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Energy harvesting solutions for railway transportation: A comprehensive review

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ABSTRACT

Railways, as one of the most important forms of transportation, have been developed rapidly throughout the world. Meanwhile, the energy consumption and carbon emissions of railway transportation are noticeable in face of global climate changes. The increasing speed of railway brings higher requirements for safety and reliability, resulting in the continuous growth of the demand for the monitoring system. In scenarios without economic access to electrical power supplies, seeking energy harvesting for self-powered monitoring or other track-side electrical system is an effective way to reduce operation and maintenance costs. Fortunately, the last decade has witnessed significant advances in energy harvesting technology, which provides new opportunities for a green and intelligent railway. The vehicle-track system is surrounded by multiple energy sources, including vibration, wind, solar, thermal, magnetic field and acoustic energy, all of which can be used for energy harvesting. Given the increasing interest in energy harvesting solutions in railway transportation, herein we present a comprehensive review of the research progress and representative works. The design and realization of energy harvesters for railway applications are surveyed in detail. On this basis, different types of harvesters are summarized and compared, and their application prospects are discussed. Moreover, the technical challenges of vibration energy harvesters including performance enhancements, coupling dynamics with the railway system and interface circuits are stressed. Finally, some suggestions are given to better fill in research gaps in future directions.

1. Introduction

Rail transportation is widely favored for its safety, economy and reliability. With the superiorities in people and goods transportation, it plays a significant role in alleviating urban traffic congestion and promoting national economic development. In the last decade, the demand for railways in many countries has increased remarkably, promoting the rapid expansion of rail transportation network.

The transportation sector has become the second largest energy consumption sector in the world [1], and road transportation accounts for about three-quarters of carbon emissions [2]. Due to the low proportion of fossil fuels in power sources, railway transportation is much more environmentally friendly than road transportation [3]. However, considering that the railway will develop rapidly for a long time in the future, rail transportation characterized by green and low carbon is still of great significance to alleviate the global greenhouse effect.

Moreover, smart railway transportation increases the demand for monitoring and trackside electronics. Smart maintenance or smart operation are based on abundant monitoring data to make decisions [4,5]. However, some railway lines and railcars do not have an economic power supply, especially in remote areas; and some sensors mounted on the railcars are not convenient to supply power by cables. More and more monitoring demands and distributed sensor placements are the challenges for the power supply.

In the past few years, energy harvesting technology has achieved great progress [6], and is widely applied in the field of ocean [7], aerospace [8], road traffic [9,10], wearables [11,12], etc. Many researchers have developed energy harvesting technologies in the railway

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industry, greatly promoting the utilization of ambient renewable/sustainable energy sources and green development. Renewable energy sources, in the form of wind energy, solar energy, vibration energy, thermal energy, magnetic field energy and acoustic energy, widely exist on railway vehicles, tracks and their vicinity, as shown in Fig. 1, which provide flexible and diversified choices for railway energy harvesters design, as well as a broad application prospect.

Conventional solar and wind energy harvesters have the advantage of high power output [13,14], and the clean energy around the railcar or rail is transformed into electric energy to supply to the traction network or the onboard or trackside electrical devices [15,16], which increases the proportion of renewable energy in power sources and brings economic and environmental benefits from a macro perspective [17]. However, excessive dependence on weather and environment greatly increases the uncertainty of solar and wind energy harvesting [18].

By contrast, other energy sources such as vibration energy, thermal energy, magnetic field energy, and acoustic energy can mostly be regarded as the internal ambient energy of vehicle-track system, which are caused by train movement or onboard devices work, and always exist as long as the train is running. Hence, these energy sources are more suitable for real-time monitoring sensors. Given low manufacturing cost and high output power, capturing vibration energy is the major means to realize self-powered sensor networks. Among a variety of energy harvesting mechanisms, the most widely applied ones are usually based on piezoelectric [19–21] and electromagnetic effects [22–24]. Nelson et al. [25,26] first tried to use piezoelectric patches and voice-coil harvesters (a form of electromagnetic energy harvester) to scavenge rail vibration energy. The obtained output power reaches the milliwatt level in theory, but it is still deficient for practical applications. To address the energy-insufficiency issue of general configuration, the performance-enhanced design of harvesters taking the vibration characteristics of the installation position into consideration has drawn much attention from many researchers [27,28]. For piezoelectric and electromagnetic transducers, the early scheme is based on the resonance principle to tune the harvester natural frequency. However, when the working environment deviates from the resonance frequency, the performance of the linear resonant harvester will decline rapidly, which does not match well with the broadband random vibration of railway track and railcar [29,30]. With the aim to broaden harvester bandwidth, energy harvesting systems with multi-degree-of-freedom (multi-DOF) [31,32] or multi-stable nonlinear structures [33,34] are proposed, which greatly improve the performance of the devices. Overall, vibration has been considered as a promising energy source in railway self-powered monitoring [35]. In addition, the harvesters based on other energy sources have successful cases for self-powered monitoring [36,37]. Apart from structure design, the performance of harvesters based on piezoelectric, thermoelectric, triboelectric and photovoltaic effects is also dependent on the material itself [38–41].

With the rapid growth of energy harvesting research, a few of technical reviews on piezoelectric [42–44], electromagnetic [45], triboelectric [46], thermoelectric [47] and photovoltaic technology [41] have been presented. However, the energy harvesters for railway applications have not been systematically reviewed and summarized. In the light of the huge demand for energy harvesting technology in railway field, herein we present a comprehensive review about railway-oriented energy harvesters to summarize the current research trend and provide guidance for future directions. Due to the flexible installation and the diversity of structural design, vibration energy harvesting is a popular research area. Therefore, the design and implementation of vibration energy harvesters (VEHs) will be introduced with emphasis. Apart from structure design, some derivative issues including performance-enhanced solutions, coupled dynamics with railway system, and interface electrical circuits are discussed, which remain to be solved before the practical applications.

This paper is organized as follows. Energy harvesting mechanisms are introduced in Section 2. The VEHs in railway field including design, optimization, and performance evaluation are elaborated in Section 3. Thereafter, Section 4 presents the design and realization of harvesters utilizing wind, solar, thermal, magnetic field and acoustic energy as power sources. Section 5 summarizes the advantages and disadvantages of different energy harvesters. Section 6 explores the application prospects of energy harvesting technology in the railway industry. In Section 7, the technical challenges of VEHs are discussed. In view of the current research gaps about railway-oriented energy harvesters, some corresponding suggestions are given for future works. This paper is concluded in Section 8.

2. Energy harvesting mechanisms

2.1. Piezoelectric effect

Piezoelectric energy harvesters are designed based on the property of piezoelectric materials, which are polarized and generate electrical energy when they experience mechanical stress or strain [48,49]. This

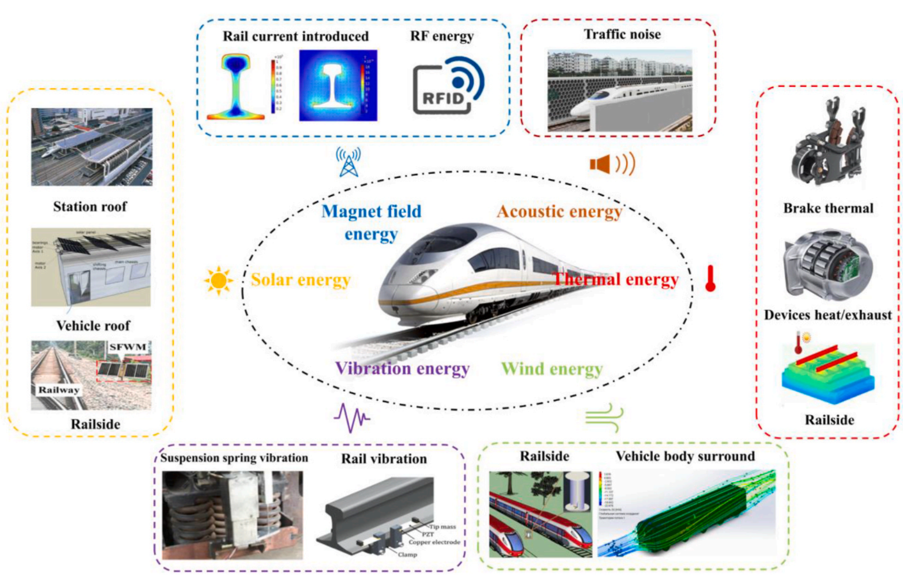

Fig. 1. Potential energy sources in the railway vehicle-track system.

phenomenon is called direct piezoelectric effect. Conversely, the converse piezoelectric effect describes the phenomenon where piezoelectric materials placed in an electric field will produce mechanical strain or stress. The piezoelectric effect can be governed by the following matrix equation [50,51]:

$$\begin{bmatrix} \delta \\ D \end{bmatrix} = \begin{bmatrix} s^E & d^t \\ d & \varepsilon^T \end{bmatrix} \begin{bmatrix} \sigma \\ E \end{bmatrix} \quad (1)$$

where δ and σ are the strain and stress vectors, $\boldsymbol{D}$ and $\boldsymbol{E}$ are the vectors of electric displacement and corresponding electric field, s^E refers to the elastic coefficient matrix without electric field, $\boldsymbol{d}$ is the piezoelectric coefficient matrix, and t represents the transpose, and ε^T is the dielectric constant without stress.

Fig. 2(a) illustrates two popular working modes of piezoelectric harvesting systems. When the piezoelectric transducer is stretched or compressed, and polarized along the 3-axis, it is in the 33 mode. In the 31 mode, the material is strained along the 1-axis and the polarized direction is the 3-axis. The former has a higher electro-mechanical coupling coefficient [52] and it can obtain a larger voltage output by increasing the layers of the piezoelectric material with a stack configuration [53]. The latter has a greater advantage in energy conversion for very low pressure sources [54]. Piezoelectric effect is not only a conventional mechanism for vibration energy harvesting, but also can scavenge wind energy based on the principle of flow-induced vibration.

2.2. Electromagnetic effect

The principle of electromagnetic harvesters is based on the electromagnetic effect introduced by the relative movement between the coil and magnet, as shown in Fig. 2(b). Under the action of external excitation, relative motion between the magnet and the coil makes the magnetic flux of the coil variable, and a voltage is generated on the coil based on Faraday's law [55]. The introduced voltage, V_{em}, is expressed by:

$$V_{em} = -N \cdot \frac{d\Phi}{dt}$$

where N is the number of coil turns, Φ is the magnetic flux, and t is the time [56].

According to the relative movement form of the magnet and the coil, electromagnetic harvesters can be classified into linear type and rotary type. For triggering resonant oscillation, linear electromagnetic harvesters are usually configured with spring structures in the form of spiral cantilever, freestanding or fixed beam [57–59]. Rotary electromagnetic generators are a conventional form of rotary structures. In addition, the rotor magnet or coil in the rotary structure can be fixed on the rotary wheel, eccentric structure or pendulum structure [60–62]. Because of its superior practicality, electromagnetic effect is widely exploited in vibration and wind harvesting. Magnetic field energy harvesting also relies on electromagnetic induction, but the variable magnetic field is generated by an alternating current instead of the relative motion of the coil and the magnet.

2.3. Triboelectric effect

Triboelectrification was regarded as a negative phenomenon to be avoided in many technologies for a long time. Since Wang Zhonglin's group first reported the triboelectric nanogenerator (TENG) in 2012, the triboelectric effect has been widely studied, and the research on relevant materials, mechanisms, structures and circuits is developing rapidly [63]. The Triboelectric effect is contact-induced electrification where the in-plane sliding or contact-separation of two materials with opposite friction polarity. Assuming that the electric potential of the lower electrode is 0 in Fig. 2(c), the generated potential of the upper electrode, V_{te}, can be expressed as

$$V_{te} = -\frac{\sigma d}{\varepsilon} \quad (3)$$

where σ is the charge density, d indicates the distance between the upper and lower layers, and ε represents the vacuum permittivity.

The common operating modes of TENG are the vertical contact-separation mode and the lateral-sliding mode. Based on the two modes, the single-electrode mode and the freestanding triboelectric-layer mode are derived. The diversity of working modes promotes a more flexible structure design and application of TENGs. In addition, TENGs are demonstrated to achieve a power density approaching 500

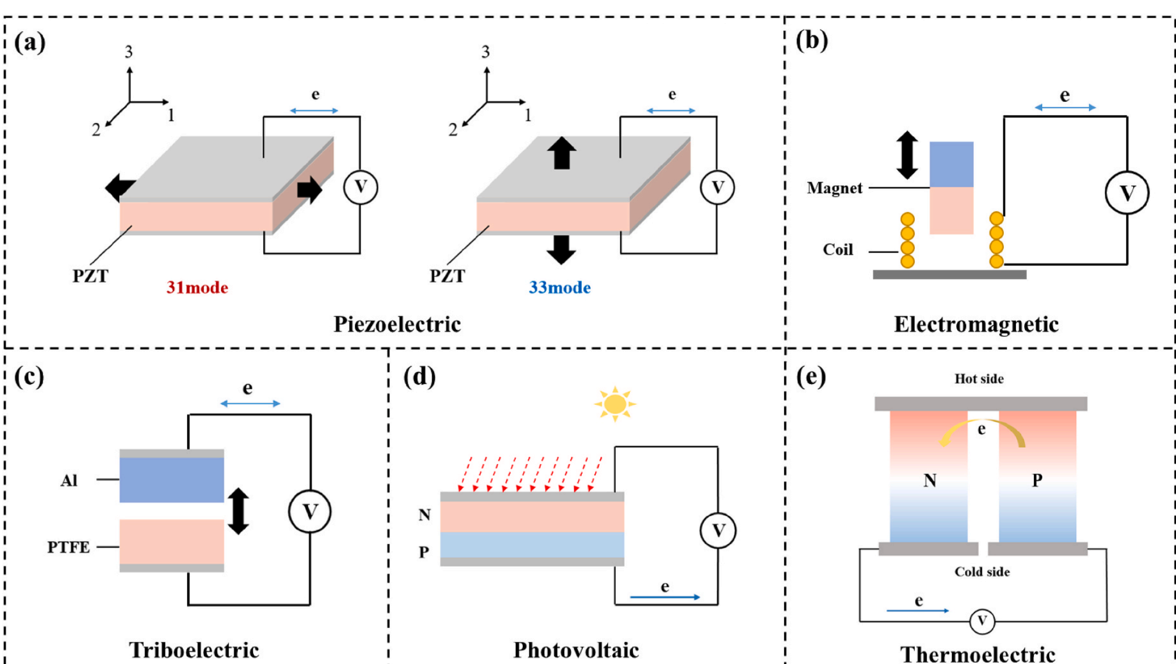

Fig. 2. Energy harvesting mechanisms: (a) piezoelectric, (b) electromagnetic, (c) triboelectric, (d) photovoltaic, and (e) thermoelectric.

W/m^2 and total energy conversion efficiency of up to 85% [46]. They have been proven to be a promising scheme in vibration and wind energy harvesting.

2.4. Photovoltaic effect

Becquerel discovered the photovoltaic effect, where different parts of the semiconductor material generate a voltage difference when subjected to sunlight, as illustrated in Fig. 2(d). A single crystalline silicon solar cell was in Bell Labs of the United States in 1954, which indicates the realization of converting solar energy into electric energy. Solar energy conversion efficiency is largely determined by materials, absorber bandgaps and optical concentration. In the existing reports, the maximum conversion efficiency of solar cells is nearly 50% [64]. As a relatively mature technology, photovoltaic systems have been widely exploited as auxiliary power supplies for trackside or onboard devices. From a macro perspective, it is also of great significance to alleviate the energy consumption pressure of railway industry and optimize the energy structure.

2.5. Thermoelectric effect

Thermoelectric effect is a phenomenon as illustrated in Fig. 2(e) in which a voltage difference exists between n-type and p-type conductors due to a temperature difference being exerted [65–67]. This is also called the Seebeck effect, first discovered by T. J. Seebeck in 1821 [68]. In this configuration, two elements are connected thermally in parallel and electrically in series. In practice, thermoelectric generators (TEG) consist of many such thermocouples in series to obtain a higher voltage in low temperature difference environment. The generated voltage of TEG is derived as [69]:

$$V_{tm} = (\alpha p - \alpha n) \cdot \Delta T \cdot N \cdot \frac{Rload}{Rload + Rin} \tag{4}$$

where α_p and α_n are the Seebeck coefficients of n-type and p-type conductors, ΔT is the temperature difference between the hot side and cold side of TEG, N is the number of thermocouples, and R_{load} and R_{in} are external and internal resistance of TEG.

3. Vibration energy harvesters for railway applications

The wheel-rail contact and track irregularity excitations lead to vibrations that are prevalent in places such as rails, tunnels, bridges and trains. Due to the broadband characteristics of railway vibration, many researchers are committed to the study of VEH for railway applications. This section introduces the mechanism and structure integration of piezoelectric vibration energy harvesters (PE-VEH) and electromagnetic vibration energy harvesters (EM-VEH), then summarizes their characteristics and performances.

3.1. Piezoelectric vibration energy harvesters

Track-side is the main application scenario of PE-VEHs. Nelson et al. [25,54] first tried to use a piezoelectric patch amounted to the bottom of the rail in the 31 working mode and achieved an average power of approximately 0.053 mW in field tests. The authors predicted that the average power can be up to 1.1 mW in the condition of loaded train yielding, which shall be enough to power some low-power sensors

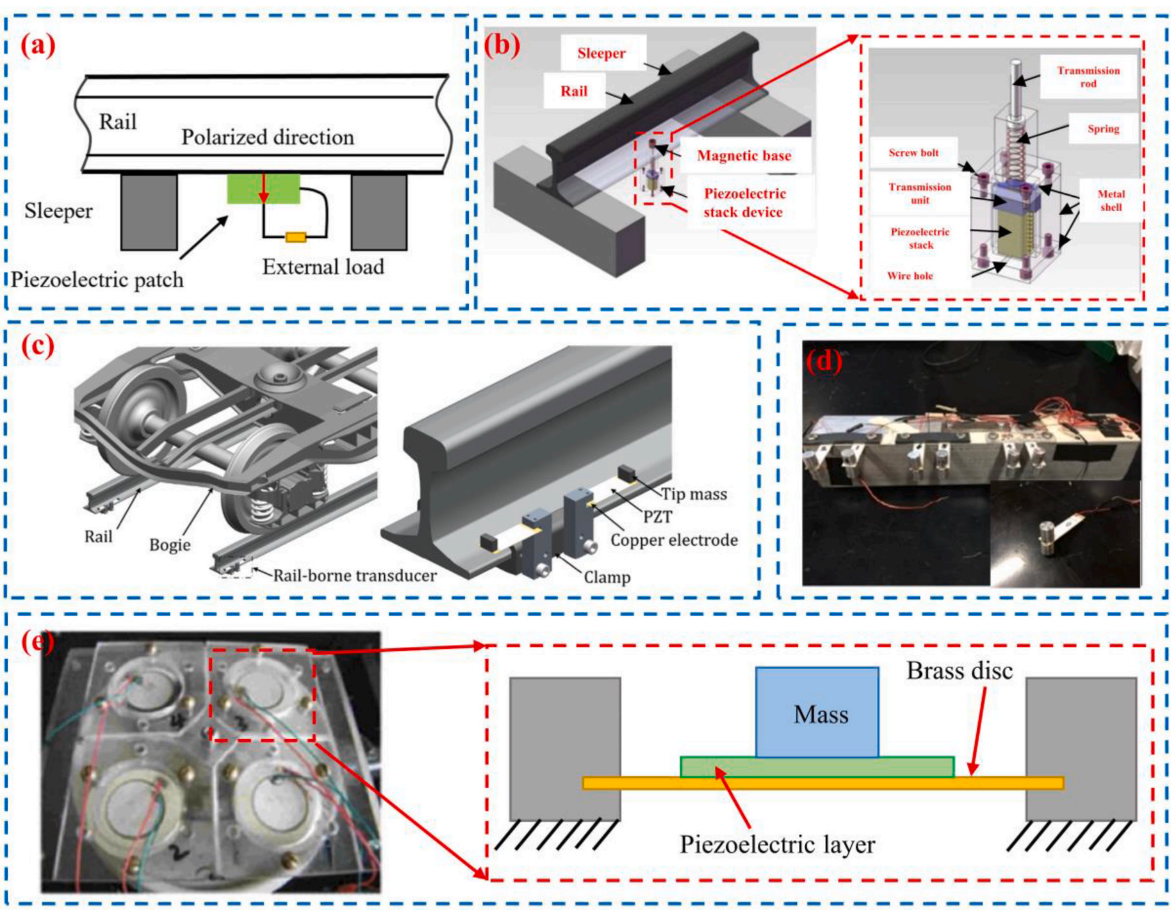

Fig. 3. Trackside PE-VEHs in railway industry. (a) Patch-type and (b) stack-type PE-VEHs [71], (c) cantilevered PE-VEH [76], (d) multi-beam PE-VEH [78], (e) broadband piezoelectric circular array [79] for track vibration energy harvesting.

requiring only a few milliwatts [70]. In addition to the patch-type piezoelectric harvester in Fig. 3(a), Wang et al. [71] proposed a stack-type piezoelectric where piezoelectric patches are connected mechanically in series but electrically in parallel, mounted at the bottom of the steel rail. As shown in Fig. 3(b), the transverse track displacement of the rail is converted by a transmission rod and a force through the compression spring and is then transferred to the piezoelectric stack, which works in the 33 mode. A mean power of 0.8 mW (stack) and 0.15 mW (patch) can be obtained when the train speed is 324 km/h (203 mph), theoretically. However, the power generation capacity of the piezoelectric stack is not high because of its high stiffness leading to a poor coupling vibration effect [72].

