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Harvesting Ambient Energy for Sustainable Transportation: A Comprehensive Review of Renewable Energy Sources and Technologies

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Abstract

Green energy recovery technologies facilitate the transformation of green energy into electricity, thereby reducing reliance on fossil fuels and optimizing the energy efficiency of transportation facilities. This publication analyses the advanced principles of ambient energy recovery technologies in the transport sector, focusing mainly on road and rail networks. The use of thermal energy from heat losses generated by engines and braking devices, the incorporation of solar energy into vehicles and facilities, and innovative wind power solutions that exploit air movement in tunnels or around rail networks are highlighted. Hydraulic energy, magnetic energy and piezoelectric vibration recovery devices are also being explored for their ability to power sensors, vehicles and installations. Despite encouraging results, obstacles remain in the way of improved performance, cost-effectiveness and adaptation to practical circumstances. Intensified cooperation between researchers, industry and policy-makers is crucial to accelerate the uptake of these technologies, while fostering a more environmentally- friendly and resilient transport ecosystem.

Keywords: Energy harvesting; Road transportation; Railway transportation; vibration harvesting; Solar energy harvesting; Wind energy harvesting; Thermal energy harvesting

Introduction

Ambient energy harvesting, also known as energy scavenging or power harvesting, is the process where energy is obtained and converted from the environment and stored for use in electronics applications.

Among these ambient sources, some are large-scale, while others are small-scale. Among ambient energy sources, some fall into the MACRO level, while others fall into the MICRO level. Macro-level sources, such as solar, wind, geothermal, hydroelectric, and nuclear sources, are noteworthy. Vibration, mechanical strain, fluid, water, and human motion are considered Micro-level sources. Micro-scale energy sources are more suitable for powering small-scale electronic devices, like sensors, portable electronic equipment, and medical devices. Energy harvesting involves converting ambient sources into electricity without wasting any energy (or an important part of this energy), and the generated energy can be stored for future use.

Truly, ambient sources play a vital role in scavenging energy, especially high-density sources that are more reliable for small autonomous devices, such as wireless sensor networks. A wide variety of sources are available for energy scavenging, including solar power, ocean waves, piezoelectricity, thermoelectricity, and mechanical vibrations. Depending on the application, energy harvesting sources should be selected. This section discusses a general overview of different sources based on the characteristics of ambient sources.

Types of Recoverable Ambient Energy in Transportation

Ambient energy is nature's energy that is never exploited by Human being, it means also the energy that we can use it without creating infrastructure to capture and transform it. There are several types of ambient energy, and in this part we will discover the most popular, usable and also efficient types of ambient energy on the earth.

The concept of ambient energy harvesting involves capturing and harnessing the small amounts of energy present in the environment, particularly useful in low-energy systems such as autonomous sensors, or for increasing the energy efficiency of vehicles and infrastructure.

Thermal Energy

Thermal energy is generated by temperature variations and residual heat produced by mechanical systems or natural sources such as the sun. The thermoelectric effect is when a voltage difference exists between n-type and p-type conductors due to a temperature difference being exerted. In practice, thermoelectric generators (TEG) consist of many such thermocouples in series to obtain a higher voltage in low temperature difference environment.

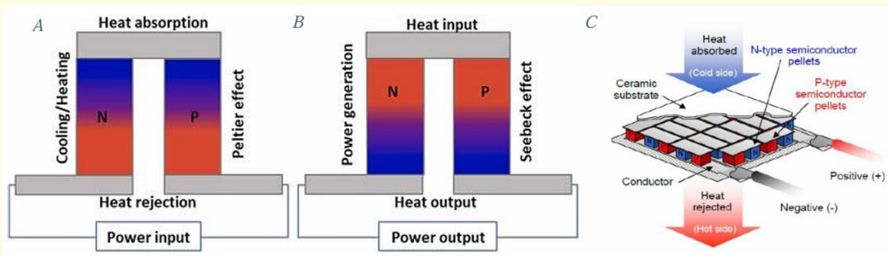

Figure 1: A: Peltier effect, B: Seebeck effect, C: Practical TEGs connect large numbers of junctions in series to increase operating voltage and spread heat flow [1].

