nastjuk I, Herrenkind B, Marrone M, Brendel A B and Kolbe L M 2020 What drives the acceptance of autonomous driving? An investigation of acceptance factors from an end-user's perspective *Technol. Forecast. Soc. Change* **161** 120319
[151] Mitali J, Dhinakaran S and Mohamad A A 2022 Energy storage systems: a review *Energy Storage Sav.* **1** 166–216
[152] Wang S, Tonge E, Sekanyo I, Portmann E and Azzouz S 2023 On the state-of-the-art of solar, wind, and other green energy resources and their respective storage systems *Eng* **4** 857–83
[153] Zhang T, Wu X, Pan Y, Luo D, Xu Y, Zhang Z, Yuan Y and Yan J 2022 Vibration energy harvesting system based on track energy-recycling technology for heavy-duty freight railroads *Appl. Energy* **323** 119673
[154] Qi L, Pan H, Pan Y, Luo D, Yan J and Zhang Z 2022 A review of vibration energy harvesting in rail transportation field *iScience* **25** 103849
[155] He L, Liu L, Zhou J, Yu G, Sun B and Cheng G 2022 Design and analysis of a double-acting nonlinear wideband piezoelectric energy harvester under plucking and collision *Energy* **239** 122370
[156] Zhang X, Zhang Z, Pan H, Salman W, Yuan Y and Liu Y 2016 A portable high-efficiency electromagnetic energy harvesting system using supercapacitors for renewable energy applications in railroads *Energy Convers. Manage.* **118** 287–94
[157] Wang H, Chen Z and Huang J 2021 Improvement of vibration frequency and energy efficiency in the uniaxial electrohydraulic shaking tables for sinusoidal vibration waveform *Energy* **218** 119477
[158] Haroun A, Tarek M, Mosleh M and Ismail F 2022 Recent progress on triboelectric nanogenerators for vibration energy harvesting and vibration sensing *Nanomaterials* **12** 2960
[159] Ahmed A, Hassan I, Helal A, Sencadas V, Radhi A, Jeong C K and Kady M F 2020 Triboelectric nanogenerator versus piezoelectric generator at low frequency ($<$4 Hz): a quantitative comparison *iScience* **23** 101286
[160] Zhao X, Wei G, Li X, Qin Y, Xu D, Tang W, Yin H, Wei X and Jia L 2017 Self-powered triboelectric nano vibration accelerometer based wireless sensor system for railway state health monitoring *Nano Energy* **34** 549–55
[161] Li Y, Ma X, Tang T, Zha F, Chen Z, Liu H and Sun L 2022 High-efficient built-in wave energy harvesting technology: from laboratory to open ocean test *Appl. Energy* **322** 119498
[162] Esmaeilion F 2020 Hybrid renewable energy systems for desalination *Appl. Water Sci.* **10** 84

[163] Zhao T, Xu M, Xiao X, Ma Y, Li Z and Wang Z L 2021 Recent progress in blue energy harvesting for powering distributed sensors in ocean *Nano Energy* **88** 106199
[164] Mohsan S A H, Khan M A, Noor F, Ullah I and Alsharif M H 2022 Towards the unmanned aerial vehicles (UAVs): a comprehensive review *Drones* **6** 147
[165] Laghari A A, Jumani A K, Laghari R A and Nawaz H 2023 Unmanned aerial vehicles: a review *Cogn. Robot.* **3** 8–22
[166] Butila E V and Boboc R G 2022 Urban traffic monitoring and analysis using unmanned aerial vehicles (UAVs): a systematic literature review *Remote Sens.* **14** 620
[167] Khan N A, Jhanjhi N Z, Brohi S N, Usmani R S A and Nayyar A 2020 Smart traffic monitoring systems using unmanned aerial vehicles (UAVs) *Comput. Commun.* **157** 434–43
[168] Masuduzzaman M, Islam A, Sadia K and Shin S Y 2022 UAV-based MEC-assisted automated traffic management scheme using blockchain *Future Gener. Comput. Syst.* **134** 256–70
[169] Outay F, Mengash H A and Adnan M 2020 Applications of unmanned aerial vehicle (UAV) in road safety, traffic and highway infrastructure management: recent advances and challenges *Transp. Res.* A **141** 116–29
[170] Kumari A and Sharma A K 2017 Infrastructure financing and development: a bibliometric review *Int. J. Crit. Infrastruct. Prot.* **16** 49–65
[171] Zuluaga S, Karney B W and Saxe S 2021 The concept of value in sustainable infrastructure systems: a literature review *Environ. Res.: Infrastruct. Sustain.* **1** 022001
[172] Große C 2023 A review of the foundation of systems, infrastructure and governance *Saf. Sci.* **160** 106060