Piezoelectric cantilever has the advantage in that relatively high strain can be obtained under given base vibration input [73,74]. The resonance frequency of the cantilever beam is usually higher than the main frequency range of rail or railcar vibration, and a mass can be placed on the free end to adjust the resonance frequency [75], as shown in Fig. 3(c). Gao et al. [76] proposed a cantilevered PE-VEH based on PZT film and resonant design to track vibration energy harvesting. A maximum power of 4.9 mW was achieved at the voltage of 24.4 V in lab tests. The output could be further improved since the designed harvester failed to match with track vibration frequency very well. Considering intense characteristics of rail vibration in a wide frequency domain, Yang et al. [77] proposed a programmable methodology to optimize the parameters of a piezoelectric cantilever. The natural frequencies of the piezoelectric cantilever were designed to be constrained by the safety limit of stress and deformation of the piezoelectric material to match the first two dominant frequencies of the rail vibration. The results showed that the maximum power values at low dominant frequency and high dominant frequency were improved by 3 times and 15 times, respectively. To broaden the frequency band, Li et al. [78] developed a piezoelectric transducer with six bimorph cantilever beams realizing a frequency range from 55 Hz to 75 Hz, as shown in Fig. 3(d). However, the maximum power is only 0.16 μW in field tests since the main frequency of excitation introduced by the low speed train was not covered by the designed bandwidth.

Wang et al. [79] designed a piezoelectric circular membrane with 4 piezoelectric plates in parallel realizing a frequency range of 110–260 Hz, as shown in Fig. 3(e). A maximum power of 21.4 mW was generated under the excitation at 150 Hz with an optimal load resistor of 11 kΩ. It is a potential design to realize the broadband piezoelectric harvester to match the frequency band of rail vibration.

In addition, there are also application cases for PE-VEHs mounted to **other off-vehicle scenarios** such as railway bridges and sleepers. Cahill et al. [80] explored the possibility of deriving energy from train-introduced vibration in bridges by attaching piezoelectric patches to the underside surface of bridges. In simulations, the PZT and PVDF generated a maximum average power of 588 μW and 307.1 μW respectively under the condition of two ICE trains in the opposite direction at a speed of 120 km/h (75 mph). Despite the lower power generation capacity, the PVDF is considered as a better choice in long-term work due to a higher mechanical tensile strength and excellent flexibility [81,82]. Wischke et al. [83] proposed a four-beam PE-VEH mounted to the sleeper, achieving an average power of 54 μW in field tests. As shown in Fig. 4(a). The beam is supported on both external frames by compliant hinges to gain a larger shock tolerance. The transducer with four resonance frequencies by tuning proof masses covers the excitation frequency of sleepers in traffic tunnels. To power the wireless sensors and monitor railroad health, Yuan et al. [84] conceived a piezoelectric array, composed of drum transducers andinstalled under sleepers to avoid drilling, as shown in Fig. 4(b). The piezoelectric transducer arrays can generate 66 mW on average with an optimal resistance of 4 kΩ in real track situation, which provides a considerable output for low power sensors. The feasibility and reliability were verified by theoretical model and lab tests.

For **onboard** vibration energy harvesting, Pasquale et al. [85,86] designed a piezoelectric cantilever tuned at a resonance frequency of 5.71 Hz and mounted to the bogie to obtain energy from bogie lateral vibration. Lab tests were performed on a 1:4 scaled bogie [87,88], as shown in Fig. 5(a), and the results showed that a maximum output power of 4 mW with a 200 kΩ resistance load was obtained. Dziadak et al. [89] proposed a double-beam harvester with three piezoelectric elements mounted to the bogie as the power module for axle box monitoring. A maximum power of 179 μW was achieved in field test with a freight wagon of about 20 tons at a maximum speed of 90 km/h (56 mph). Matheus et al. [90] explored the feasibility of a multi-beam piezoelectric energy harvester to provide power for wagon onboard monitoring. With the aim of increasing the output power and reducing the structure mass, the optimal geometry and tip mass configuration of planar zigzag and orthogonal spiral structures were obtained based on the prediction model and an interactive adaptive-weight genetic algorithm. The optimization results showed that the orthogonal spiral geometry had the potential to gain a maximum power of up to 20.9 mW and the zigzag structure presented a better optimized energy density of 16.6 mW/kg$(ms^{-2})^2$ conversely. Cho et al. [91] proposed a novel piezoelectric system with magnetic pendulum movement harvesting

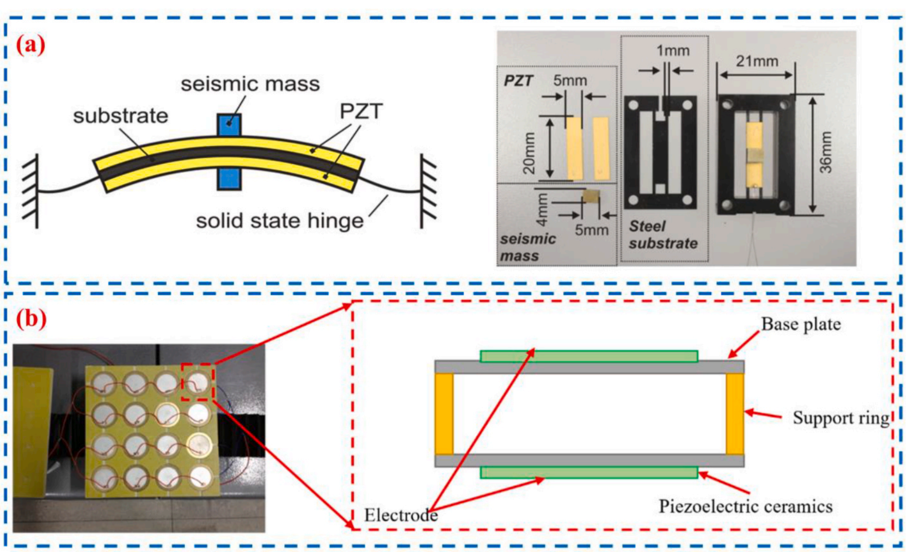

Fig. 4. PE-VEHs for other off-vehicle scenarios. (a) Four-beam PE-VEH mounted to sleeper side [83], (b) drum piezoelectric array mounted under sleepers [84].

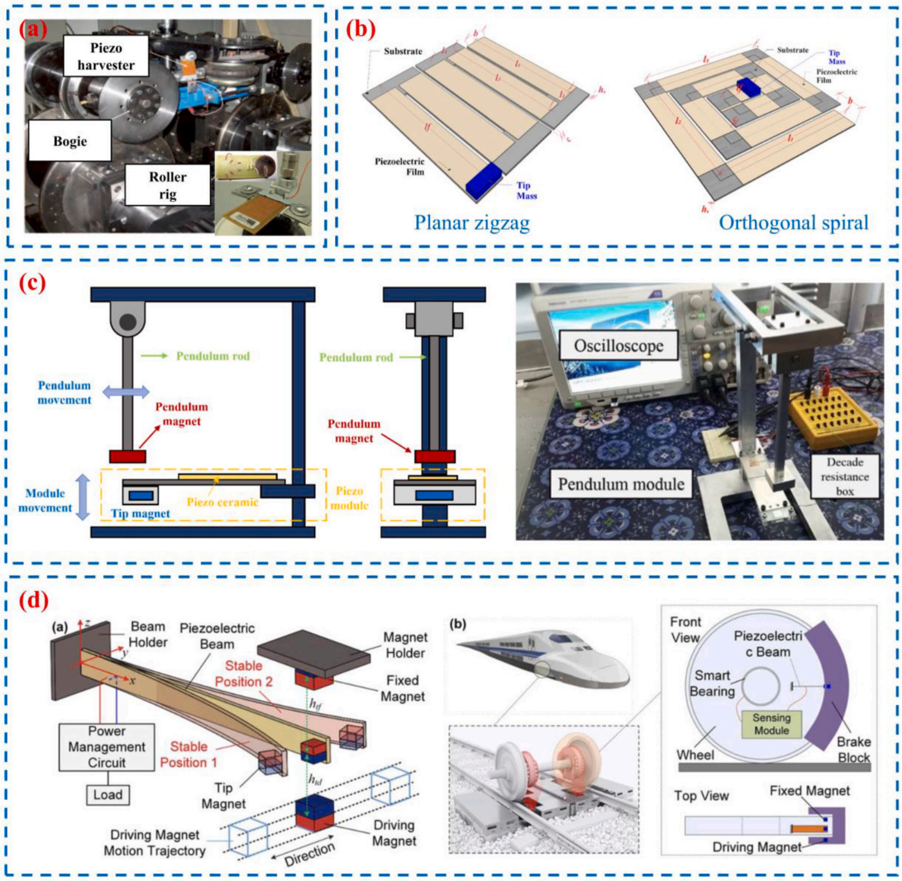

Fig. 5. Onboard PE-VEHs in railway industry. (a) Onboard piezoelectric cantilever for bogie lateral vibration energy harvesting [85,86], (b) design and optimization of multi-beam PE-VEHs mounted to wagon main beam [90], (c) PE-VEH with pendulum magnet for installation in vehicle [91], (d) bi-stable piezoelectric harvester with frequency up-converting mechanism [92].

vibration energy as well as inertial energy in railway vehicles, as shown in Fig. 5(c). When the pendulum rod swings due to vehicle vibration, the pendulum magnet amplifies the movement of the tip magnet at the free end and makes the cantilever vibrate. In such a system, the swing direction of the pendulum rod and the attraction and repulsion of the magnets will affect the power performance. The experiment results showed that the harvesting system can reach a maximum average power density of 40.24 μW/cm^3, equal to a power of 12.68 μW, under attraction between two magnets of the pendulum motion in the Y-direction. Fu et al. [92] developed a bi-stable piezoelectric harvester with frequency up-converting mechanism, as shown in Fig. 5(d). The driving magnet is mounted to a vibration source with a frequency much lower than the resonant frequency of the piezoelectric cantilever, and bends the piezoelectric cantilever by the interaction force with the tip magnet. The repulsive force between the tip magnet and the fixed magnet makes the system bi-stable, and the beam displacement will be amplified when the magnet force is large enough to stimulate oscillation between the equilibrium states. One interesting aspect is that the piezoelectric voltage waveform is always single-frequency although the system excitation may be random and broadband, which can effectively extract energy by synchronized switch harvesting an inductor (SSHI) circuit with a specific switching frequency. In lab tests, the power performance of the bi-stable frequency up-converting harvester with SSHI was up to 525% compared with the up-converting harvester without bi-stable configuration and SSHI. This design is considered to have potential applications in train wheel installation for converting vehicle motion energy to implement a self-powered smart bearing.

The PE-VEH is characterized by simple structure, small volumes and high power density. Compared with electromagnetic transducers, which may significantly reduce performance due to the misalignment between the permanent magnet and the coil [93], PE-VEHs have a better tolerance. The self-powered wireless sensor nodes and micro-electronics integrated in PE-VEHs make them applicable for many scenarios in the railway industry, especially in the case of limited installation space. The reviewed PE-VEHs in this section are summarized and listed in Table 1, where the power density is calculated based on the power value listed in the table and the volume of the whole harvester.

3.2. Electromagnetic vibration energy harvesters

3.2.1. Linear and nonlinear electromagnetic vibration energy harvesters

EM-VEHs with a simple linear motion between the coil and magnet can be divided into three types: direct voice-coil, spring resonance, and magnetic suspension [94] due to structural differences. The first two types can be classified as linear EM-VEHs, and the EM-VEHs with magnetic suspension configuration can be considered as the nonlinear category due to the nonlinear force between magnets.

The early research on conventional EM-VEHs for railways is mostly for **track-side** installation and applications. Nelson et al. [25]developed a voice-coil generator to obtain energy from rail deflection, as illustrated in Fig. 6(a). An average power of 4 mW was generated by a train passing by at a speed from 16 to 19 km/h (10–12 mph), which was considered sufficient to power track-health monitoring sensors at low power levels.

The EM-VEHs with a mechanical spring where a coil or a magnet is attached and moving relative to the excitation are described as spring-resonant harvesters, which have the advantage of higher peak power when the resonant frequency of the devices coincides with the excitation frequency. Gao et al. [94] proposed a spring-resonant harvester with

Table 1
Summary of PE-VEHs for railway industry.

	Year	Mechanism	Installation	Frequency [Hz]	Power [mW]	Power density [W/m^3]	Simulated or field test excitation
Track-side							
Nelson et al. [25,54]	2008	Piezoelectric patch	Rail bottom	/	1.1 (avg)	/	Loaded (heavier) train yields in simulation
Wang et al. [71]	2015	Piezoelectric patch	Rail bottom	/	0.9 (max)	10^4	X2 train with five cars at 324 km/h in simulation
	2015	Piezoelectric stack	Rail bottom	/	0.12 (max)	0.36	X2 train with five cars at 324 km/h in simulation
Gao et al. [76]	2016	Piezoelectric cantilever	Railside	23	4.88 (max)	1.79	Rail acceleration: 5 g, displacement: 0.2–0.4 mm, 7 Hz in lab test
Li et al. [78]	2014	Multi-beam piezoelectric	Railside	55–75	1.6×10^{-4} (max)	/	Maximum amplitude: 175 mg in **field test**
Wang et al. [79]	2014	Circular diaphragm piezoelectric array	Rail bottom	110–260	21.4 (max)	/	A fixed pre-stress condition: 0.8 N, vibration acceleration: 9.8 m/s^2, 150 Hz in lab test
Cahill et al. [80]	2014	Piezoelectric patch	Bridge bottom	/	0.588 (avg)	/	Double-train (ICE) at 120 km/h in simulation
Wischke et al. [83]	2011	Multi-beam piezoelectric	Sleeper side	437, 461, 480, 498	0.054 (avg)	3.32	**Field test** with one train passing by
Yuan et al. [84]	2014	Drum piezoelectric array	Sleeper bottom	/	66 (ave)	4×10^3	Overload conditions of Shanghai metro at 60 km/h in simulation
Onboard							
Pasquale et al. [85,86]	2011	Piezoelectric cantilever	Bogie	5.71	4 (max)	/	Bogie lateral acceleration: 1.53 g, 5.71 Hz in lab test
Dziadak et al. [89]	2022	Double beam harvester with three piezoelectric elements	Bogie	14	0.18 (max)	/	**Field test** with freight wagon of weight about 20 tons at maximum 90 km/h
Cho et al. [91]	2016	Piezoelectric cantilever with pendulum magnet	In vehicle	3.8	0.013 (avg)	40.24	Pendulum frequency of 3.8 Hz, pendulum rod moving along the y-axis, attracting force between the magnets in lab test
Fu et al. [92]	2019	Bi-stable piezoelectric harvester with frequency up-converting mechanism	Wheel	1–16	0.06 (max)	/	Harvester with SSHI circuit under a excitation with frequency of 15 Hz in lab test

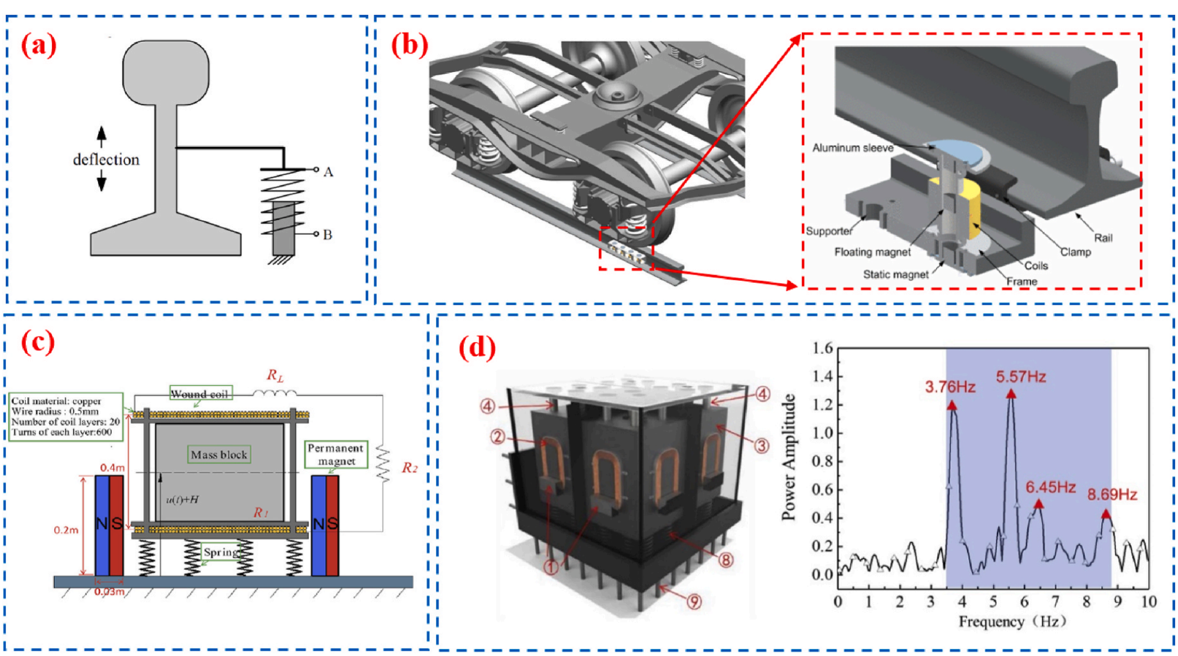

Fig. 6. Track-side EM-VEHs in railway industry (part 1). (a) Voice-coil harvester [25] and (b) spring-resonant harvester with single DOF for track-side installation [94], (c–d) spring-resonant harvesters with single [95] and 4-DOF for track slab side on the bridge [96].

magnet-spring connecting structure, and the copper beads fixed in the circular groove of magnet guarantee reliable radial support as well as magnet movement, as shown in Fig. 6(b). A peak power of 29.8 mW was achieved under the simulation rail vibration of 1.2–2 mm amplitude at 6 Hz.

In railway systems, the single DOF oscillation system is not enough to cope with broadband vibration. To address this problem, the spring-resonant harvester with multi-DOF provides a possible solution. Nonlinear oscillation system based on levitation force is another effective solution.

Hou et al. [95] explored the energy harvesting of bridge vibration based on the accurate calculation of train-rail-bridge response. The EM-VEH placed adjacent to the track slab consists of several springs, two permanent magnets, the mass block, and wound coils, as shown in Fig. 6 (c). A peak power of 35.3 W at 190 V was achieved in the environment vibration with a peak acceleration of 3.71 m/s^2. The peak power density of 176.5 $\mu W/cm^3$ presents a considerable advantage in existing similar devices. With the purpose of expanding the frequency band to better match the multi dominant frequencies of slab vibration, the multi-frequency EM-VEH with 4 modules is presented in Fig. 6(d) [96]. In three prototypes with different emphases designed by the author, a peak power of 66.27 W, an average power of 1.41 W and a peak power density of 112.4 $\mu W/cm^3$ were obtained.