In the transportation domain, there are several thermal energy sources that we can exploit them, such as in internal combustion vehicles, a large proportion of the fuel's energy is lost in the form of heat, particularly through engines and exhaust systems, with losses of up to 60-70% [2]. Braking systems also generate a significant amount of heat, especially in heavy or high-speed vehicles, for example train, High speed train, trailer… [3]

Solar Energy

Solar energy presented by light, that is emitted by the sun. With solar technologies we can capture this light and transform it into useful forms of energy. This energy can be recovered by several technologies as solar photovoltaic energy technology which is nothing but directly converts sunlight into electricity using a concept based on the photovoltaic effect, like it shows on the below, also concentrated solar power technology presents another efficient technology utilize mirrors to concentrate sunlight onto a receiver, generating thermal energy that can be used to power turbines or generate electricity like the figure below shows.

Similar to the thermal energy, solar energy can be also used in the transportation domain. For instance, Solar energy has great potential in the rail sector, thanks to the photovoltaic (PV) effect, which converts light into electricity. For example, a 3846 m^2 PV system on the roof of a station in Tokyo generated 340 MW annually, while Bharat Heavy Electricals installed a 1.7 MW PV system to power trains in India [4].

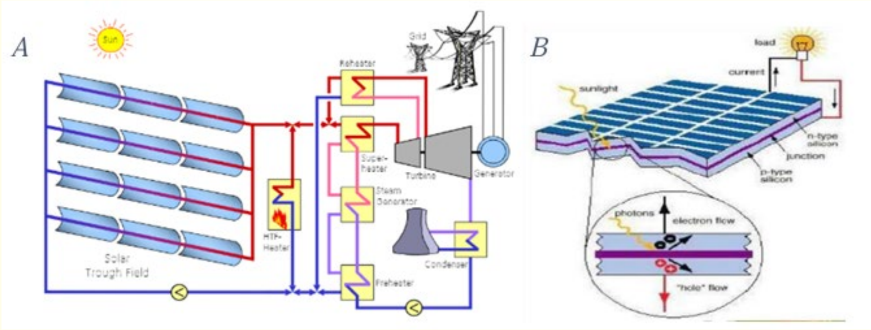

Figure 2: A: Principle of the parabolic trough solar power plant; B: Photovoltaic Cell [4].

Wind Energy

Wind energy is a renewable energy source that uses the force of the wind to generate electricity, mainly via wind turbines. The blades of the wind turbine, a multiplier (which can be avoided in some other systems), an electrical generator, a power electronic system used as a converter and an electrical transformer connected to the grid are the main elements used in a conventional wind system, as shown in Figure below. The wind turbine blades collect and convert the kinetic energy of the wind into mechanical energy. This mechanical energy then generates electricity by turning a generator [5].

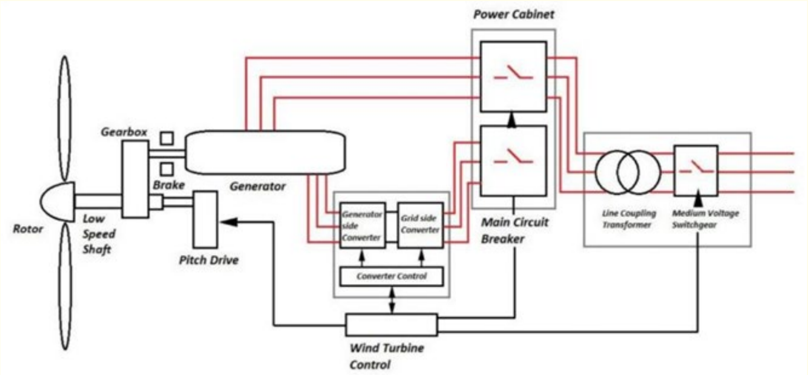

Figure 3: Block Diagram of a typical grid-connected WECS [6].

In the transport sector, it can be harnessed indirectly to power infrastructure such as railway stations or electric vehicle charging points, via wind farms. Wind power is a practical solution for generating electricity in areas remote from power grids, particularly around railway systems. Traditional wind turbines use electromagnetic generators, while triboelectric nano- generators (TENG) have been developed for low-power applications. Innovative concepts based on wind-induced vibrations have also emerged, enabling power to be generated even at low wind speeds. Studies have shown that turbines placed on the roofs of railcars or in railway tunnels can capture the wind energy generated by moving trains. Thanks to their efficiency and low cost, TENGs open up new prospects for self-powered systems in railway infrastructures [7].

Hydraulic Energy

Hydraulic energy, also known as hydroelectric energy, is a renewable energy source that harnesses the power of moving water, such as rivers or ocean currents, to generate electricity.