Gao et al. [94,97] investigated the performance of the nonlinear EM-VEH with two fixed magnets on top and bottom of the base in rail vibration energy harvesting, as shown in Fig. 7(a). The harvester presented a continuous output capability with the excitation frequency ranging from 3 to 7 Hz. With the aim of possessing the capability of energy harvesting across a wider frequency range as well as delivering more output power, a multi-stable EM-VEH for railway or suspension installation was conceived in Ref. [98]. As shown in Fig. 7(b), the device was designed with a two-layer concentric tube structure. The suspending magnet in the inner tube consists of two aluminum caps circumferentially filled with copper beads for smooth axial movement and connected to a wood rod. Two outer sleeves are attached to an outer polymethylmethacrylate tube for fixing the eight outer magnets. In addition, the top cap and bottom support are installed on the outside of the outer tube. The two magnetic rings inside with the same shape play as top and bottom magnets. Phenomena of dynamical bifurcation, escape from potential wells, high energy orbits, and chaotic oscillation were revealed by experimental investigations. The experimental results showed a peak power output of over 2 W obtained at a frequency bandwidth of 5–12 Hz, which is sufficient for common sensor nodes.

In 2021, Sun et al. [99] proposed a rail-borne magnetic-floating energy harvester for rail corrugation inspection as illustrated in Fig. 7 (c). For the triple-magnet attractive and repellent configuration, the best coil positions were found respectively. In sinusoidal sweeping vibration tests, the triple-magnet repellent configuration showed a better power potential and perceived more frequencies, which is more suitable for rail corrugation inspection. The moderate and severe rail corrugation can be judged by the filtered voltage and wavelet transform method. In addition, the device can provide a stable output of 5 V/10 mA to power rail-side sensors with a DC-DC booster conversion circuit in actual rail vibration.

Onboard EM-VEHs are usually designed for suspension systems or vehicle bodies. Nagode et al. [100,101] proposed another voice-coil harvester to utilize vertical vibration of suspension, which is normally absorbed by dampers or friction wedges and converted to heat. As shown in Fig. 8(a), the magnet is formed by multiple magnet sheets and steel spacers, and one end is connected to the rotor. The stator is surrounded by multiple small coils in series inside, and the coils and magnet are separated by plastic rings. A peak power output of 1.8 W with 180 Ω was generated in the excitation of ±19 mm at 1.5 Hz.

Bradai et al. [102] developed a spring-resonant harvester with coil-spring connecting structure oriented to the vertical vibration of wagon bogie. The added mass on the coil housing or spring stiffness can be tuned to make the resonant frequency of the device suitable for the vibrating environment. To adapt to the difference in the dominant

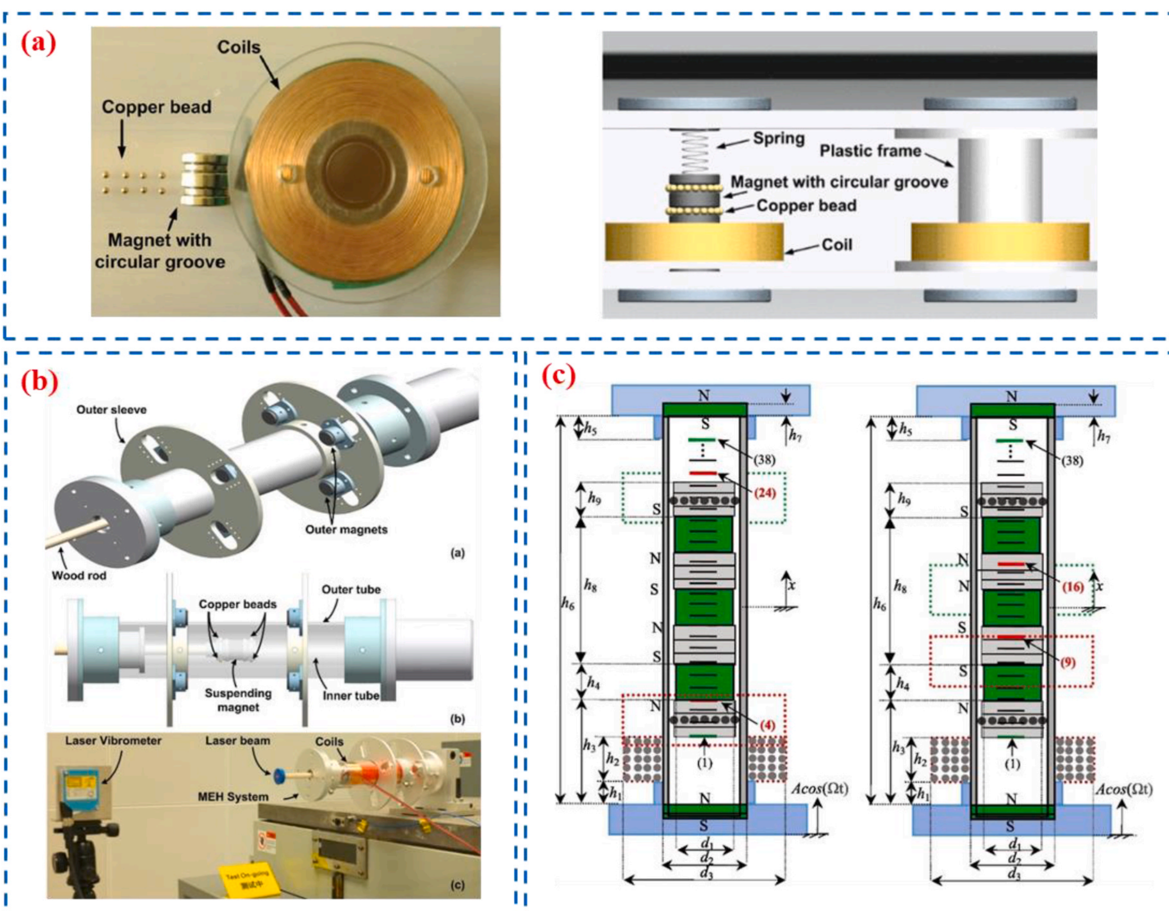

Fig. 7. Track-side EM-VEHs in railway industry (part 2). (a) Magnetic suspension harvester [94,97], (b) magnetic suspension harvesters with multi-stable configuration [98], (c) magnetic suspension harvesters with the triple-magnet attractive and repellent configuration for rail corrugation inspection [99].

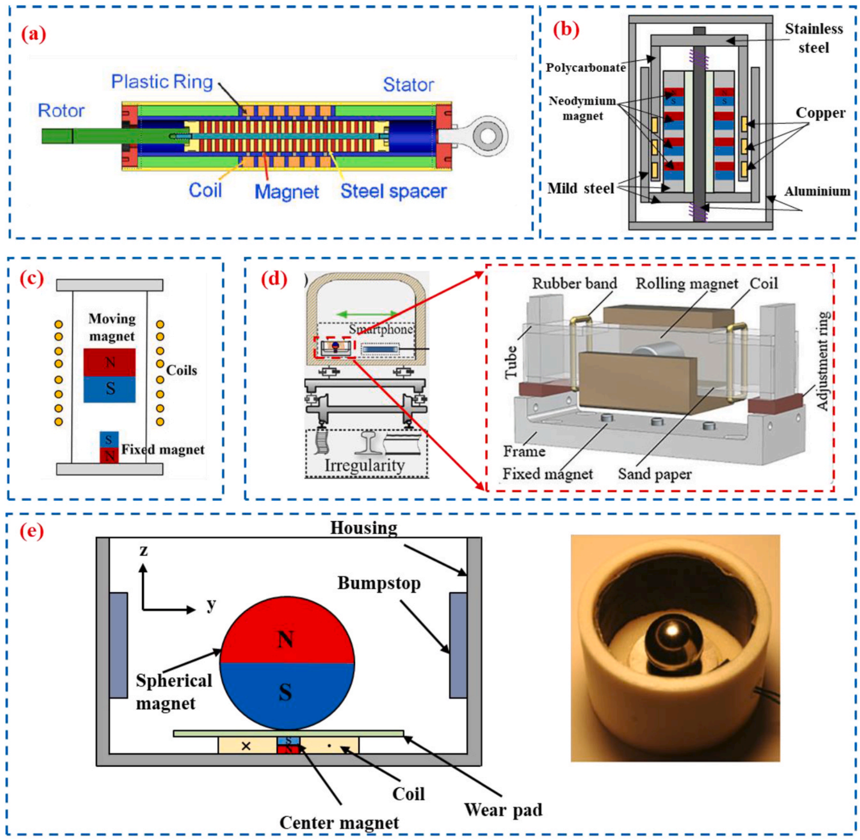

Fig. 8. Onboard EM-VEHs in railway industry. (a) Voice-coil harvester for wagon bogie installation [100,101], (b) spring-resonant harvesters with 2-DOF mounted to wagon body [103], (c) magnetic suspension harvester mounted to freight car body installation [104], (d) nonlinear EM-VEH with cylindrical rolling magnet in vehicle [105], (e) Nonlinear EM-VEH with spherical permanent mounted to bogie [106].

vibration frequencies of the freight wagon in unloaded and loaded conditions, a spring-resonant harvester with 2-DOF mounted to wagon body was developed by Ung [103]. The magnetic core of the prototype is formed by four high strength neodymium ring-type magnets arranged with like-poles neighboring. The stainless steel plate with the coil surrounded serves as a support mechanism as well as additional mass, as shown in Fig. 8(b). The experimental results showed that the 2-DOF harvester derived a peak power of 212 mW and 218 mW from a sinusoidal vibration with 0.4 g peak acceleration at 6.5 Hz and 14.5 Hz, respectively, which improves the robustness of the load change of the freight wagon.

Pasquale et al. [104] proposed an onboard magnetically levitated generator with one fixed magnet on the base of the frame, as illustrated in Fig. 8(c). In experiments, the author simplified the car body vibration by the sum of two sinusoidal functions representing the two most important frequency components. A maximum voltage of 2.5 V and a corresponding current of 50 mAwere obtained under the input of a simplified coach vibration at 80 km/h (50 mph).

Wang et al. [105] presented a nonlinear EM-VEH based on a cylindrical rolling magnet and several fixed magnets for lateral vibration of the car body of a metro, as shown in Fig. 8(d). The change of fixed magnet number can enable the system with mono-stable and tri-stable configurations. Lab tests showed that the harvester with one fixed magnet setup achieved a maximum instantaneous over 4 mW under the lateral vibration of car body of the metro.

In addition, the researchers made attempts to scavenge the vibration energy in multiple directions simultaneously. Genevieve et al. [106] developed a harvester to utilize low frequency mechanical vibration energy, which has the main components of a spherical permanent magnet, a center magnet, wear pad and wire coil arrangement, as shown in Fig. 8(e). When the car body vibrates, the sphere moves freely on the X–Y plane of the wear-pad, which is arranged above the coil to reduce the motion friction. The motion of the sphere is limited by the rubber bonded to the inside of the harvester casing. Due to the restoring force between the sphere and center magnet, the relative motion of the sphere and the coil makes a variable magnetic flux and electromotive force is generated across the coil according to Faraday's law. This system has two working modes with the polarization of two magnets in the same direction (attracting fields, 'AF') or in the opposite (opposing fields, 'OF') direction. The test results showed that the OF mode achieved higher power output. Under the simulated excitation of the train platform, an 18.5 mW peak power with 680 Ω load was generated in OF mode. The reviewed EM-VEHs in this section are summarized and listed in Table 2.

3.2.2. Rotary electromagnetic vibration energy harvesters

The rotary EM-VEH is defined by the rotary energy transducers, even if the original motion is linear displacement (which can translate into rotation). The core component of rotary EM-VEHs is usually in the form of rotary generators. Some of them are equipped with motion conversion mechanisms converting other types of relative motion to rotational motion and driving a rotary generator. The earliest vehicle kinetic energy harvesting scheme was to install the axle generator at the end of the axle to provide power for the devices on the unpowered freight wagons. Nagode et al. [107] proposed an axle generator with an open structure for quick and convenient installation. As shown in Fig. 9(a), three sets of friction wheelsets are arranged in the shell at 120° intervals. One of them transmits the motion of car axle and drives the generator by two sets of gears with an 8 times ratio. The other two wheelsets are free to maintain contact between the driving wheelset and the axle. Two halves of the device are hinged on the same axle and are tied by spring-loaded bolts during installation. In tests, the axle generator with a "Y"

Table 2
Summary of linear and nonlinear EM-VEHs for railway industry.

	Year	Mechanism	Installation	Frequency [Hz]	Power [mW]	Power density [W/m^3]	Simulated or field test excitation
Trake-side							
Nelson et al. [25]	2008	Voice-coil	Railside	/	4 (avg)	/	**Field test** with train speed varying from 16 to 19 km/h
Gao et al. [94]	2016	Spring-resonant	Railside	6	29.8 (max)	70.95	Rail displacement: 1.2–2 mm, 6 Hz in lab test
Hou et al. [95]	2018	Spring-resonant	Track slab side on the bridge	5.5	3.53×10^4 (max)	176.5	Peak Acceleration: 3.71 m/s^2, 5.5 Hz in simulation
[96]	2020	Spring-resonant with multi-DOF	Track slab side on the bridge	5.6	1.41×10^3 (avg)	10.64	Peak Acceleration: 2.98 m/s^2, 5.6 Hz in simulation
Gao et al. [94, 97]	2016	Magnetic suspension	Railside	3–7	12.3 (max)	1.74	Rail displacement: 0.6–1 mm, 4.5 Hz in lab test
[98]	2018	Magnetic suspension with multi-stable	Railside/ suspension system	5–12	2×10^3 (max)	343.13	At frequency bandwidth of 5–12 Hz in lab test
Sun et al. [99]	2021	Magnetic suspension	Railside	36.4, 49.8	50 (avg)	481.44	Real track vibration with a DC-DC booster conversion circuit in lab test
Onboard							
Nagode et al. [100,101]	2010	Voice-coil	Suspension system	/	1.8×10^3 (max)	/	Amplitude: ±0.75, 1.5 Hz in lab test
Bradai et al. [102]	2018	Spring-resonant	Wagon bogie	27	10 (max)	/	Amplitude: 0.5 mm amplitude (average 0.3 mm), 27 Hz in lab test
Ung et al. [103]	2015	Spring-resonant with 2-DOF	Wagon body	5.8, 14.6	212/218 (max)	/	Sinusoidal wave, peak acceleration: 0.4 g, 6.5/14.6 Hz in lab test
Pasquale et al. [104]	2012	Magnetic suspension	Freight car body	4.44	125 (max)	70.18	Simulated vibration of freight train at 80 km/h in lab test
Wang et al. [105]	2021	Nonlinear harvester with rolling magnet	In vehicle	8–9	4 (max)	29.63	Under the lateral vibration of car body of metro in lab test
Genevieve et al. [106]	2013	Nonlinear harvester with spherical permanent	Bogie	< 10	18.5 (max)	/	Recorded bogie acceleration data with a bandwidth of 0–50 Hz, a peak of 0.007 g^2/Hz and an RMS acceleration of 0.45 g in lab test

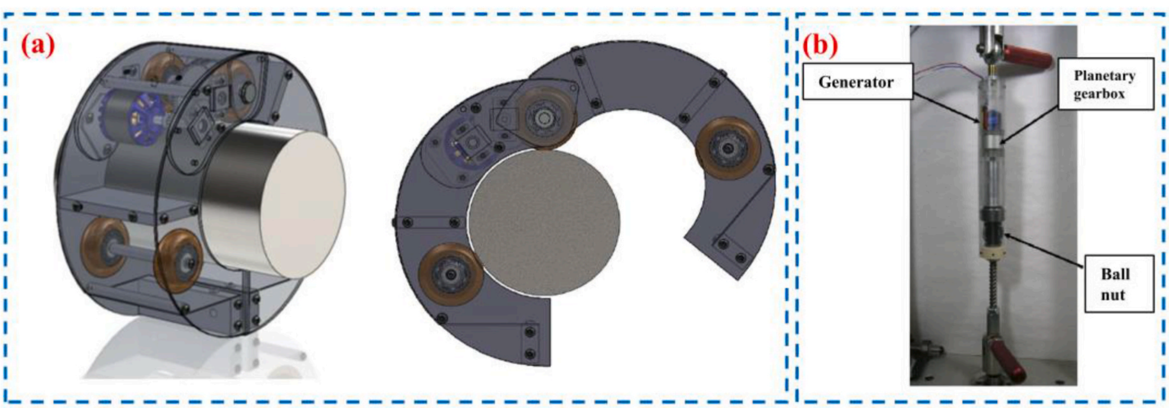

Fig. 9. Rotary energy harvester proposed by Nagode et al. (a) axle generator [107], (b) rotary EM-VEH with nut-screw transmission [101].

configuration of three phases connection presented a power of 290 W at the vehicle speed of 88.5 km/h (55 mph), which is adequate for numerous devices. However, different from VEHs, the energy source of the axle generator is the kinetic energy of the vehicle axle, which causes extra running resistance and traction power consumption.

Vibration energy in the vehicle suspension is a form of kinetic energy. For vehicles, it is waste energy, which is eventually converted into heat by shock absorbers or wedges. Reasonable uses of vibration will not affect the energy consumption of the train or even can improve the vehicle dynamics. Hence, Nagode et al. [101] continued to investigate energy harvesting from vehicle suspension vibration. In addition to the linear EM-VEH mentioned above, a rotary one fitted inside the suspension coil spring was proposed, as shown in Fig. 9(b). The ball screw transforms the linear motion of suspension in rotation, and the planetary gearbox is connected to the screw and amplifies the rotation speed of generator. A peak power of 77 W was obtained in the excitation of ±19 mm and 1 Hz, which is an order of magnitude higher than powers encountered with linear EM-VEH.

Nelson et al. [108,109] proposed a rotary EM-VEH mounted to and spanning two rail ties harvesting energy from rail vertical displacement, with the goal of generating 40 W for a grade crossing warning light system. The energy harvesting system was realized by the rack gear, pinion gear, clutch, gearbox and PMDC generator, as shown in Fig. 10(a). A maximum power output of 7.41 W was calculated for a loaded train traveling at 88.5 km/h (55 mph), theoretically. In field tests, the harvester generated a 0.22 W average power when the speed of the loaded trains is 18.5 km/h (11.5 mph), which is not enough for power requirements. The first-generation prototype cannot utilize the upward vibration of the track resulting in a low power generation efficiency of the generator. Therefore, the second generation prototype that can simultaneously scavenge power from upward and downward displacements of the track was developed [110], as shown in Fig. 10(b). The

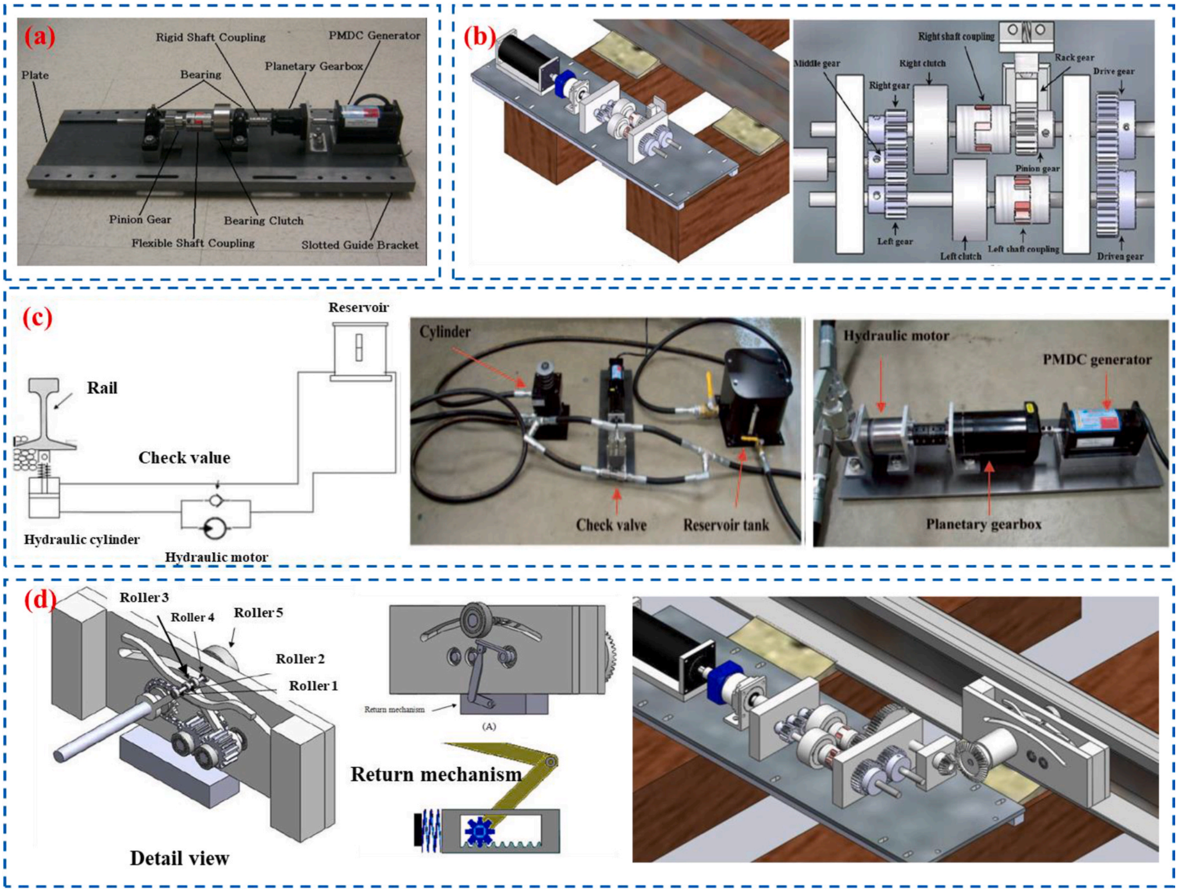

Fig. 10. Track-side rotary EM-VEHs proposed by Nelson et al. (a–b) nut-screw based EM-VEHs realizing unidirectional [108,109] and bidirectional energy rail vibration energy harvesting [110], (c) the hydraulic power harvester [111], (d) the vibration amplification mechanism for unfavorable conditions [109,112].

pinion gear is driven by engaging with a rack gear fixed to the subgrade. The deployment of the two one-way clutches realizes the mechanical rectification of the bidirectional rotation of the pinion gear. They are engaged or freewheeled when the corresponding input shaft of them rotates clockwise (CW) or counterclockwise (CCW). When the rail travels downward, the pinion gear rotates CW and the right clutch is engaged. The right gear is driven to rotate CW resulting in the CCW rotation of middle gear and DC generation. When the rail travels upward, the pinion gear rotates CCW. The left shaft rotates CW by the motion transmission of driven gear pair. The left clutch is engaged and the left gear rotates CW leading to the CCW rotation of middle gear and DC generation. Hence, regardless of the upward or downward track displacement, the generator always rotates in one direction. This prototype was equipped with a gearbox with doubled speed ratio (1:100) compared to the last generation and presented a better power generation capacity. In simulations, a maximum power over 300 W can be realized in the condition of a loaded train traveling at 96.5 km/h (60 mph). Even at the train speed of 18.5 km/h (11.5 mph) with load, an average power of 42 W can be generated.