The process relies on turbines that convert the kinetic energy of water into mechanical energy, which in turn rotates turbines that generate electricity through generators.

The water, often stored in a reservoir or dam, is released to flow through a turbine. The moving water turns this turbine, creating mechanical energy, which will be converted to an electric energy via a generator linked to the turbine and this energy finally will be routed to a transformer for distribution to power grids [8]. And this is what the figure above presents.

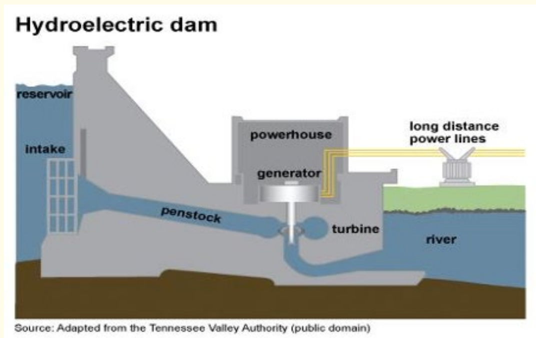

Figure 4: Hydroelectric energy production process [9].

Hydroelectric energy can be used in the transportation domain to power electric vehicles, trains and road infrastructure such as ports and tunnels. It can also be used to produce green hydrogen for fuel cell vehicles. By integrating hydroelectric energy, the transport sector can reduce its carbon footprint and greenhouse gas emissions.

Magnetic energy

Electromagnetic energy presents the energy transported by the electromagnetic waves, like light, radio-waves, microwaves, and electromagnetic fields generated by electrical currents. This energy is the combination between an oscillating electric and magnetic field and can be used in a wide range of applications, including transportation.

Researchers such as L. Wang et al. have developed a mechanical energy recovery prototype using a rack-and-pinion system and a speed bump-type device. As the vehicle passes, kinetic energy is converted into electricity via an electromagnetic generator, with a maximum power output of 647 W per axle as presented in the figure below [10].

Dr. L. Zuo and his team have tested another device using a cam-arm mechanism to capture energy from high-speed vehicles, generating up to 24 W at 5 mph. As well as, in China, L. Qi et al. designed an energy recuperator with pinion and bevel gearing as shown in the figure below, achieving a maximum power of 66,025 W with an efficiency of up to 62.38% in simulation and 57% in real tests [10].

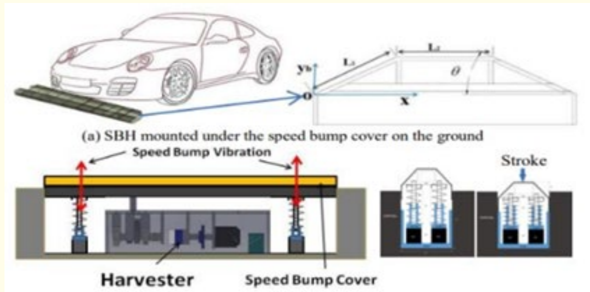

Figure 5: Rack-and-pinion system and a speed bump-type device [10].

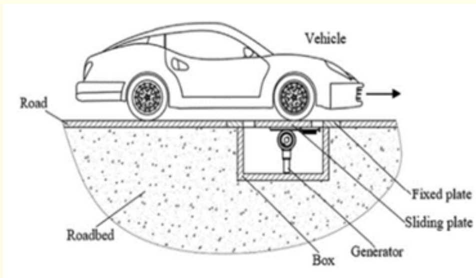

Figure 6: Pinion and bevel gearing energy harvesting system [10].

Acoustic Energy (Sound)

Acoustic energy is the energy transported by the sound waves and generated by the vibrations. This energy presented in the environment as longitudinal mechanical waves where matter undergoes compression and expansion. Although acoustic energy is often perceived as audible sound, it can also include ultrasonic or infrasonic vibrations, inaudible to the human ear [11].

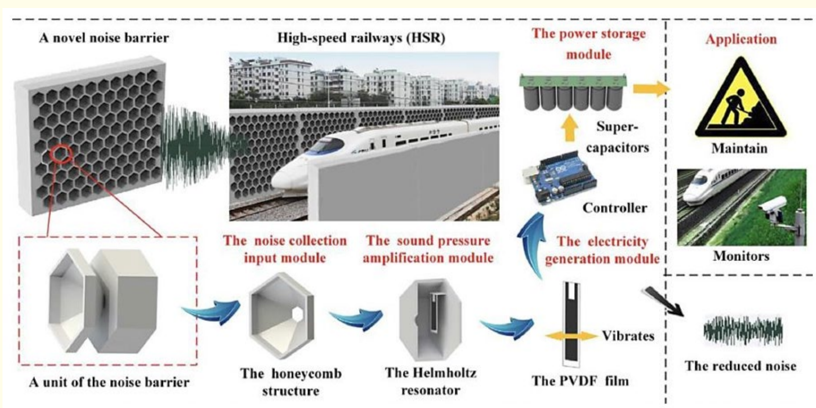

Figure 7: Overall scheme of the acoustic energy harvester integrated with a HR and a PVDF film [12].

With the rapid expansion of the rail network, the aerodynamic and rolling noise of high- speed trains has become a major environmental issue. Reducing noise inside cabins is crucial to passenger comfort. Acoustic energy recovery can be achieved using acoustic resonators and transducers, which amplify sound pressure at certain frequencies. Studies have shown that devices such as Helmholtz resonators and PVDF films can capture and convert sound energy into electricity, although the power density obtained is still limited. Further research is needed to improve the efficiency of this technology in railway applications [12].

Ambient energy recovery technologies in road/rail transport

The adoption of innovative technologies to recover and harness lost energy is essential to the transition to more sustainable and autonomous transport systems. In road and rail transport, natural energies such as heat, sun, wind and mechanical movements offer considerable potential for reducing energy losses and optimizing overall system efficiency. This section looks at current advances and practical applications of thermal, solar, wind and piezoelectric recovery technologies, highlighting their impact on the energy sustainability of installations and vehicles.

Thermal energy recovery technologies

Current advances in heat recovery technologies focus on improving thermoelectric materials and integrating these systems into increasingly lightweight, autonomous vehicles. Materials such as bismuth telluride (Bi_2Te_3) and nanostructured silicon optimize thermal-to- electrical conversion thanks to improved electrical conductivity and reduced thermal energy losses. These materials are essential for increasing the efficiency of thermoelectric generators (TEGs) in environments where available heat is limited.

In the automotive sector, TEGs are now being integrated into prototype hybrid and electric vehicles to offset the energy consumption of auxiliary systems such as air conditioning and heating. These systems also contribute to fuel savings by reducing alternator load, and several manufacturers are exploring heat recovery circuits on exhaust systems, notably in internal combustion engines.

Thermal energy can easily be neglected in rail vehicle systems. In rail vehicles, a great deal of heat is lost through friction and power losses, and also dissipated around various components such as axleboxes, friction dampers, brake discs or linings. Today, a considerable proportion of freight and passenger locomotives are still powered by diesel engines. Sensible conversion and utilization of the exhaust heat from diesel engines would not only improve the efficiency of the propulsion system, but also go some way to alleviating certain environmental problems. Heghmanns has optimally designed an exhaust heat recovery system for internal combustion engines on railway locomotives. Analysis results show that fuel savings of up to 0.7% can be achieved. Exhaust gas heat recovery systems have not yet been used in concrete railway applications, but their effectiveness has been proven by experience in the automotive industry [13].

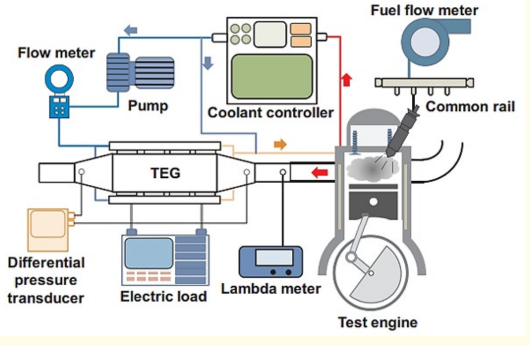

Figure 8: Schematic diagram of the experimental energy recovery system of a hexagonal thermoelectric generator for passenger vehicle applications [14].

Thermal energy recovery is seen as a promising avenue for energy conversion and has been the subject of much research. Depending on the thermal characteristics and application scenarios of railroads, current research focuses mainly on thermoelectric generators rather than pyroelectric generators, which recover energy from the temperature gradient in the spatial and temporal domains separately.