In view of the constrained output power of previous devices in unloaded conditions or at low speeds, a hydraulic power harvester was proposed in Fig. 10(c) [111]. A hydraulic cylinder is mounted on the bottom of rail, retracting and extending during the train passing by, and brings pressurized fluid to the hydraulic motor. The DC generator is driven to rotate after amplifying the rotary speed of the hydraulic motor by the planetary gearbox. A poppet check valve in parallel with the hydraulic motor is necessary to permit the fluid to flow towards the bottom chamber of the cylinder during extension. The reservoir must be placed about 11 feet higher than the check valve to surpass the opening pressure of check value. An average power of 11.8 W was realized in the rail deflection of 3.8 mm at 0.37 Hz. However, when the deflection amplitude is less than 2.8 mm, the output of the hydraulic power is still constrained.

In Fig. 10(d), a cam-based device was designed combined with energy harvesters [109,112] to enhance power capacity of the harvester with mechanical transmission in unfavorable conditions. When a train passes by (from the bottom right to top left in Fig. 10(d)), roller 5 as well as roller 1 and 4 are driven to the right along the curved grooves, resulting in CW rotation of the follower 2 driven by roller 2. When a train passes by from a negative direction, follower 1 is driven CCW by a roller. The CW rotation of follower 2 or CCW rotation of follower 1 is converted to CW rotational of the main shaft via a pair of spur gears and a chain gear system. In addition, a return mechanism was developed to avoid two followers unable to reset. The second-generation prototype combined with the cam-based magnifying mechanism realized an average power of 50 W when a loaded train was traveling at 18.5 km/h (12 mph).

Zuo's group has carried out long-term research and improvement on the mechanical rotary EM-VEH to harvest energy from rail track deflections. They were the first to come up with a harvester based on twin pairs of rack-pinion transmission [113], as shown in Fig. 11(a). This configuration can effectively reduce the working frequency of each rack-pinion pair and prolong the service life. Two one-way clutches embedded gears 1 and 2 make two gears only rotate CCW. When racks move up and down, only one clutch is engaged and drives the corresponding gear CCW. Another clutch is disengaged and the corresponding gear is driven CCW by the middle gear between gears 1 and 2. The electrical generator and flywheel are driven CCW by shaft 3. Flywheel speed regulation enables the harvester to provide a more reliable and continuous output. In the excitation with 6.4 mm amplitude and 1 Hz

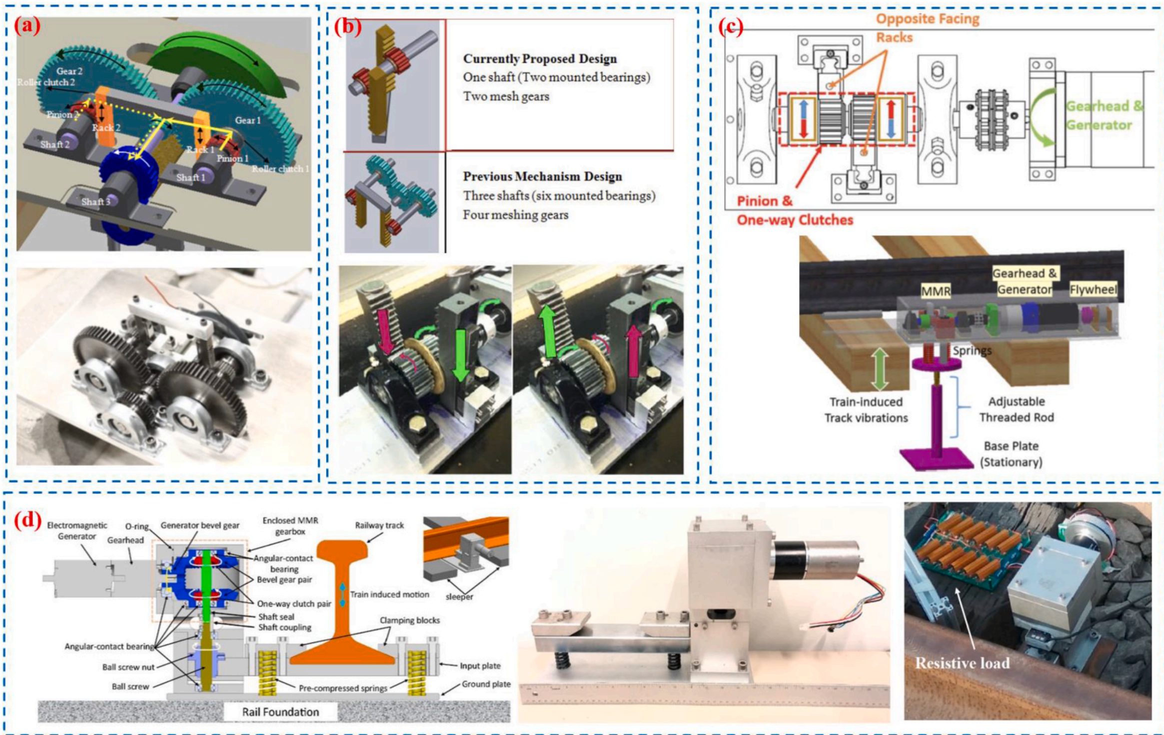

Fig. 11. Track-side rotary EM-VEHs proposed by Zuo et al. (a) the first generation prototype [113], (b) the second generation prototype with mechanical efficiency improvement [114], (c) the third generation prototype with anchorless mounting [115], (d) the fourth generation prototype with novel MMR [116].

frequency, the overall system realized an efficiency of 22.2% and 1 W average power output. Then, their second generation device with a prominent mechanical efficiency improvement was proposed, as shown in Fig. 11(b) [114]. With the same motion conversion principle, the previous three shafts with six mounted bearings and four meshing gears were simplified by a single shaft system with two mounted bearings and two meshing gears. The gearhead is added to amplify the low speed of pinion shaft and provide an optimal angular velocity for the efficient operation of generator. In tests, the harvester was loaded at a sinusoidal excitation with 3 mm amplitude and the frequency is from 2 Hz to 5 Hz. The mechanical efficiency as well as overall efficiency was improved by a factor of 2–3 compared with the last version. The best mechanical efficiency of 71.1% was achieved with 0.19 Ω external resistance at 2 Hz, and an overall best efficiency of 46.7% was obtained with 2 Ω external resistance at 3 Hz and 4 Hz.

In the third version, the basic transmission mechanism of the second generation was followed, but the DC generator was replaced by the AC generator, as shown in Fig. 11(c) [115]. In addition, an anchorless mounting mechanism was developed. An adjustable threaded rod is used to preload the springs under the harvester. The other end of rod is fixed on the stationary base plate, which rests on the ballast. The mounting mechanism is easy to install quickly and will not damage the substructure of the track and avoid potential risks. The overall harvesting system was simplified as a spring-mass-damping system and was delved deeper in modelling. They also first conducted field tests to validate the proposed design in real conditions. The calculated average power of harvester with an equivalent of 16.7 Ω in the Y connection according to recorded data was about 6.9 W average and 54 W peak when a test train composed of 100 cars ran at 64 km/h (40 mph).

Pan in Zuo's group developed a compact ball-screw-based design with a novel mechanical motion rectifier (MMR) [116], as shown in Fig. 11(d). Compared with the rack-pinion configuration, the ball screw mechanism is considered more advantageous in excitation with small displacement due to reducing the backlash during the converting process. When the track as well as nut move up, the ball screw will spin CCW (from the top view). The upper bevel gear is engaged with an embedded clutch and drives the right bevel gear to spin CCW (from the side view). The generator is driven CCW after the acceleration of gearhead. If the track moves down, the lower bevel gear engaged with clutch will become a driven gear and rotate CW (from the top view), and the upper bevel gear will be the idle one. The core parts of MMR with three bevel gears and two one-way clutches ensure the unidirectional rotation of generator regardless of the track motion. Field test results showed an average power of 2.24 W when the two-unit rapid train runs at 30 km/h (19 mph). The four generations of trackside rotary EM-VEHs proposed by Zuo's group have been summarized in Fig. 12.

Another device with this novel MMR and rack-pinion transmission was proposed by Zuo's group as shown in Fig. 13 [117]. The previous two pairs of rack-pinions are simplified with one pair. The authors investigated the performance of this system in harvesting the vibration energy of suspension system. The harvester mounted to a loaded rail car with a total weight of around 23 tons obtained a peak phase power of 73.2 W and an average power of 1.3 W in 20 s at 30 km/h (19 mph) on field tests.

Zhang's group first proposed a rotary EM-VEH with rack-pinon transmission in 2016, as shown in Fig. 14(a) [118]. The principle of MMR in the system is similar to that proposed by Nelson et al. in Fig. 10 (b). The improvements are that: (1) the two one-way clutches of the novel device are embedded in gears. (2) the generator speed is amplified only by gears and a rack and no extra gearbox is added. In tests, an overall system efficiency of 55.5% was obtained. The design of the second-generation prototype was optimized based on the harvester in Fig. 11(a). Two pairs of rack-pinions are simplified to one pair and the same conversion effect is realized, as illustrated in Fig. 14(b) [119]. Another difference is that the prototype is not equipped with a flywheel. The peak voltage of 58 V (in excitation of 1 Hz, 0.25 mm amplitude) indicates the capacity of the harvester to supply power for some track-side equipment. Their latest research is trying to integrate kinetic energy harvester with railway Dowty Retarders (DRs), as shown in Fig. 14(c) [120]. The device accumulates the vibration energy during train

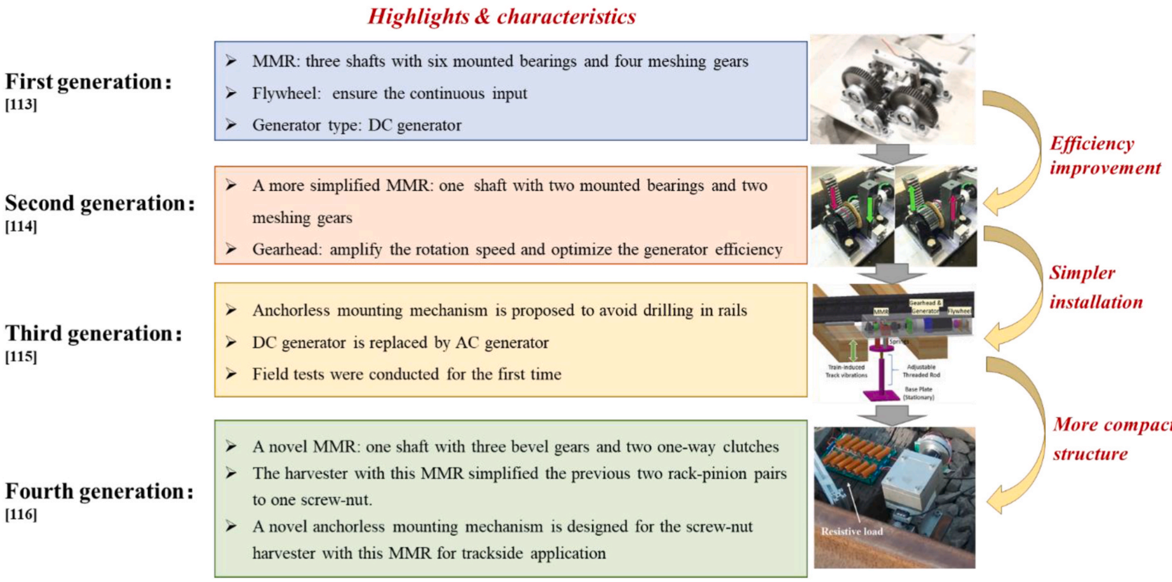

Fig. 12. Design comparison between four generations of track-side rotary EM-VEHs proposed by Zuo et al.

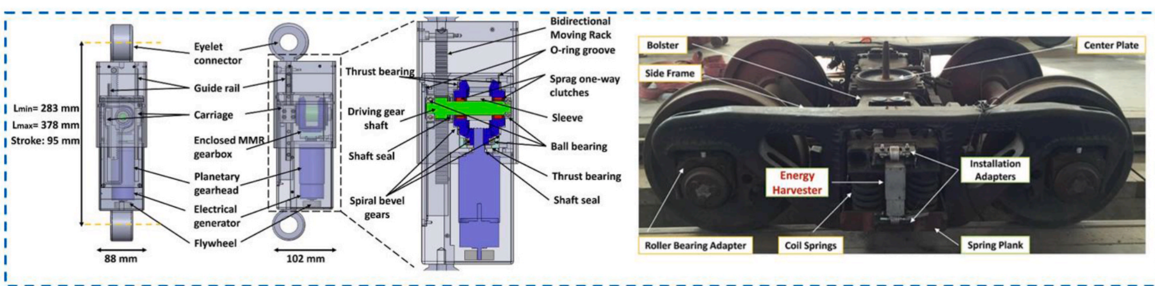

Fig. 13. Onboard rotary EM-VEHs proposed by Zuo et al. with novel MMR for suspension vibration energy harvesting [117].

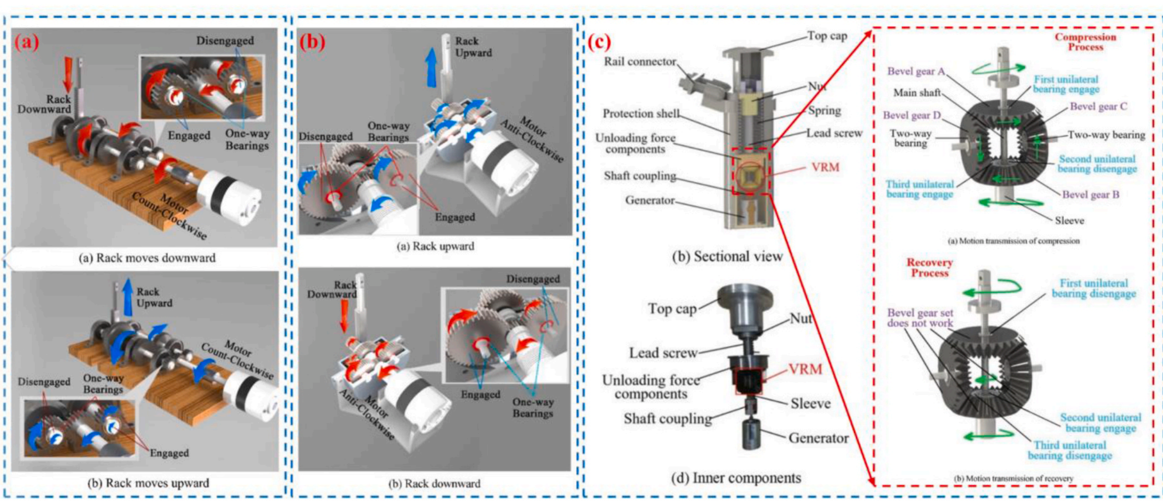

Fig. 14. Track-side rotary EM-VEHs proposed by Zhang et al. (a–b) the prototypes for rail vibration energy harvesting [118,119], (b) the prototype with closed-loop MMR for railcar braking deceleration [120].

deceleration and assists train braking simultaneously. The mechanical transmission part is composed of a special closed-loop shaped gear and a screw-nut pair. When the decelerating train acts on the device, the spring is compressed and the lead screw spins CCW. At this moment, bevel gear A is engaged with the first unilateral bearing, driving bevel gears C and D (two-way clutches embedded). Subsequently, the bevel gear B is driven to rotate CW although the second unilateral bearing is disengaged from the main shaft. The sleeve rotates CW due to the engagement of the third unilateral bearing and drives the generator coupling with it to rotate in the same direction. When the train starts, the return force of the spring drives the nut moving up, and the lead screw spins CW. The first unilateral bearing is disengaged now, and bevel gear

A keeps stationary. The sleeve, as well as the generator, are directly driven CW by the main shaft due to the engagement of the second unilateral bearing. The third unilateral bearing is disengaged, thus the bevel gears B, C, D also keep stationary as the bevel gear A. The closed-loop gear set does not work during the recovery process. The proposed design ensures the constant rotation of the DC generator and improves the efficiency. An efficiency of 51.9% was obtained with the excitation of an amplitude of 7.5 mm and frequency of 2 Hz in experiments.

Gao's group is committed to the onboard applications of EM-VEHs in railway vehicles. In recent research, a new compact EM-VEH with an inertial pendulum is proposed by Gao et al. [121]. It was designed to be mounted on the bogie side frame or on the car body for powering self-powered sensor nodes for freight rail transport. As shown in Fig. 15 (a), the inertia pendulum and gear ring are fixed together by screws and share the same shaft. The inertia pendulum is driven by the inertia motion, and the shaft and gear ring follow. Then, the gear is driven by the engagement with the internal teeth of the gear ring, resulting in the rotation of the DC generator and electricity generation. The radius of the energy harvester can be adjusted to match the frequency of the vibration source. In addition, a DC-DC circuit with supercapacitors was designed for the function of energy conversion and management. The whole system realizes an efficiency of 40–65% above the startup voltage of 1 V. As a complete product, the innovations are as follows: (1) A compact structure integrates the energy harvester and a DC/DC circuit with supercapacitors. In field tests, the harvester fixed on the bogie side frame of C70E freight wagon generated a stable 4.7 V voltage and 50 mA current, which can drive some low-power sensors for onboard monitoring. (2) It can scavenge the vibration energy in multiple directions in the same plane. In addition, they [122] developed a novel vibration-to-rotation conversion mechanism for rotary EM-VEHs mounted on the shock absorbers of a metro via the interaction between a magnet array on cylinder and a linear vibrating magnet, as shown in Fig. 15(d). The linear vibrating magnet fixed on the vibration source drives the cylinder embedded in a ring gear to rotate through the tangential force between magnets. A maximum open voltage of over 20 V was achieved in a low-frequency hand-shaking test. However, this motion conversion mechanism is only applied to small-scale harvesters.

Wang et al. [123] proposed an all-in-one rotary EM-VEH mounted to the axle of the train to harvest wheelset energy, as shown in Fig. 16. The circular array magnet is a rotor driven by a rotating shaft, meanwhile, the coils rotate synchronously due to the static friction between the bearing and shaft. With the increase of rotation amplitude, the gravity torque of the counterweight attached to the foundation drives the coil's oscillation, which achieves a desired relative displacement with the magnet and generates current in the coils. In the tests with a wheel speed ranging from 420 to 820 rpm, the harvester generated an average power of 32.21 mW, and a corresponding power density of 1982 W/m^3 at a matched resistance of 150 Ω. It also exhibited the power supply capacity for low-power devices, such as LEDs, smartwatch, temp/humidity, etc. The reviewed rotary EM-VEHs in this section are summarized and listed in Table 3.