Ahi and Choi have proposed a thermoelectric generator (TEG) that converts the temperature gradient between the axle bearing housing surface and the outside air into electricity. In the researchers' previous research, the temperature difference between these two elements is around 15°C when the vehicle is in motion. Taking into account installation space constraints, a 20 × 20 cm^2 commercial thermoelectric module was selected for the entire thermoelectric system. The thermoelectric energy recovery system (TEHS) is illustrated in the Figure below. The heat sink with optimal cooling fins transfers heat from the cold side to maintain a temperature difference on both sides, providing favorable conditions for energy production [15].

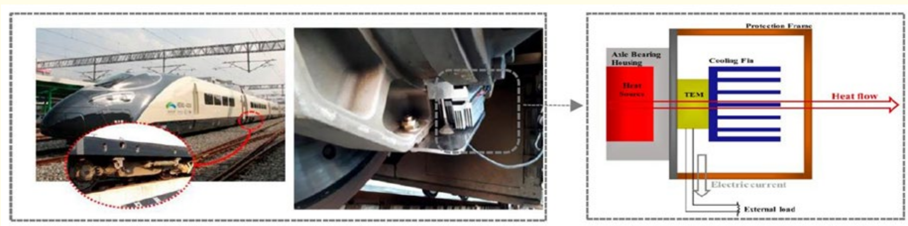

Figure 9: Architecture of a thermoelectric energy harvesting system.

Solar energy recovery technologies

Solar power is becoming increasingly important in road transport, with innovations designed to reduce dependence on fossil fuels and improve vehicle energy efficiency. Manufacturers such as Lightyear and Aptera have introduced solar-powered cars capable of running partially on energy captured by photovoltaic panels integrated into their bodywork. These vehicles can travel several dozen kilometers a day without recharging, harnessing clean, free energy. This breakthrough paves the way for more sustainable transport models, especially for daily commuting.

The use of solar energy for roads represents a promising step forward in the field of renewable energies. Photovoltaic (PV) panels integrated into road surfaces transform traffic lanes into electricity generators. While the technology is used in a variety of applications, such as powering public grids, adapting it to roads poses unique challenges in terms of design and materials. Panels need to be traffic-resistant, offer a non-slip surface while remaining transparent, and be waterproof to ensure efficient, long-lasting use.

Prototypes such as the solar roads developed by Solar Roadways and Colas have demonstrated the potential of this technology. For example, a 2800 m^2 solar road in France produced enough electricity to power public lighting. Similar initiatives, such as the SolaRoad project in the Netherlands, have also shown encouraging results, producing 78 kWh/m^2 per year, although durability issues, such as deterioration of the non-slip coating, have been observed [16].

In 2011, a $3846m2$ photovoltaic system installed on the roof of a Tokyo railway station generated 340 MW of annual power, representing around 0.3% of the station's energy consumption. Alam and Khan have designed a solar-piezoelectric hybrid system for railway stations, theoretically capable of powering a 10 kW load for 10 hours a day. Bharat Heavy Electricals Limited (BHEL) has developed a 1.7 MW photovoltaic system for Indian Railways, which is connected to a traction substation and helps power train traction [4].

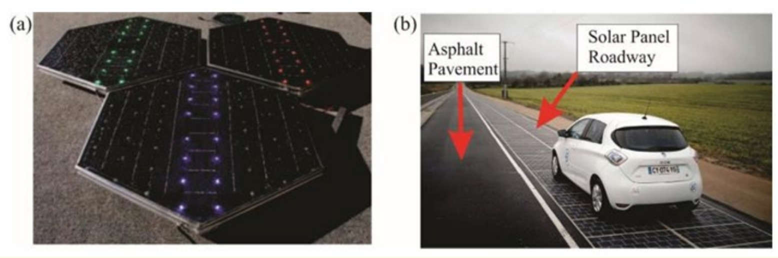

Figure 10: (a) Nussbaum solar panel for roadways, with LEDs, shown in full daylight ; (b) First pilot solar panel roadway in France.

On-board applications for photovoltaic systems have also been evaluated. Pavel and Yuri Vorobiev have carried out a feasibility study of photovoltaic modules installed on the roofs of railway carriages. The test wagon fitted with two photovoltaic modules ran at 120 km/h, coupled to three popular trains in southern India. It is estimated that 18 kWh were produced per day, representing diesel savings of around 1,700 liters per year. The train, equipped with 100 solar panels, can do without additional power from the national grid in the UK [17].