4. Energy harvesting from other energy sources

4.1. Wind energy harvesting

High winds are prevalent around the world, and areas surrounding the railway system are no exception. For remote areas and other scenarios where direct electricity supply is difficult, generating electricity by extracting wind energy offers a practical solution. Generally, the manufacturing costs of wind turbines are low, while the energy generated is considerable. Hence, wind energy conversion is an important renewable approach to help alleviate the greenhouse effect.

Conventional wind turbines realize energy conversion by electromagnetic generators. With the development of nanomaterials, some wind energy triboelectric nanogenerators have been developed for low-power applications [124,125]. Flow-induced vibrations have been studied by many researchers in recent years. Based on flow-induced vibrations theory, many novel concepts about wind turbine design have been developed [126]. The flow-induced VEHs convert wind flows into vibration [127], then generate electricity by piezoelectric, electromagnetic or triboelectric effects [128–131]. The advantage is that a certain amount of power can be generated even in low-speed wind. As a result, it can be considered as an extension of the application scenario of

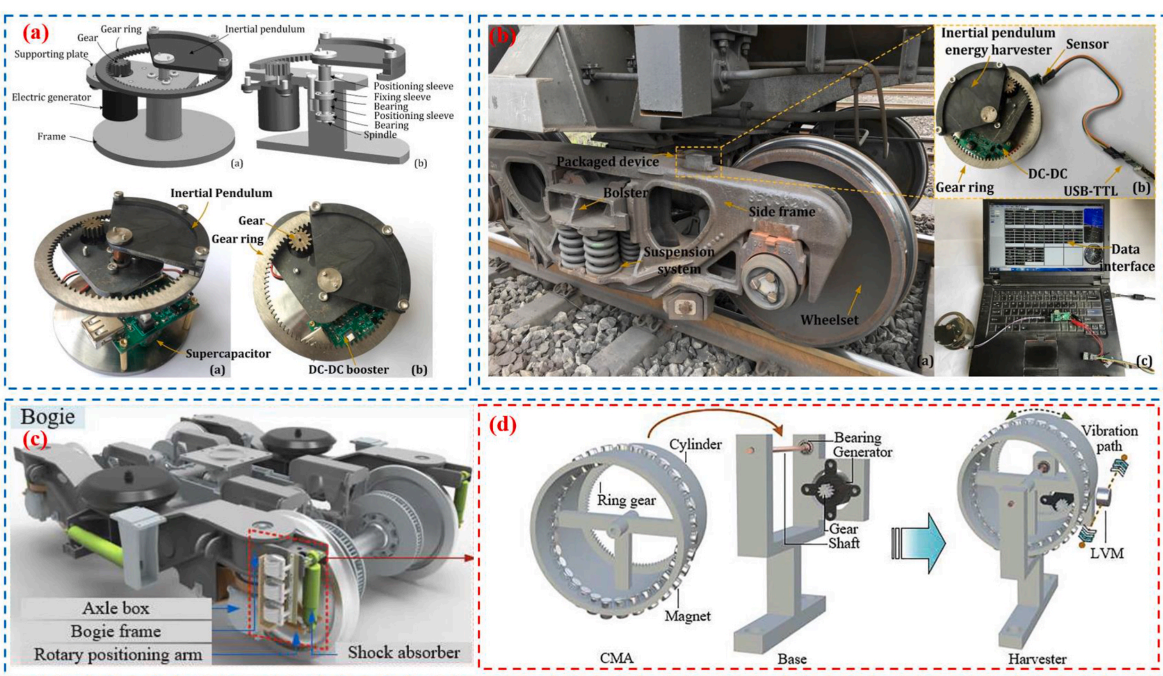

Fig. 15. Onboard small-scale rotary EM-VEHs proposed by Gao's et al. (a) structure configuration and (b) field tests for pendulum-resonance-based EM-VEH [121], (c) installation and (d) structure configuration for EM-VEH with magnet array [122].

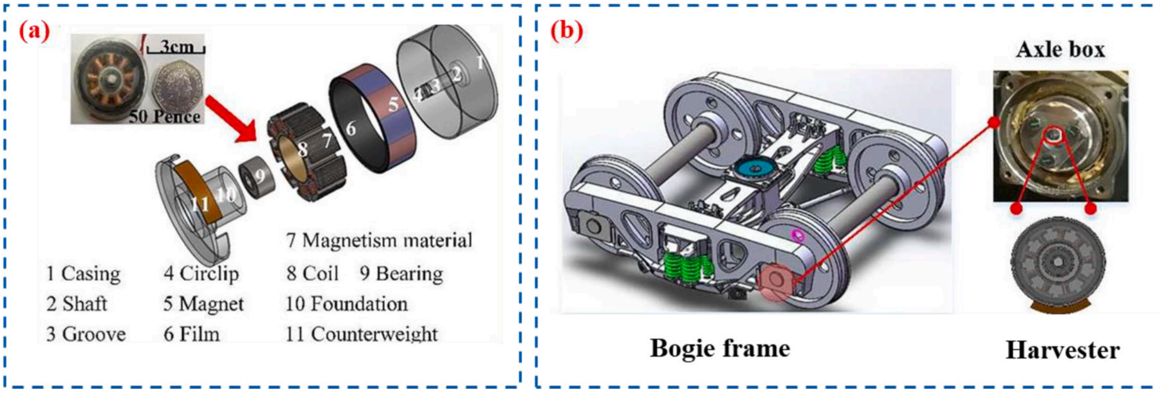

Fig. 16. Small-scale rotary EM-VEHs proposed by Wang's et al. (a) structure configuration and (b) application for harvesting wheelset energy [123].

Table 3
Summary of rotary electromagnetic energy harvester for railway industry.

	Year	Mechanism	Installation	Power [W]	Power density [W/m^3]	Efficiency [%]	Simulated or field test excitation
Nagode et al. [101]	2012	Axle generator	Car axle	290 (avg)	/	/	Car speed of 88.5 km/h in lab test
	2010	Ball screw transmission	Suspension system	70 (max)	/	/	Amplitude: ±19 mm, 1 Hz in lab test
Nelson et al. [108,109]	2009	Rack-pinion transmission	Span two sleepers	3.9 (avg)	/	/	A deflection of 19 mm at train speed 12 km/h in lab test
[110]	2011	Rack-pinion transmission	Span two sleepers	306 (avg)	/	/	Loaded train with speed of 96.5 km/h in simulation
[111]	2013	Hydraulic power harvester	Bottom of the rail	11.8 (avg)	/	/	Maximum amplitude: 3.8 mm, 0.37 Hz in lab test
[109,112]	2013	Cam-based mechanism for harvester	Rail side	50 (avg)	/	/	A loaded train is traveling at 18.5 km/h with the magnifying mechanism and harvester [110] in simulation
Zuo et al. [113]	2012	Rack-pinion transmission with flywheel	Span two sleepers	1/1.4 (avg)	/	22.2/16.9	6.4 mm (1 Hz)/12.7 mm (0.5 Hz) in lab test
[114]	2013	Rack-pinion transmission with flywheel	Span two sleepers	11.4–47 (max)	/	45–47	Amplitude: 2 mm, 2–5 Hz in lab test
[115]	2018	Rack-pinion transmission with flywheel	Span two sleepers	6.9 (avg)	/	/	**Field test** with freight cars at a constant speed of 64 km/h
[116]	2019	Ball screw transmission	Span two sleepers	2.24 (avg)	/	/	**Field test** with rapid train at 30 km/h*
[117]	2019	Rack-pinion transmission	Suspension system	1.3 (avg)	380.15	68	**Field test** with loaded car of weight around 23 tons at 30 km/h
Zhang et al. [118]	2016	Rack-pinion transmission	Rail bottom	/	/	55.5	Amplitude: 6 mm, 2 Hz in lab test
[119]	2017	Rack-pinion transmission	Rail bottom	12.07 (avg)	4.23×10^3	/	Track vibration by vehicle-track model in simulation
[120]	2021	Ball screw transmission	Rail side	/	/	51.9	Amplitude: 7.5 mm, 2 Hz in lab test
Gao et al. [121]	2020	Electromagnetic harvester with inertial pendulum	Bogie side frame or on the car body	0.263 (avg)	951.80	40–65[a]	**Field test** with C70E freight wagon
[122]	2022	Electromagnetic harvester with magnet array	Shock absorber	0.05 (rms)	/	/	Train runs at 80 km/h in simulation
Wang et al. [123]	2021	Rotary electromagnetic harvester	Axle	0.032 (avg)	1.98×10^3	/	Wheel speed ranging from 420 to 820 rpm in lab test

[a] It refers the efficiency of overall harvesting system including interface circuit.

VEHs.

Nurmanova et al. [132] investigated the feasibility of a wind energy harvester implemented on a wagon roof. Simulation results showed that one unit can generate 12.67 kW and 5.65 kW of power on fast and slow routes respectively; however, the air resistance of the train increased by 5.9%, which would significantly increase the fuel consumption. Similar evaluations based on simulations of vertical axis wind turbines placed between two high-speed tracks and high-speed tunnels were conducted in Refs. [133,134]. The results were all positive, and indicated that wind energy harvesting has great economic potential.

In addition, some researchers are committed to the design of small-scale wind turbines to meet the monitoring needs of the trackside or tunnel. Tran et al. [135] established a co-simulation model of wireless sensor network (WSN) with a plastic four-bladed horizontal-axis wind turbine [136] in the application scenario of a subway tunnel. Gao et al. [137] tried to capture train-induced wind energy using turbines and vortex-induced vibration using piezoelectric cantilever beams. In field tests, the piezoelectric cantilever beam mounted on the rail of turnout area generated a peak-peak voltage of 1 V when the bluff body train ran at the speed of 5 m/s. Simultaneously, horizontal-axis wind turbines and vertical-axis wind turbines achieved optimal powers of 5 W and 110 mW, respectively, with a 1:20 train model at 10 m/s. Pan et al. [138] proposed a portable wind energy harvester integrated with an S-rotor and H-rotor to capture the natural wind energy as well as piston wind energy in high-speed railway tunnels. The working principle is shown in Fig. 17. The S-rotor is rigidly connected to a shaft, while the two one-way bearings are arranged between the H-rotor and the shaft. In low-speed wind, the concave section of the S-rotor provides a higher torque driving the S-rotor and generator to rotate CCW. The one-way bearings are disengaged with the H-rotor. When high-speed trains pass

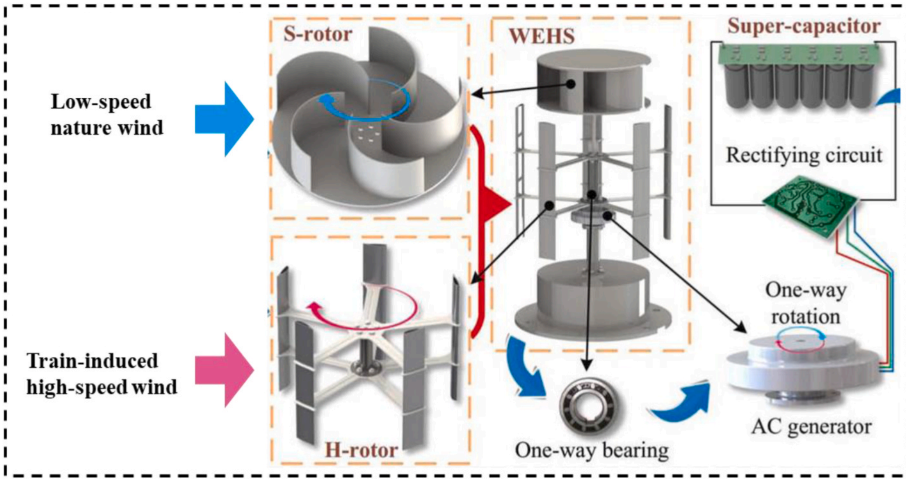

Fig. 17. Work principle of the portable wind energy harvester integrated with S-rotor and H-rotor [138].

the tunnels, high-speed airflow is caused by the piston effect. The H-rotor is driven by a higher speed than the S-rotor. Then, the one-way bearings are engaged and transmit the wind energy to the S-rotor. When the wind speed was 11 m/s in a wind tunnel test, a full-size prototype achieved a maximum power of 107.76 mW and 23.2% system efficiency with an external resistance of 8 Ω.

TENGs, with the superiorities of high efficiency, portability, and low cost, have set off a new wave of research in wind energy harvesting. They make up for the low efficiency of traditional wind turbines in the breeze, providing a novel option for low-powered self-powered systems. The first type of TENGs for wind energy harvesting is based on the flow-induced vibration principle, which converts wind into aerodynamic vibration including vortex-induced vibration, flutter or galloping by specific structures [139,140]. The second type of TENGs is usually equipped

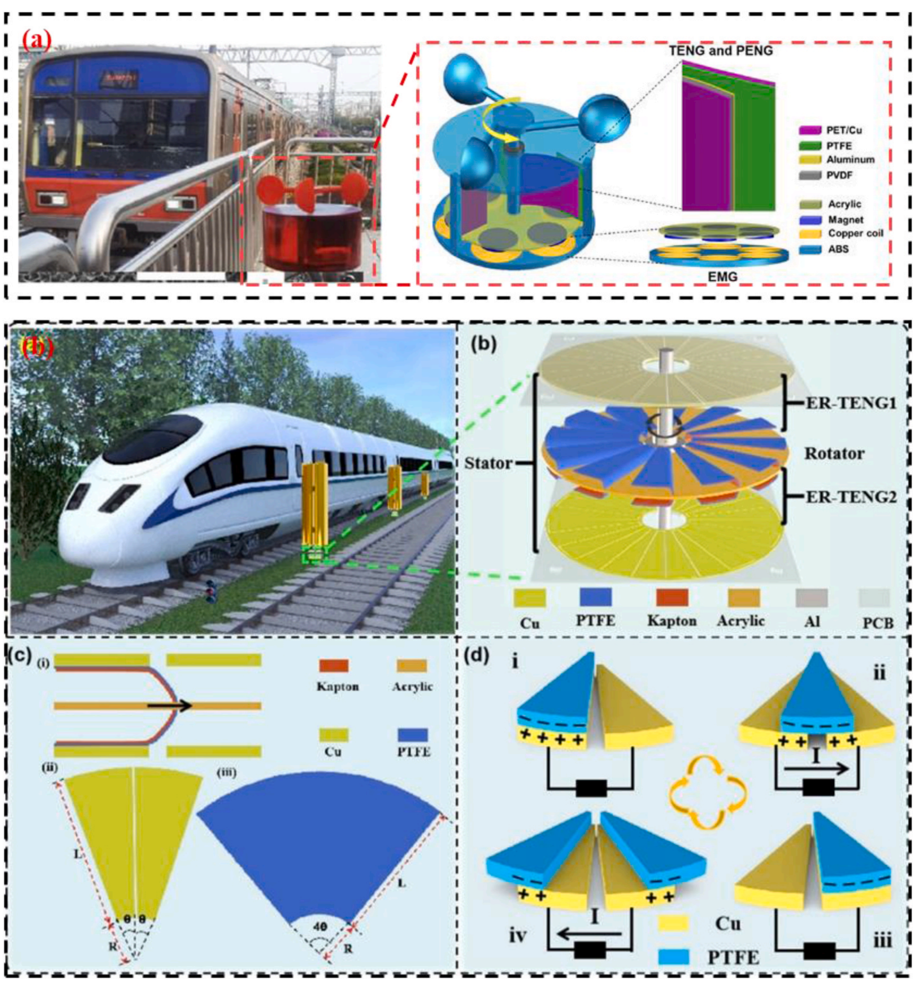

Fig. 18. TENG for railway wind energy harvesting. (a) 3D-printed hybrid miniaturized windmill nanogenerator proposed by Rahman et al. [142], (b) TENG with lateral-sliding configuration proposed by Wang et al. [143].

with wind wheels or wind cups to capture wind, and contact-separation or lateral-sliding of triboelectric elements is realized by rotary structure [141]. Currently, TENGs for wind energy harvesting in railway applications mostly adopt the second scheme. Rahman et al. [142] developed a 3D-printed hybrid miniaturized windmill nanogenerator for self-powered applications in subway tunnels, as shown in Fig. 18(a). The top wind cups are exploited to convert the wind flow into the rotation of a rotator shaft. The flexible rotor blade fixed on the rotator shaft is a PVDF film put on polyethylene terephthalate (PET) substrate. The polytetrafluoroethylene (PTFE)–PET stator plates are evenly arranged around the rotator shaft. The rotor shaft is also equipped with an acrylic plate with several fixed magnets, and the copper coils are fixed on the base for electromagnetic induction with magnets. When the flexible rotor blade rotates and interacts with the surrounding PTFE-PET stator plates, the nanogenerator generates electricity with collaborative work of triboelectric, piezoelectric, and electromagnetic effects. In the lab tests with a wind speed of 6 m/s, three parts achieved a maximum power of 1.67 mW, 1.38 mW and 268.6 mW at an external load of 10 MΩ, 330 kΩ and 180 Ω, respectively. Wang et al. [143] proposed a TENG harvesting energy from wind induced by high-speed trains. Notably, the vital components of the harvesting device are based on the lateral-sliding configuration, which was first proposed by the author's group in 2013 [144]. As illustrated in Fig. 18(b), the top and the bottom of the double-layer symmetrical structure are two printed circuit boards with 12 pairs of the Cu electrodes attached. The stator is an acrylic disc with 12 separate PTFE and Kapton films embedded. When the PTFE film is sliding relative to the Cu electrode, the charges flow between two Cu electrodes, thus generating a current. When the PTFE film coincides with Cu electrode, the charge exchange is completed, and no current is generated. The TENG was combined with the vertical blades to validate the performance. In the simulated wind of 20 m/s, the double-layer elastic rotation TENG realized an average power of 9.5 mW with a loading resistance of 50 MΩ. Importantly, owing to reasonably selected materials and elastic structure design, the novel design is characterized by doubling the energy efficiency and quadrupling the durability of conventional rotation sliding TENG.

4.2. Solar energy harvesting

Similar to wind energy, solar energy is ubiquitous in nature and has considerable energy potential. Based on the photovoltaic (PV) effect [145,146], the conversion from solar energy to electric energy can be realized. In 2011, a PV system with an area of 3846 m^2 mounted on the roof of a Tokyo station generated an annual power of 340 MW, which is about 0.3% of the energy consumption of the station [147]. Alam et al. [16] designed a solar-piezoelectric hybrid power system for railway stations, which can theoretically drive a 10 kW load for 10 h a day. Bharat Heavy Electricals Limited (BHEL) developed a PV system with 1.7 MW power for Indian railways, which is connected to a traction substation and helps power train traction. Kameya et al. [148] proposed an energy storage and rapid charge system for the solar light rail. PV panels on the station roof and the nearby wind turbines convert solar and wind energy to electricity stored in the primary electric double layer capacitor (EDLC). When the train passes by, the secondary EDLC aboard will be rapidly charged by the primary EDLC.

The onboard applications of PV systems have also been evaluated [149–151]. Vasisht et al. [152] conducted a feasibility study of PV modules mounted on the roof of rail coaches. The test coach retrofitted with two PV modules ran at 120 km/h (75 mph), coupled with three popular trains in south India. It is estimated that 18 kWh was generated a day, resulting in a diesel saving of about 1700 L every year. The train with 100 solar panels can achieve no need for additional power from the national grid in the UK. Wei et al. [153] designed an auxiliary power supply system for railway trains taking the installation of PV panels, MPPT algorithm and system energy management into consideration. These studies indicate that the applications of PV systems are capable of producing a notable economic impact as well as the ecological one.

The photovoltaic noise barrier is a reliable application scenario for PV technology, realizing noise reduction and power generation simultaneously. The feasibility and economic benefits of photovoltaic noise barriers have been verified [154,155]. Gu et al. [156] proposed a photovoltaic noise barrier with a length of 360 m along the Chinese metro railway, and realized an electricity production of 5000 kWh annually.

Darby et al. [157–159] designed a monitoring system using solar cells to measure parameters like bogie suspension displacement, side frame acceleration, brake pipe pressure, drawbar force and the location of freight wagons. Liu et al. [160] developed an online monitoring system for rail vibration signals in remote areas using solar batteries to improve the system service life. Hao et al. [15] proposed a portable solar energy harvester with foldable-wings mechanism for trackside self-powered applications, as shown in Fig. 19. The harvester controls the folding and unfolding of the mechanism according to weather and day and night conditions detected by the photosensitive sensor and pressure sensor mounted on the solar panel. An expansion DC motor works to shrink or expand the expansive PV panels. The rotation motor is used to control the rope retractor to realize the folding and unfolding of the harvester. This structure can reduce the dust accumulation on the surface of solar panels, thus avoiding performance degradation and extending the life of the harvester. In past experiments, this harvester achieved a maximum power of 10 W at a resistance of 5 Ω, which is enough for some low power devices.

4.3. Thermoelectric energy harvesting

Thermal energy can be easily ignored in vehicle-track systems. From the perspective of the vehicle, abundant waste heat due to friction and power loss is produced and dissipated around several components such as axle boxes, friction dampers, brake discs or shoes. As of now, a considerable part of freight and passenger locomotives are still powered by diesel engines. The reasonable conversion and utilization of diesel engine exhaust heat will not only improve the efficiency of the power system, but also alleviate some environmental issues to a certain extent. Heghmanns et al. [161,162] optimally designed an exhaust heat harvesting system for fuel engine of railway locomotives. The analysis results showed that a maximum fuel saving of 0.7% can be achieved. The exhaust heat harvesters have no practical railway application case yet, but have been proven effective by experiments in the automotive industry [163].

In addition, the intensity of solar radiation is different between the railway track and the substratum below the track foundation resulting in a natural temperature difference available for power generation. Hence, effective thermal energy harvesters are of great significance in promoting energy sustainability. Thermal energy harvesting has been considered as a promising way of energy conversion [164] and extensively investigated. According to the thermal characteristics and application scenarios of railways, the current research mostly focuses on thermoelectric generators rather than pyroelectric generators, which harvest energy from the temperature gradient in space and time domains, separately.

Ahi and Choi proposed a TEG converting the temperature gradient between the surface of axle bearing house and outdoor air into electricity [165]. In the author's previous research, the temperature difference between them is about 15 °C [166] when the vehicle is running. Considering installation space constraints, a 20 × 20 cm^2 commercial thermoelectric module was selected for the whole thermoelectric system. The thermoelectric energy harvesting system (TEHS) is illustrated in Fig. 20. The heat sink with the optimal cooling fin transfers the heat of the cold side to maintain temperature difference on both sides, providing a favorable condition for power generation of TEG. The outside frame protects the cooling fins from external impact when the train runs. The TEHS was mounted on a high-speed train and the field

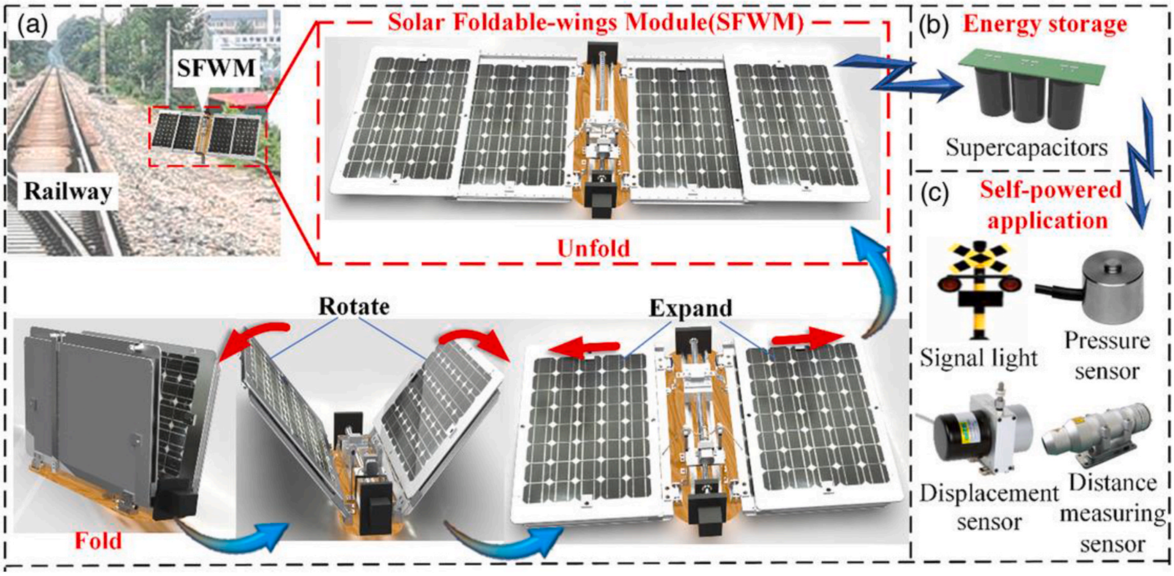

Fig. 19. Overall scheme of the portable solar energy harvester with foldable-wings mechanism for trackside self-powered applications [15].

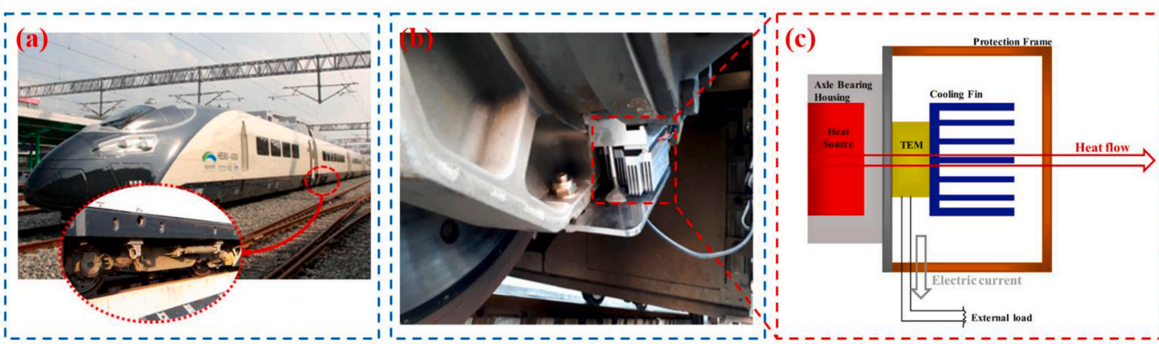

Fig. 20. TEG converting axle bearing house heat for power generation [165]. (a)field test with TEHS mounted on a high train, (b) detail view of TEHS installation under axle bearing house, (c) structure and working principle of TEHS.

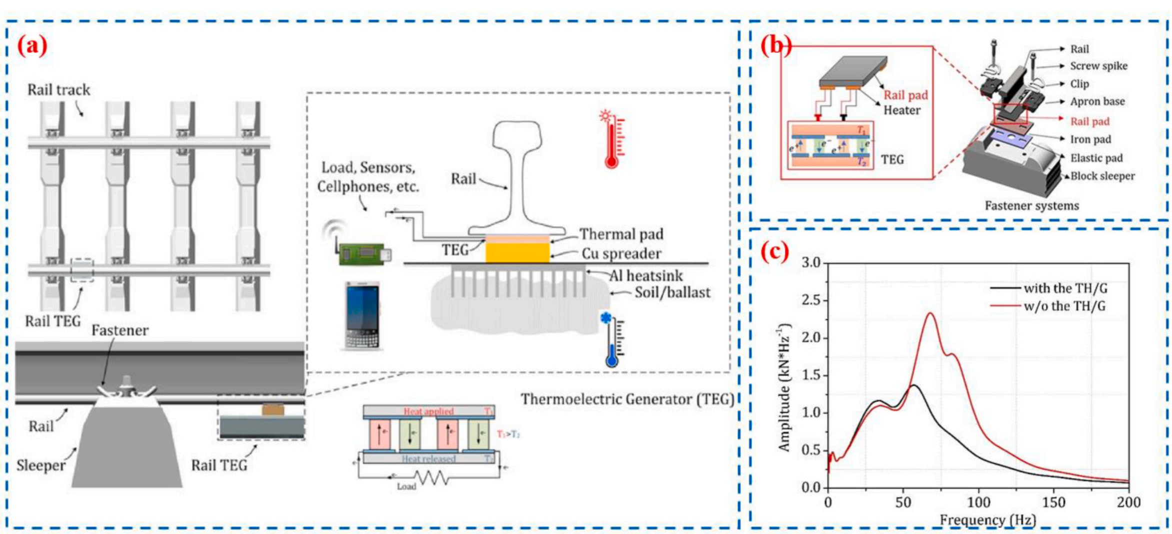

Fig. 21. TEG utilizing the temperature gradient between rail and soil. (a) TEG design and application scenarios [167], (b) novel railway fastener system integrated with TEG, (c) comparisons of wheel-rail contact force with and without TEG [169].

tests were performed on a test track with a maximum driving speed of 300 km/h (186 mph). An open circuit voltage of 0.4 V was generated when the maximum temperature of the axle bearing house was 38 °C. In addition, the authors predicted a maximum of 19.3 mW can be achieved with 1.9 Ω external resistance at 0.192 V based on the measured axle bearing house temperature curve during Osong–Dongdaegu operation.

Gao et al. [167] collected rail and surrounding infrastructure temperature data of one station of the Shanghai-Hangzhou high-speed railway line for one year. They found that the maximum temperature the rail can reach is above 55 °C in summer. In Ref. [168], the maximum soil temperature with a depth of 20 cm from July to August is about 25 °C, which means a temperature gradient of at least 30 °C is available between the soil and rail. Hence, a TEM was developed and installed between the rail bottom and soil/ballast to generate electricity. As shown in Fig. 21(a), thermal pads are placed on both sides of the square TEG, and the lower thermal pad can reduce the contact thermal resistance between TEG and Cu spreader. Cu sprayer and Al heatsink with high thermal conductivity are helpful to heat dissipation of TEG at low temperature side, so as to maintain the temperature difference between the two sides of TEG. In field tests, the maximum electrical power was about 5.8 mW with an optimal external resistance of 7 Ω in a temperature gradient of 8 °C. Laboratory tests were conducted to further tap the potential of TEG in railway track thermoelectric energy harvesting. At a temperature gradient of 29.2 °C, a power of 316.8 mW was delivered through a resistance of 9.6 Ω. In addition, a DC-DC buck-boost circuit for TEG with an open voltage of 0.9 V realized a conversion efficiency of above 60%.

In extremely cold areas, the vibration reduction ability of rail pads gets worse, which may be a potential threat to the normal operation of the railway. Yang and Gao [169] considered that the TEG they proposed can alleviate this phenomenon. A novel railway fastener system integrated with TEG is shown in Fig. 21(b). The TEG with the size of 54 × 54 × 40 mm converts the temperature gradient between rail and soil, then heats rail pads. In several lab tests with the ambient temperature changing from −20 to −5 °C, the temperatures of rail pads heated by 4 TEGs were increased by about 9 °C. In addition, the dynamic simulation results indicated that the fastener system reduced the vibration of the vehicle-track system by 41.5% in extremely cold areas.

4.4. Magnetic field energy harvesting

In an electrified railway, traction current flows back to the traction substation through the rails. The AC traction current produces a varying magnetic field around the rail. The coil induces AC current in the varying magnetic field based on Faraday's Law, which is the basic principle of magnetic field energy harvesting. To scavenge this untapped energy source, Kuang et al. [170] proposed a magnetic field energy harvester for powering wireless sensors. The harvester placed below the rail is formed by two magnet flanges with a large surface, a magnet rod, and the coil wrapped around the rod, as shown in Fig. 22(a). The two flanges and one rod function as flux collectors, which partly enclose the rail, and concentrate more flux through the coil under the high strength varying magnetic fields around both corners of the rail foot. This structure greatly improved the effective permeability and output power, generating an average power of 5.05 W with a distance of 48 mm to the rail carrying a 520 A/50 Hz current.

Radio-frequency (RF) energy harvesting can also be classified as magnetic field energy harvesting. RF is a kind of high-frequency AC current. When the frequency of the generated magnetic field is over 100 k Hz, it can be spread in the air to achieve long-distance transmission. RF identification (RFID) is a common application of RF energy harvesting technology. It is a widely applied method to identify objects [171], which usually is formed by a reader, a tag and antennas [172]. Li et al. [173] presented a track monitoring system based on RFID technology to reduce the maintenance costs of tracks. A battery-less sensor tag is designed for harvesting RF energy from the reader mounted on the train, then returning the measured rail vibration data to the reader by wireless transmission. This tag can be activated at a maximum distance of 2.3 m and achieve a maximum energy conversion efficiency of 25% and corresponding power output of 0.33 mW.

4.5. Acoustic energy harvesting

With the rapid expansion of the railway network, its impact on the surrounding environment has gradually drawn the attention of researchers. Especially when a high-speed train is passing by, the subsequent aerodynamic noise and rolling noise have become an obvious

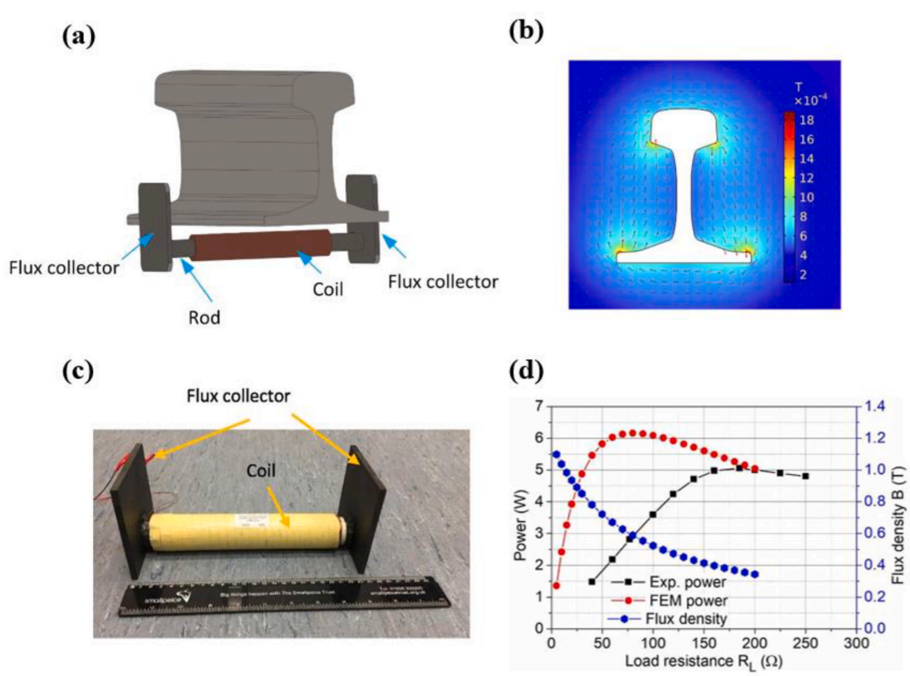

Fig. 22. Magnetic field energy harvester for varying magnetic field generated by rail AC current [170]. (a) Basic structure and application scenario, (b) the magnetic flux density generated at the rail current of 300 A and 50 Hz, (c) magnet field energy harvester prototype, (d) the performance of harvester versus load resistance.

environmental issue [174]. Meanwhile, noise reduction in high-speed train cabins is also very important to improve passenger comfort. Acoustic energy harvesting is possible by acoustic resonators and transducers. Apart from absorbing the acoustic components of some specific frequencies, acoustic resonators can also be used for sound pressure amplification for some frequency bands [175].

Noh et al. [176] measured the noise level and investigated the noise characteristics inside the high-speed train. It was found that a low frequency noise of 50–100 Hz mainly exists in the cabin and between vehicles. A Helmholtz resonator (HR) was designed to amplify the sound pressure at a specific frequency of 174 Hz. The rectangular piezoelectric element with an area of 3.5×10^{-3} m^2 in HR generated a peak power of 0.7 V at the cavity vibration. Wang et al. [177] presented an acoustic energy harvester integrated with an HR and a PVDF film to solve the noise problem around the railway as well as scavenging sound energy for electricity generation, as illustrated in Fig. 23. The HR amplified the sound pressure by 20.86 times at 447 Hz. The PVDF film is placed at the bottom to convert the incident acoustic energy. A maximum power of 1.24 μW at 74.6 mV was obtained at the sound pressure level of 110 dB in lab tests. A 1.5×1.3 m^2 noise barrier manufactured by the authors can achieve a voltage of 35.8 V under the same working conditions.

From the perspective of power generation only, the power density of piezoelectric components under acoustic vibration is far worse than that under direct vibration. Hence, acoustic energy harvesting for railway self-powered applications needs to be further considered and validated.

5. Summary, comparison and discussions

The gradual maturity of energy harvesting technology provides many options for dealing with various energy sources in railway system. Table 4 summarizes and compares the performance of different technologies when dealing with the same or different energy sources.

The design of low-power and middle-power energy harvesters is mainly concentrated on vibration-based energy harvesters. Due to the random broadband characteristics of railway vibration, appropriate structural design to improve efficiency is the main research point. For PE-VEHs, a high open circuit voltage can be easily obtained. However, the actual power that can be extracted is very low because of the high output impedance. A piezoelectric cantilever is a relatively mature structure, which can obtain power at the milliwatt level. There is still a gap from the practical application. By using a drum piezoelectric transducer array, the generated power can be over 100 mW [84], which is considerable for low-power monitoring. The high-power density of PE-VEHs makes it more advantageous in space-limited environments. In addition, it is a feasible scheme to design the piezoelectric transducer array to achieve enhanced performance. As opposed to piezoelectric elements, electromagnetic energy harvesters are featured with low impedances, which is conducive to the extraction of energy. Linear EM-VEHs with spring-resonant configurations possess a larger peak power in resonance, but the continuous output capacity cannot be guaranteed. Nonlinear EM-VEHs with magnetic suspension structures present a wider effective frequency band due to interactions between the magnets. Based on the optimization of the above two structures, the multi-DOF and multi-stable system further broadens the frequency band, and has a relatively stable and continuous output capacity, which is reflected in a higher output power under real rail/vehicle vibration. The EM-VEHs offer a more reliable solution for scavenging railway vibration.

The small-scale EM-VEHs generally exhibit a higher power performance compared to PE-VEHs. However, it is noted that metallic environment should be avoided due to the existence of moving magnet. For rotary EM-VEHs, the simplification and efficiency improvement of MMR is the core issue. Some field tests verify the effectiveness of the rotary device. They possess a high-power output above 1 W, but high manufacturing costs. Hence, this type of harvesting is suitable for power supply of trackside devices such as signal lights and switches, or acts as the distributed power supply of unpowered freight cars to promote more onboard applications of advanced devices.

Thermal energy harvesting is mostly based on TEGs in the environment with a temperature gradient. It has the advantages of high efficiency, simple structure, easy installation, etc., but the application scenarios are limited. The onboard device heat/exhaust and braking temperature rise can be the energy sources. In addition, the temperature gradient between the track and the soil can also be tapped.

Solar and wind energy harvesting have been very mature schemes. The high-power harvesters are enough to supply power for train traction, and the low-power ones can be arranged for self-powered monitoring. For high-power solar and wind power plants, although the construction costs are very high, they will still bring considerable economic effects according to a large number of investigations. The unpredictability of wind and solar energy harvesting is mainly affected by the weather. Moreover, the actual performance of the solar harvester will be severely degraded due to surface dust, and there is no power output at night.

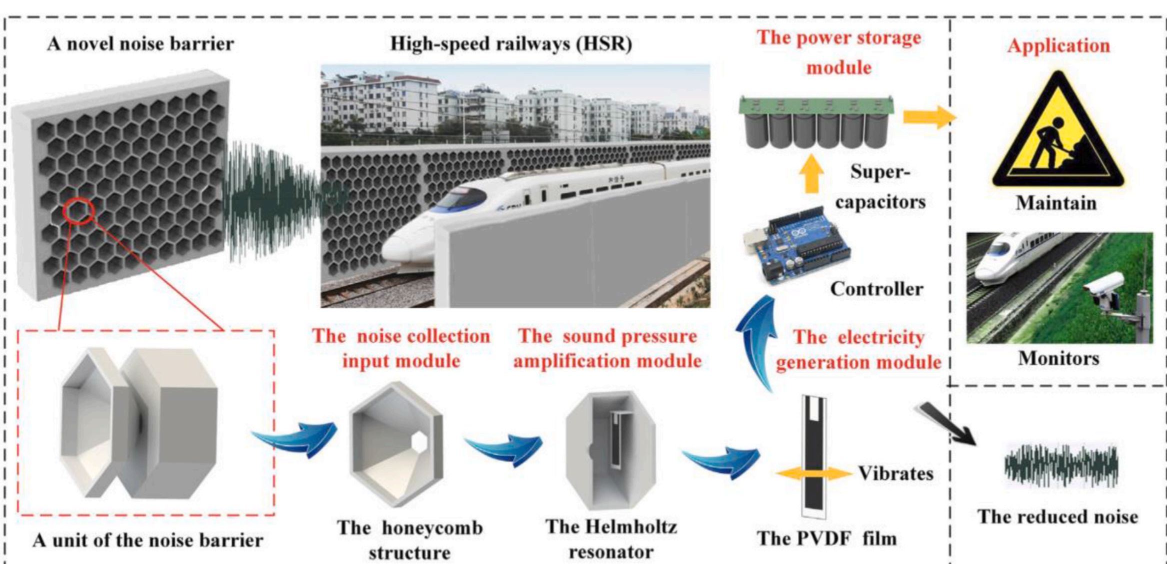

Fig. 23. Overall scheme of the acoustic energy harvester integrated with a HR and a PVDF film [177].