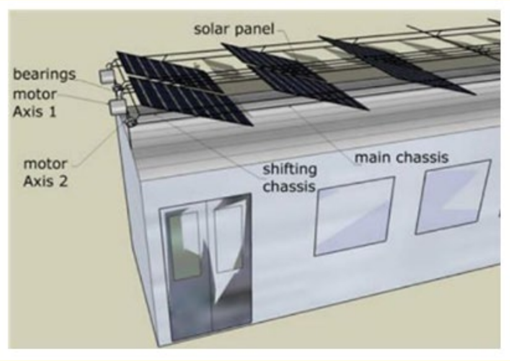

Figure 11: Example of a photovoltaic solar panel installation with a sun-tracking system on the roof of a rail car.

Wind energy recovery technologies

The use of wind power in road transport represents an innovative approach to harnessing the air flows generated by moving vehicles or natural wind. This technology aims to convert the kinetic energy of these flows into electricity, thereby reducing dependence on traditional energy sources. Although still in the development stage, it shows interesting potential, particularly for applications such as powering road infrastructure or vehicle auxiliary systems.

Prototypes using fixed wind turbines along roadsides or in tunnels have already been tested. For example, vertical-axis turbines installed near freeways capture energy from airflows created by passing vehicles, generating enough power-to-power public lighting or traffic signs. These systems, which take advantage of the turbulent winds specific to these environments, offer a localized solution for generating renewable energy directly on site.

Some vehicles also incorporate micro-wind turbines to harness airflow while on the move. These compact wind turbines, often placed on the roof or in the air intakes, generate electricity to power the vehicle's internal systems. However, challenges remain, such as the impact on aerodynamics and the need to optimize efficiency to minimize drag.

Strong winds are common throughout the world, and the areas surrounding the railway system are no exception. For remote areas and other scenarios where direct power supply is difficult, generating electricity by extracting wind power offers a practical solution. In general, the cost/production ratio of wind power is attractive. Thus, wind energy conversion is an important renewable approach to help mitigate the greenhouse effect.

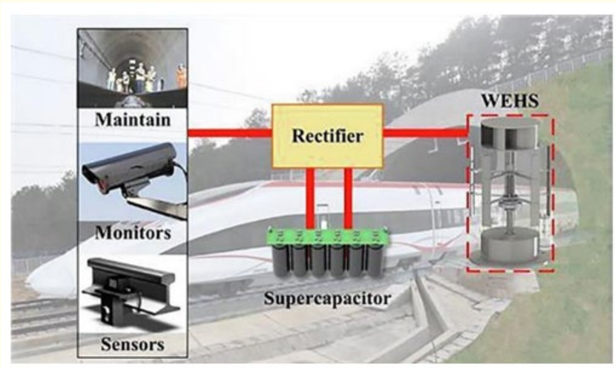

Figure 12: Application of wind energy harvesting system in TGV tunnels.

Conventional wind turbines convert energy using electromagnetic generators. With the development of nanomaterials, some triboelectric nanogenerators for wind energy have been developed for low-power applications. Flow-induced vibrations have been studied by many researchers in recent years. Based on the theory of flow-induced vibration, many innovative wind turbine design concepts have been developed. Flow-induced VEHs (Vibration Energy Harvesters) convert air flows into vibrations, and then generate electricity through piezoelectric, electromagnetic or triboelectric effects. The advantage is that a certain amount of energy can be generated even at low wind speeds. Consequently, this can be seen as an extension of the HEV application scenario.

Piezoelectric energy recovery technologies

Energy recovery using piezoelectric materials represents an innovative and promising approach in the search for sustainable energy solutions. Among the materials currently in use, PZT (lead titanate zirconate) and PVDF (polyvinylidene fluoride) stand out. PZT is a brittle ceramic material with a high piezoelectric coefficient, while PVDF, a tough, flexible polymer, offers better thermal stability but lower efficiency. These materials are integrated into piezoelectric devices combining mechanical and electronic elements to generate and condition the electricity produced.

For road applications, piezoelectric elements have to meet stringent requirements in terms of robustness and durability. They are often encapsulated in resistant materials such as concrete or steel to protect them from loads and environmental conditions. Various designs, such as cymbal-shaped transducers or cantilever systems, have been tested, but present challenges in terms of fragility or performance. For example, research has shown that specific configurations, such as arches or trapezoidal bridges, optimize energy efficiency while supporting high loads [16].