Table 4
Summary and comparisons of energy harvesters based on different principle for railway industry.

Energy source	Transduction	Power [mW]	Power density [W/m^3]	Advantages	Drawbacks
Vibration energy	PE	1.6×10^{-4}–100	0.36–10^4	High output voltage, high power density, low cost, simple design, easy to install	Large output resistance, low output power, poor reliability
	EM (linear)	4–3.53×10^4	10.64–176.5	Low output impedance, high peak power, simple design, easy to install, good reliability, low cost	Performance degradation when not resonant, avoid metallic environment
	EM (nonlinear)	0.24–2×10^3	1.74–481.44	Broadband, low output impedance, high power under rail or vehicle vibration, easy to install, good reliability, low cost	Performance degradation when not resonant, avoid metallic environment
	EM (rotary)	32–3.06×10^5	380.5–4.23×10^3	High output power, high efficiency	High cost, large volume, difficult to install, complex structure
Thermal energy	TEG	19.3–316.8	55.84–132.41	High efficiency, low output resistance, low cost, easy to install, simple design	Fewer scenarios for installation, extra cooling structure
Wind energy	EM	> 100	/	High output power, low installation requirements, mature technology	High construction cost (for large- scale), affected by the weather
	PE[b]	/	/	Simple design, easy to install, low cost	Low output power, poor reliability, work only when trains pass by
	TE	9.5	/	Power generation in the breeze, high output voltage, low weight, low cost, easy to install	High impedance, low output current, affected by the weather
Solar energy	PV	> 10^4	/	High output power, low installation requirements, mature technology	Affected by the weather, no power at night, surface dust affects output.
Magnetic field energy	EM	5.05×10^3	2.1×10^3	High output power, low cost, easy to install	Only suitable for electrified railway, installation distance limit
	RF	0.33	/	High integration, good reliability, long distance information exchange	Complex design, high equipment sensitivity requirements
Acoustic energy	PE	1.24×10^{-3}	/	Power generation as well as noise reduction	Combined with acoustic resonators

PE: piezoelectric, EM: electromagnetic, TEG: thermoelectric, PV: photovoltaic, TE: triboelectric, RF: radio frequency.
[b] A peak-peak voltage of 1 V was obtained when the train with bluff body ran at the speed of 5 m/s.

Apart from electromagnetic principle, wind energy harvesters based on triboelectric effect have been proven to be feasible for some low-power sensors and devices, which possess the advantage of power generation in the breeze. Another method of wind energy utilization is to generate electricity by wind-induced vibration. From the current research results, the performance of piezoelectric transducers under wind-induced vibration is not ideal.

The concept of magnetic field energy harvesting was proposed later in the railway field. The energy harvesting of the alternating electromagnetic field around the rail provides a new idea for the power supply of trackside devices, but the application scenario is limited to the electrified railway. In addition, RF energy harvesting can be considered as a high-frequency magnetic field energy harvesting, which has certain application potential in maintenance-free monitoring of railway tracks. However, RF energy harvesters depend on the performance of the devices, and the design is complex. At present, magnetic energy harvesters are designed and applied to specific applications, and related research is rare in the railway field.

The acoustic energy harvester can scavenge sound-introduced vibration energy as well as noise reduction at the sub-microwatt level. The design of an acoustic energy harvester needs to be optimized by combining the characteristics of acoustic resonators with energy harvesting technology.

Different energy harvesting technologies have their own advantages and disadvantages. During the design of energy harvesters, the most reasonable scheme should be determined according to the application scenario and power demand. In addition, hybrid energy harvesting can be adopted to achieve higher output power and higher space utilization when multiple energy sources exist.

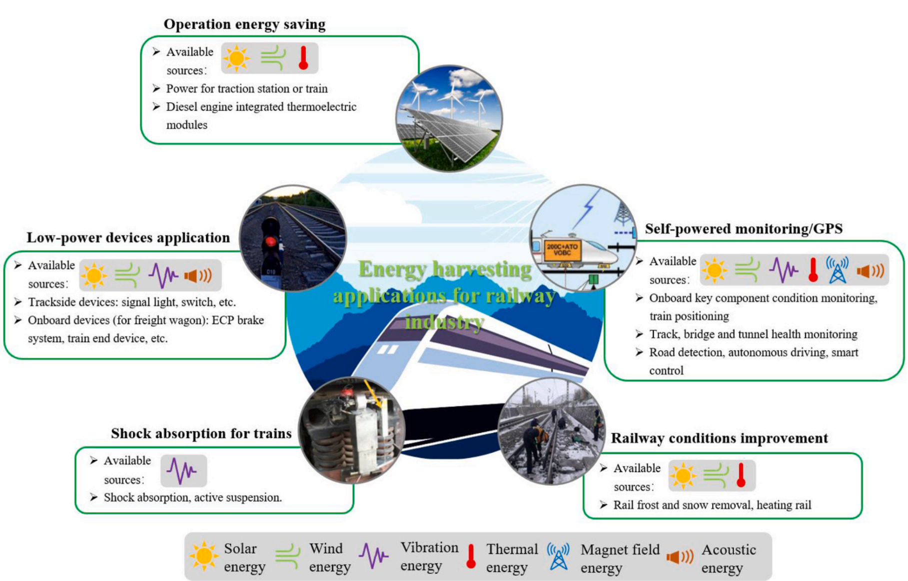

Fig. 24. Application prospects of energy harvesting technology in railway industry.

6. Application prospects in railway industry

This section mainly discusses the application prospects of energy harvesting technology in the railway industry. Most energy harvesters mounted on trackside or railcars convert ambient available energy into electricity, providing power for large railcars or traction substation operation, and small amounts of power for sensor nodes or GPS self-power. Moreover, the functions of energy harvesters are more than power supply in some applications. As shown in Fig. 24, the potential application scenarios will be exploited from the aspects including operation energy saving, self-powered monitoring/GPS, railway conditions improvement, low-power devices application and shock absorption for trains.

6.1. Operation energy saving

The world railway network is in a stage of rapid expansion, and energy consumption is a concomitant problem. Wind energy and solar energy are becoming the cheapest energy sources gradually due to the maturity of technology. They widely exist in remote areas and can relieve the pressure of railway power supply. The high-power solar and wind power stations can be constructed around traction substations or along the track sides, feeding energy back to the substation or traction grid. The onboard installation of PV panels or wind turbines can directly provide electricity for the train operation. However, the impacts on train operation need to be analyzed in detail. From the perspective of railway car operation energy saving, thermoelectric energy harvesting also presents great potential. A TEG integrated with a diesel engine can be applied to exhaust gas utilization of diesel-electric locomotives to realize fuel saving [161,162].

The clean and renewable energy converted and utilized by energy harvesting technology will greatly promote low-carbon railway transportation. Meanwhile, the economic benefits are quite considerable in the long term. Hence, more expandable space should be reserved for energy harvesting in future railway construction.

6.2. Self-powered monitoring

Intelligent railway, autonomous driving, and Internet of Things (IoTs) are current trends for railway transportation. Abundant sensors and small-scale electronics are embedded in key components of trains and placed around rail to realize real-time monitoring and information interaction. Energy harvesting by using local energy sources provides a better solution for distributed sensor placement to deal with inconvenient power supply and complicated wiring. For tracks, bridges and tunnels in remote areas, most of the monitoring systems are powered by batteries. They need to be replaced manually at intervals, resulting in a lot of labor maintenance costs. Hence, self-powered health monitoring is necessary to reduce manual maintenance and avoid accidents. Real-time onboard monitoring is still a challenge for unpowered freight wagons [178]. Schiavo et al. proposed a fully automatic WSN for freight wagons where the energy consumption of nodes was designed below the performance of some classic VEHs (40–100 mW) [179], which indicates that the energetically autonomous WSN nodes can be implemented based on existing energy harvesting technology.

Due to the development of sensors and low-power communication technology, the power demand of wireless network nodes is commonly at the milliwatt level [97]. Therefore, most energy sources with proper conversion can meet the power of low-power monitoring. Many energy harvesting technology options provide a more robust solution for intelligent monitoring and capitalize on the natural advantages in some specific scenes such as the bridge with violent vibration, the tunnel with severe wind, etc.

6.3. Railway maintenance improvement

The state of rail is closely related to the operation of railway trains. When the snow comes, the adhesion coefficient of the track will decrease, and the traction and braking performance of the train will be affected. In addition, the track will rise and shrink seasonally with climate change. In extremely cold areas, the mechanical properties of rail will deteriorate obviously, increasing the probability of track material damage and failure [180,181]. According to the investigation, about 60% of the track fracture occurred in winter. Track snow removal in remote areas inevitably faces high maintenance costs. The snow removal devices demand a large and continuous power supply in extremely cold weather, which should be powered by solar or wind energy to effectively prolong the battery replacement cycle or fully realize self-power. Apart from solar and wind energy, the gradient between the track surface and the soil offers another option. TEG converting the thermal energy into electricity and heating the rail may improve rail temperature to a certain extent [169]. However, whether the heating system has a negative impact on the rail needs to be further studied.

In addition, Wheel-rail lubrication is also very essential for railway maintenance. The railway lubrication station powered by renewable energy is also a manifestation of the contribution of energy harvesting technology to railway maintenance improvement.

6.4. Low-power devices applications

Energy harvesting technology is enormously helpful in improving power supply solutions of existing low-power devices and promoting novel applications in railway. Railway trackside is usually equipped with signal lights and switches to ensure the normal operation and scheduling of trains. Based on solar energy, wind energy, vibration energy, acoustic energy and other resources, the energy harvesters arranged nearby have enough capacity to meet their daily energy consumption.

Standard freight wagons are only equipped with pneumatic pipelines for braking and without electrical pipelines, which has restricted the application of smart devices aboard for a long time. The basic monitoring requirements of freight wagons are realized by low-power wireless communication technology powered by batteries. To improve transportation efficiency, freight cars are required to be faster and carry heavier loads. Because the traditional air braking system transmits the brake command through the air, there will be a time difference between when each wagon receives the signal in the long-group freight train, resulting in braking inconsistency. This brake inconsistency will be reflected in the large coupler force, which will eventually result in coupler fracture. The electronically controlled pneumatic (ECP) brake system is considered as an alternative. The electric signal transmission can realize almost synchronous braking and release of each wagon, effectively relieving the brake inconsistency. However, the power of the ECP braking module on each wagon is about 24 W, which is a challenge for unpowered wagons. The axle generators and rotary EM-VEHs with mechanical conversion mechanisms are feasible in existing energy harvesters [107,182]. They can work as the distributed power supply for wagons converting the kinetic energy or vibration of the wagon into electricity, and can generate power ranging from tens of watts to hundreds of watts. Not only that, but the long-term power problem of wagon monitoring and train end device can be solved by nearby energy supply. Moreover, the installation of PV panels and wind turbines on the wagon can be supplemented as an alternative power supply means.

6.5. Shock absorption for trains

Shock absorption is very important to ensure the safety of high-speed train operation, improve ride comfort and reduce maintenance costs [183]. The shock absorbers are usually installed on the bogie to reduce vertical and horizontal vibration. Due to the difficulty of customization of bogies and the limitation of railway gauge on additional devices installed on bogies, the application of VEHs with shock absorption effect is hindered. Most VEHs for railcars are designed with the goal to act as an economic power supply, and avoid affecting the original dynamic characteristics of the vehicle-track system. In reality, the existing rotary EM-VEHs can obtain an equivalent damping exceeding 100 k Ns/m by mechanical structure amplification [117], which presents great potential in shock absorption. The concept of regenerative suspensions has been proposed in the automobile industry [184]. The energy-regenerative shock absorbers realize the shock absorption through the electromagnetic damping force of the generator; meanwhile, the heat energy which should have been dissipated in the conventional shock absorber is transformed into electricity due to the driven generator [185]. On this basis, active control method is proposed to further optimize the shock absorption effect [186,187]. The equivalent damping of shock absorbers is directly affected by the external circuits, so the design and control of circuits need to be a focus. In view of the similarities between automobile and train suspensions, the energy-regenerative and active suspensions for railway vehicles are promising.

7. Technical challenges, research gaps, and future directions

Wind and solar energy harvesting technology are mature and have been widely used. By contrast, vibration energy harvesting is still in the research stage, and there are still some challenges in practical application. In this section, we will discuss some technical difficulties for railway VEHs. According to the research progress and gaps of various energy harvesting technologies in railway field, some suggestions are given for future work.

7.1. Performance enhanced methods of VEH

Vibrations in the railway environment are characterized as broadband. The steady-state track vibration has a wide frequency band from tens to hundreds of hertz [77]. The track deflection induced by wheel-rail contact force is about 1–4 Hz with a displacement of 1–12 mm [116,188]. The dominant frequency of car-body vertical vibration of railway vehicles is generally concentrated at 1–3 Hz, and the dominant frequency of bogies ranges from 20 to 80 Hz [102,189,190]. In early research, the piezoelectric patches and voice-coil generator mechanisms were applied to track energy harvesting. Then, a structure of resonators for a specific frequency was proposed that can obtain high peak power in resonance conditions. One of the main limitations is poor performance when the excitation deviates from resonant frequency. To address this problem, broadband design is the hotspot of the current vibration energy harvesting. The systems with multiple degrees of freedom or multiple stability are the two main solutions after validation.

For energy harvesting systems based on the piezoelectric effect, the piezoelectric cantilever used as a mono-stable system, has been widely applied in the railway industry. Multi-DOF systems with multiple piezoelectric cantilevers in series are proposed in several other studies [78,83,90]. Through the design of different mass blocks and cantilever beam parameters, the response of multi-DOF systems features several different individual peaks, which effectively broaden the frequency band and improve the power performance in broadband excitation. For the purpose of being more applicable for broadband excitation environments, some advanced solutions, including bi-stable [191], tri-stable [192] and quad-stable [193] nonlinear configurations, have been proposed as shown in Fig. 25(b)-(d). The main feature of multi-stable structures is a ferromagnetic piezoelectric cantilever, which is a piezoelectric cantilever with a magnet attached at the end of the beam. One or more magnets are usually placed near the magnet at the end of the beam. With the nonlinear force induced by magnetic attraction and repulsion between magnets, there will be some potential wells in the potential energy function. The number of potential wells corresponds to the steady-state number of the system. The inter-well motions will lead to larger mechanical snap-through displacement, which presents a higher output performance. The nonlinear behavior of the multi-stable system is determined by the material, shape, and arrangement of the magnets. Multi-stable energy harvesters can also be built with pre-deformation or pre-loading [194].

Performance optimization of electromagnetic energy harvesters has

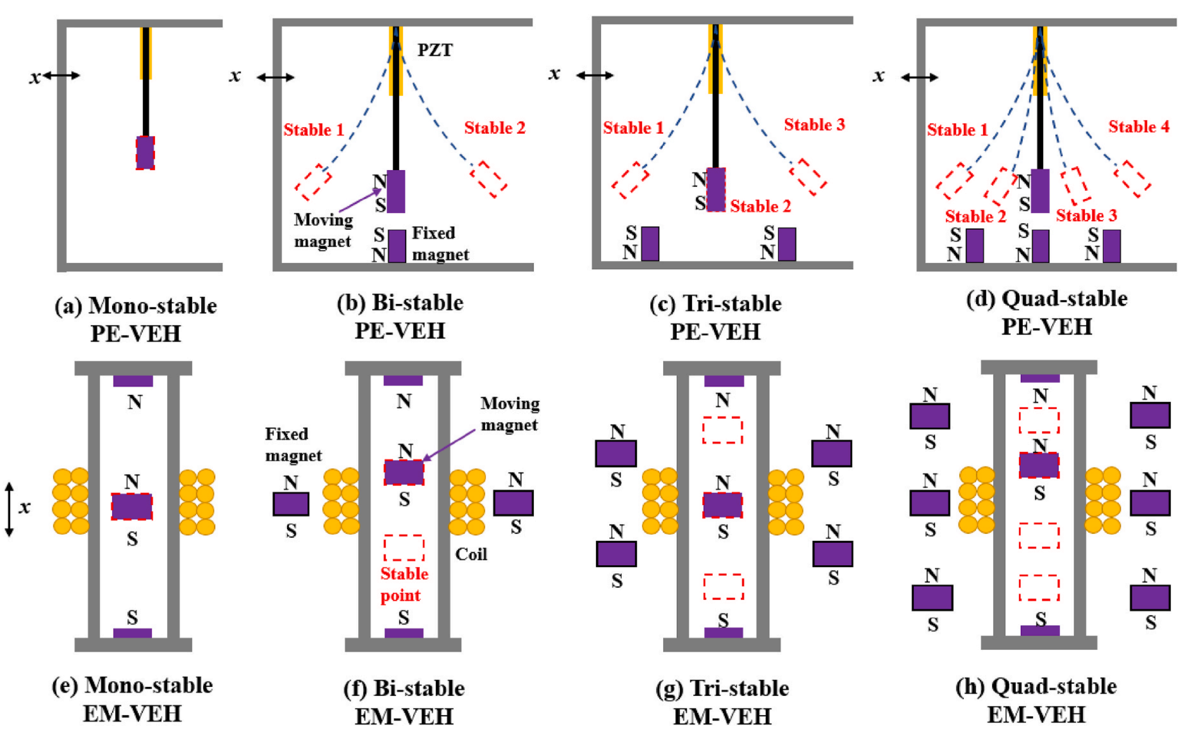

Fig. 25. Classical multi-stable structures of PE-VEH and EM-VEH.

been developed for linear and nonlinear types, respectively. For the linear harvester in the spring-resonant configuration, the multi-DOF systems are usually composed of several submodules [96,103]. Each submodule is tuned to an independent resonance frequency by optimizing the spring stiffness or mass. Then, the overall multi-DOF system possesses a good response in multiple different excitation frequencies. The concept of a multi-stable electromagnetic energy harvesting system has also been proposed in recent years. The performance of nonlinear electromagnetic energy harvesters based on magnetic levitation has been investigated in bi-stable [195], tri-stable [98] and quad-stable [33, 98] configurations based on the arrangement of outside fixed magnets. The basic structures of multi-stable systems are shown in Fig. 25(f)–(h). Compared with mono-stable systems, multi-stable systems have superiorities in frequency band and output capability.

For bi-stable systems, the best case is that the excitation can stimulate the motion between wells [196,197]. When the excitation frequency or amplitude is not large enough, the transition between steady states cannot be activated, and only intra-well oscillations will lead to a poor performance. It was proven that the efficiency of bi-stable systems was low with random unstable environment excitations [198]. The tri-stable and quad-stable systems have shallower potential wells, leading to inter-well oscillations more easily in the weaker excitation [199]. Generally, the lower the potential barrier, the easier it is for the multi-stable system to be involved in the inter-well oscillations, and the effective frequency range will be widened. Hence, the output performance in broadband excitation will be improved. One problem with the nonlinear energy harvester is there are generally high-energy and low-energy branches. How to maintain the vibration system in high-energy branch is a challenge.

A large part of the most advanced research focuses on the design of multi-stable energy harvesting systems. However, there are few reports about their application performance in the real world. Similar structures can be referred to and optimized to match railway environmental vibration in the future.

The core issue in the design of rotating EM-VEHs is the design of mechanical conversion mechanisms. Apart from a screw-nut mechanism and rack-pinion mechanism [200,201], both a two-leg mechanism and helical gear mechanism are proposed for the conversion from linear motion to rotary motion [202,203]. The mechanism that transforms bidirectional rotation into unidirectional rotation is called mechanical motion rectifier (MMR). A lot of early studies aim to simplify the structure of the MMR to obtain a higher mechanical efficiency. At present, a commonly used MMR can operate using several gears and two one-way clutches [116]. Similar structures have also been applied to the kinetic energy harvesting of ocean wave and human motion [204,205]. The mechanical efficiency of rotary EM-VEHs in the railway field can be over 70% in the existing literature [114]. In addition, a flywheel is added at the end of the generator to improve the output characteristics of the harvester, and thus obtain a more stable and continuous voltage output [115,117] which increases the amount of energy actually obtained due to the interface circuit with open voltage. The equivalent damping and output performance of this kind of harvester are positively correlated with gear ratio in most cases; however, clutch slips will occur under large torque due to too much harvester damping and lead to an abnormal drop of output power [116,117]. In the future, rotary EM-VEHs with higher efficiency and a more stable output are expected. Another main problem associated with EM EH is the friction in the powertrain. The friction and mechanical damping will increase with larger gear ratios. If we can reduce the friction by a factor of 2, we should be able to double the power output.

7.2. Research on interface circuits

The design of interface circuits is an important step in the practical application of energy harvesters. The output characteristics of energy harvesters are different due to different principles, which leads to a difference in interface circuit design. The design of the interface circuit follows the concept of maximum power point tracking (MPPT), namely, the matching between the external load and the internal resistance of the harvester.

For piezoelectric energy harvesters, Ottman et al. [206,207] tried to realize the load adaptation by tuning the duty-cycle or switching frequency, which proved that MPPT techniques were possible in circuit efficiency improvement. However, the required impedance to achieve maximum power for some transducers is unachievable [208]. It means that an induction needs to be connected to the piezoelectric element, which is not suitable in practical design due to the large required inductance value (about tenth of Henrys) leading to a bulky and inefficient inductor [209]. Subsequently, the concept of synchronous charge extraction (SCE) [210] was proposed by adding a small inductor and switch connected to the piezoelectric element. The switch is open most of the time during a vibration period and closed only when the voltage of the piezoelectric transducer achieves the maximum point. Then, the energy accumulated on the piezoelectric element is quickly transferred to the small inductor, which completes the energy extraction in a very short time. Using this structure, the extracted energy is almost unaffected by the load. On this basis, the researchers proposed some alternative schemes such as parallel synchronized switch harvesting on inductor (P–SSHI) [211,212], series synchronized switch harvesting on inductor (S–SSHI) [213,214] and synchronized switch harvesting on capacitors (SSHC) [215,216] to implement complex impedance matching.

For electromagnetic energy harvesters, Arroyo et al. [217] proposed a synchronous magnetic flux extraction (SMFE) interface circuit by referring to SCE structure. Tse et al. [218] designed an MPPT circuit to counteract the impact of the coil inductor and obtained a better performance compared to a purely resistive load.

The performances of the above interface circuits are reflected in sinusoidal excitation, which does not take random characteristics of railway vibration into account. Hence, Balato et al. [219] designed an interface circuit based on MPPT for onboard monitoring of freight wagons. The constant MPPT voltages corresponding to the maximum power are obtained based on vibration characteristics at different vehicle speeds. Then, the target voltage of the circuit can be determined by the signal of the external speed sensor and the MPPT voltage-speed curve, thus realizing the maximum power tracking. Costanzo et al. [220] customized an MPPT interface circuit based on a Speed Driven Adaptive (SDA) technique for the rotary EM-VEH mounted on the suspension of a freight wagon [117]. As shown in Fig. 26, the optimal voltage is obtained by multiplying the generator speed and the coefficient K_v. Because it is difficult to calculate, the optimal value of K_v is solved by a customized P&O MPPT algorithm. Then, the PI controller works to tune the duty cycle of DC/DC to ensure optimal voltage tracking. In time-varying suspension vibration, an average power of 1.1 W was obtained, 57% higher than that achieved by a common P&O algorithm. In addition, Costanzo et al. [221] proposed another MPPT scheme via an active AC/DC converter used for regenerative train suspensions. The optimal duty cycle for an active converter was demonstrated to be related to generator speed. The effectiveness was validated through lab tests where generator rotation was driven by a half sinusoidal signal. It is noted that the active AC/DC converter with complex control technologies usually leads to high control losses compared with the passive one. A more viable and promising active converter should combine with low power management techniques [222,223].

Overall, for low-power VEHs, an interface circuit with high efficiency is necessary for practical applications. The corresponding research is rare now, so it still should be concerned in the next work. For rotary EM-VEHs with tens of watts, MPPT technologies are feasible due to widespread applications in wind energy harvesting. They both generate electricity by driving rotary generators. Considering the fast time-varying characteristics of railway vibration, the calculation speed of the MPPT algorithm should be guaranteed for accurate tracking.

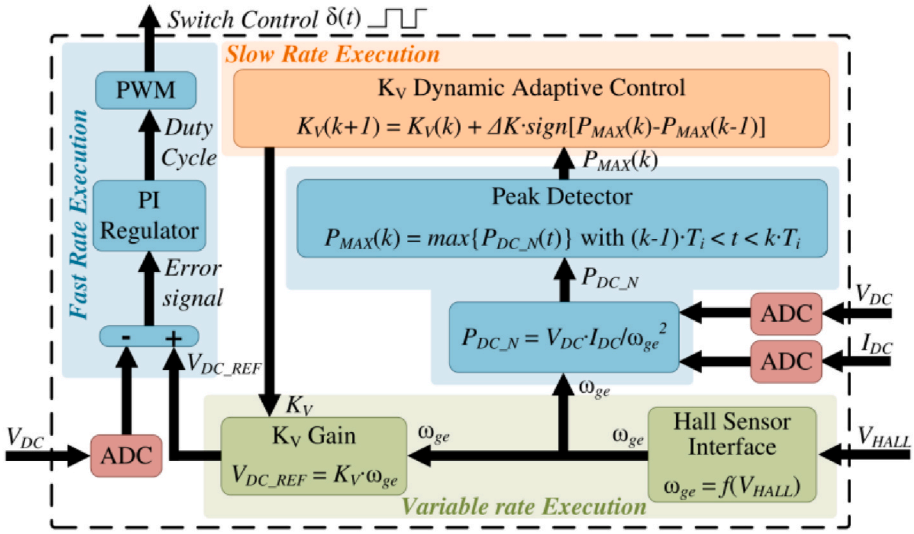

Fig. 26. MPPT algorithm of based on SDA for the rotary EM-VEH [220].

7.3. Coupled dynamics of VEH and vehicle-track system

In order to guarantee the safety of railway operation, it is necessary to explore the coupling dynamics of railway system with harvesters. For VEHs, whether one has onboard installation or trackside installation will have a different impact on the dynamic system of the vehicle or track. The analysis of coupling dynamics has two main purposes: (1) The real vibration and harvester performance in the coupling relationship can be revealed for guiding the systematic design of harvesters. (2) The influence on the original railway system and the safety of the harvester can be evaluated.

Wang et al. [71] installed in series a proposed drum piezoelectric transducer between the ballast and sleeper, and the transducer is equivalent to a spring connecting them in dynamic analysis. The rail-borne piezoelectric transducer proposed by Gao et al. [76] is rigidly connected to the rail web. The piezoelectric cantilever beam structure is regarded as parallel with the rail, and it serves as an additional mass and moment of inertia to the rail, as shown in Fig. 27(a). Then, Gao et al. [224] studied the influence of an electromagnetic energy harvester on vehicle-track systems by symplectic method and the same equivalence of the harvester to the rail was made. The results indicated that the installation of the harvester has no influence on the random vibration response of the vehicle and bogie, but has certain effects on the vibration of the wheelset and rail. After the harvester installation, the Power Spectrum Density of the acceleration showed a frequency shift of about 54 Hz at the dominant frequency of 730.2 Hz, and there is almost no change in the low frequency band below 200 Hz.

Pan et al. [116,117] conducted the dynamics analysis for the proposed two types of rotary EM-VEHs. The ball-screw-based one is mounted between two adjacent sleepers, as shown in Fig. 27(c). The harvester can be regarded as parallel with a sleeper, and equivalent to a constant inertia mass, a pre-loaded spring and an adjustable damping between track and foundation. The force of the harvester on the track can be expressed as:

$$\begin{cases} Fengage = m_e\ddot{x} + c_e\dot{x} + 2k(x+\delta_0) \\ c_e = \dfrac{6\pi^2 n_g^2 k_t k_e}{l^2(R_i+R_e)} \\ m_e \approx \dfrac{4\pi^2}{l^2} n_g^2 J_{ge} \end{cases} \tag{5}$$

where m_e and c_e are the equivalent mass and equivalent damping of

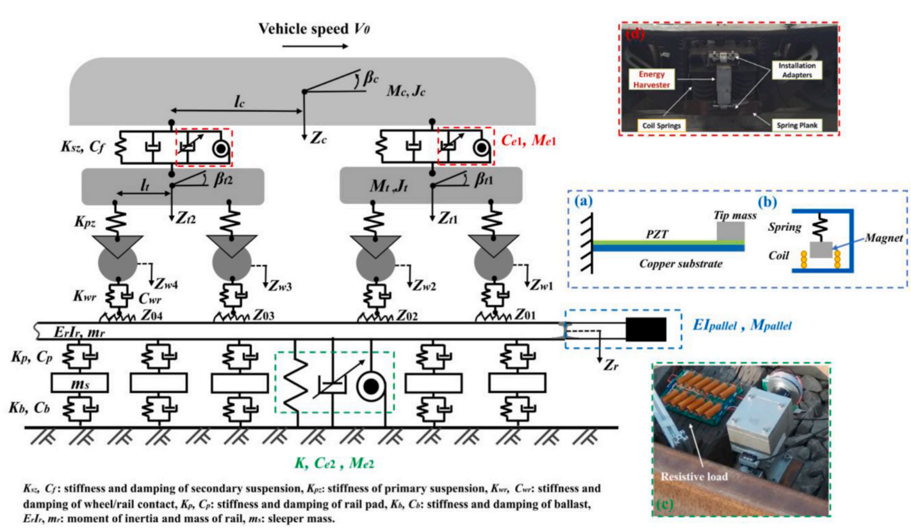

Fig. 27. Equivalent model of VEHs in vehicle-track coupling system. (a) Piezoelectric cantilever [76], (b) EM-VEH with spring resonant structure [224], (c) rotary EM-VEH based on nut-screw transmission [116], (d) rotary EM-VEH based on rack-pinion transmission [117].

harvester;x is the rail displacement; k is the pre-loaded spring stiffness; δ_0 is the pre-loaded length; n_g is the gear ratio under the mechanical rectifier and gear box; k_t and k_e are the speed and torque constants of AC generator; l is the ball screw lead; R_i and R_e are the single-phase resistance and external resistance of generator; and J_{ge} is the moment of inertia of generator.

Two harvesters with different gear ratios were designed. The one with a larger gear ratio achieved higher output power; however, it had a greater influence on the track displacement due to larger equivalent damping, which is consistent with the aforementioned equations governing the force of the harvester. The maximum RMS displacement difference at 80 km/h (50 mph) is about 3 μm, which has almost no effect on the dynamics characteristics of the vehicle-track system. The rack-pinion-based energy harvester was designed to be mounted on a secondary suspension system, in parallel with coil springs, as illustrated in Fig. 27(d). The suspension displacement under coupling relation was solved, but the difference between original displacement and displacement with harvester is not given.

Overall, the dynamic influence of small-scale energy harvesters on vehicle-track systems is negligible. For rotary EM-VEHs mounted on trackside, the equivalent damping of the harvester is large, but far less than rail damping, hence the impact is not obvious. However, the on-board EM-VEH is bound to have a significant impact on the vertical vibration of the railcars, because its equivalent damping is in the same order of magnitude as the commonly used railcar vertical shock absorber. There is no detailed analysis about this issue in the existing literature. The damping of EM-VEH needs a reasonable design to obtain as much energy as possible from the vibration of the railcar. In addition, it is noted that the equivalent damping is mainly determined by the transmission ratio of EM-VEH and circuit load. Hence, the coupled relationship between the vehicle-track system, EM-VEH and interface circuit should be systematically studied in parameter design and optimization.

7.4. Future research directions

Based on the above review and summary, it is considered that the railway energy harvesting technology needs to be further improved in terms of efficiency, practicality and durability for future engineering applications. Some specific suggestions are listed in Fig. 28.

7.4.1. Enhancing the interdisciplinary research

Energy harvesting is a technology involving material, mechanics, electronics, and control while railway dynamics is an effective tool to reveal railway-harvester interactions and evaluate railway safety. Interdisciplinary research on energy harvesting and railway dynamics will be necessary and effective in future research, and the following schemes can be adopted:

(1) Further development of advanced materials. The energy conversion and efficiency of harvesters based on piezoelectric, triboelectric and photovoltaic and thermoelectric effects are affected by materials to varying degrees. In addition, some advanced materials can improve the service life of energy harvesters and broaden their application scenarios.
(2) Harvester mechanism, circuit and control strategy considering railway vibration characteristics. The vibration of railway tracks, vehicles and components is generally random and irregular, and presents intense broadband characteristics. Multi-DOF and multi-stable systems are proven to be superior to the general linear design; however, it is still necessary to further optimize the mechanisms and parameters according to the railway vibration characteristics.
(3) Interdisciplinary research for systematic design. In the existing research, the design of harvester and interface circuit is mostly carried out independently, and the collaborative optimization based on their coupling relationship should be investigated in depth in the future to improve system integration and overall efficiency. For the harvesters interacted with railway vehicle-track system, for instance, large-scale rotary EM-VEHs, the coupling analysis of vehicle-harvester-circuit needs to carry out for systematic optimization design and control strategy.

7.4.2. Improving the practicality for railway engineering applications

The most important factor of whether the energy harvesting technology can be widely used in the railway industry is practicality. To accelerate the commercialization of research findings and enhance the practicality for railway engineering applications, the following aspects can be further researched:

(1) Hybrid energy harvesting systems. Current energy harvesters in the railway field are mainly based on one effect and take one energy source as the target. Considering the variety of energy sources in railway systems and the different energy harvesting methods, hybrid energy harvesting systems scavenging multiple energy sources or based on multiple energy conversion

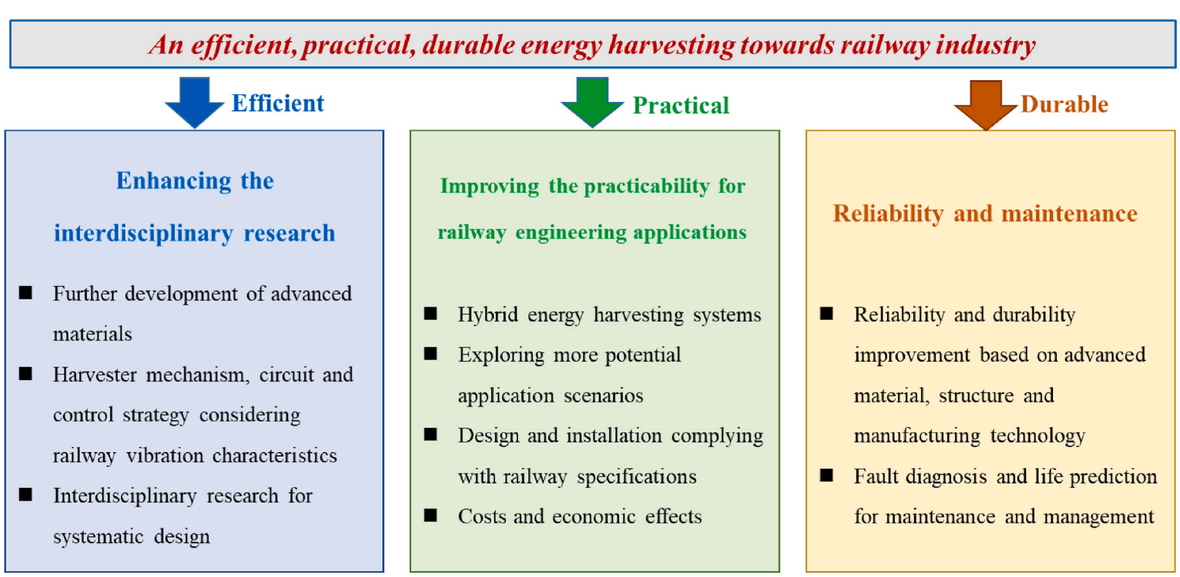

Fig. 28. Future research directions for railway energy harvesting.

mechanisms can be explored to enhance power performance and improve adaptability to environmental changes. They will have advantages in power density, robustness, and energy conversion efficiency compared to common energy harvesting systems.

(2) Exploring more potential application scenarios. Energy harvesting can be used as a foundation to promote the development of key technologies of highspeed railways, including IoTs, unmanned/intelligent driving, fault diagnosis, regenerative shock absorbers, etc. Carrying out customized adjustments for the unique requirements of each technology to further expand its practicality and application potential.
(3) Design and installation complying with railway industry standards. From the perspective of installation, the installation and size of the energy harvester should strictly abide by the railway gauge and railway specifications. The standardized design and production shall be carried out for extensive application of energy harvesters.
(4) Costs and economic effects. The technical and economic analysis is an important metric to measure practicality, which also determines whether the technology is suitable for large-scale application. Proper cost control enables energy harvesting products in railway industry not only to be functional, but also to bring higher economic effects.

7.4.3. Reliability and maintenance

Researchers usually pay more attention to performance than reliability in the design process; however, many energy harvesters are exploited in harsh environments or their mechanisms are in frequent mechanical motion. Hence, the reliability and maintenance issues need to be valued, and the current situation can be improved from the following two aspects:

(1) Reliability and durability. The mechanical structures in vibration and wind energy harvesters work frequently leading to aggravated wear. The harvester design in material, structure and manufacturing technology needs to be balanced with performance.
(2) Fault diagnosis and life prediction for maintenance and management. Fault diagnosis can be exploited for rapid fault location and health management of harvesters with high value, for instance, large-scale wind turbines. Life prediction can be carried out from theoretical analysis and tests, which is conducive to guiding the maintenance or replacement cycle of energy harvesters and thus avoiding system paralysis caused by sudden failure.

8. Conclusions

In view of the rapid expansion of the railway network in the world and the increasingly advancing energy harvesting technology, the application scenarios of energy harvesting technology in railway industry will be promising. This paper presents a comprehensive review of energy harvesting solutions in the railway industry. From the perspective of vibration, thermal, solar, wind, magnetic field and acoustic energy harvesting, the design, optimization and implementation of harvesters in railway applications are introduced in detail. The existing harvesters are classified, summarized and compared, and their application prospects are discussed. The scheme of vibration energy harvesting (VEH) focuses on the design of the structure, and they are considered to have potential in self-powered wireless network nodes, IoTs, and trackside or onboard electronics. In wind and solar energy harvesting, the high-power or low-power system can be realized for corresponding scenes. It is noted that they are vulnerable to weather and environment, so their actual performance is unpredictable. The thermal, magnetic field and acoustic energy harvesters have not been extensively studied. Compared with VEHs, they have unique advantages but are only suitable for some specific applications.

The reports of vibration energy harvesting account for a dominant part in railway energy harvesting in recent years. As the current research frontier, we thoroughly discuss the technical difficulties and future trends of railway vibration energy harvesting from the following aspects:

(1) From the perspective of performance-enhanced design, low-power energy harvesting systems with multi-DOF or multi-stable structures are the main means to broaden the frequency band. The multi-DOF design has been proven to be effective in excitation with multiple dominant frequencies. In theory, the multi-stable nonlinear system also has a wide frequency band, but due to the requirement of the excitation level for the inter-well oscillations, the actual performance still needs to be studied in railway vibration environment.
(2) Most of the current high efficiency interface circuits of energy harvesters are verified by sinusoidal excitation. In future research on interface circuits, the optimization based on railway vibration characteristics needs to be considered.
(3) The coupling dynamic analysis between the VEH and the vehicle-track system is necessary. The safety of harvesters applied in railway should be guaranteed. In addition, if the energy harvester is designed for shock absorption, its shock absorption effect needs to be solved by dynamic analysis.

Meanwhile, the interdisciplinary research, practicability enhancement, reliability and maintenance issues of railway harvesters still need to be further explored in the future.

CRediT authorship contribution statement

Jianyong Zuo: Conceptualization, Funding acquisition, Project administration, Writing – review & editing. **Liwei Dong:** Conceptualization, Writing – original draft, Writing – review & editing, Data curation, Software. **Fan Yang:** Formal analysis. **Ziheng Guo:** Resources. **Tianpeng Wang:** Supervision. **Lei Zuo:** Conceptualization, Funding acquisition, Writing – review & editing.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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