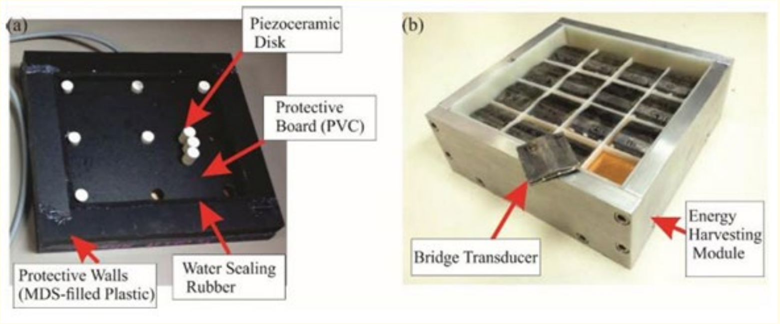

Figure 13: (a) Assembled energy collector without cover (annotated after Xiong et al.); (b) Prototype, top cover removed, showing top layer of transducers [16].

Energy generation and storage remain crucial aspects. Piezoelectric devices produce small amounts of energy, usually stored in supercapacitors or rechargeable batteries. The latter are ideal for applications requiring a constant power supply, although their charging speed decreases over time. Supercapacitors, on the other hand, offer enhanced performance thanks to their energy density and low discharge rate.

On the other hand, wheel-rail contact and track irregularities generate vibrations that are present in many areas such as rails, tunnels, bridges and trains. Because of the broadband characteristics of railway vibrations, many researchers have been interested in the study of vibration energy recuperators, using a variety of methods, of which piezoelectric vibration energy recuperators (PE-VEH) are the most interesting.

The main application of piezoelectric vibration energy recovery vehicles (PE-VEH) is along railroad lines. Nelson et al. first tried using a piezoelectric patch mounted under the rail, in working mode 31as shown in the figure below, and obtained an average power of around 0.053 mW in field tests.

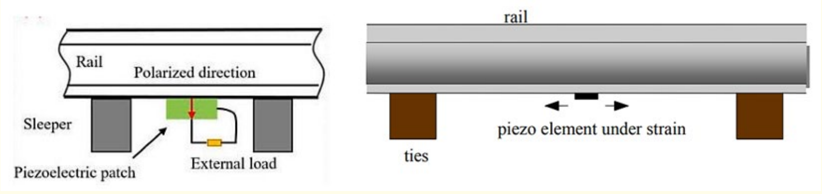

Figure 14: A piezoelectric element generates a voltage under a time-varying wagon load.

The researchers predicted that an average power of up to 1.1 mW could be achieved when the train was loaded, which would be sufficient to power some low-power sensors requiring only a few milliwatts. Wang et al. proposed a stacked piezoelectric patch structure in which the piezoelectric patches are connected mechanically in series but electrically in parallel, mounted under the steel rail. The transverse displacement of the rail is converted by a transmission rod and a force through the compression spring, then transferred to the piezoelectric stacked structure, which operates in mode 33. An average power of 0.8 mW (stacked structure) and 0.15 mW (patch) can be achieved at a theoretical train speed of 324 km/h.

The piezoelectric cantilever has the advantage of being able to achieve relatively high deformation under a given basic vibration input. The resonant frequency of the cantilever beam is generally higher than the main frequency range of rail or wagon vibration, and a mass can be placed at the free end to adjust the resonant frequency, as shown in the figure below.

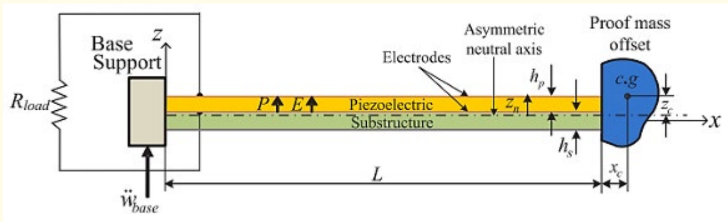

Figure 15: The piezoelectric cantilever.

Gao et al. proposed a cantilevered PE-VEH based on a PZT film and resonant design for the recovery of vibration energy from rail-road tracks. A maximum power of 4.9 mW was achieved at a voltage of 24.4 V in laboratory tests. Output could have been improved, however, as the device designed did not match the vibration frequency of the tracks very well. Given the intense characteristics of rail vibration over a wide frequency range [18].

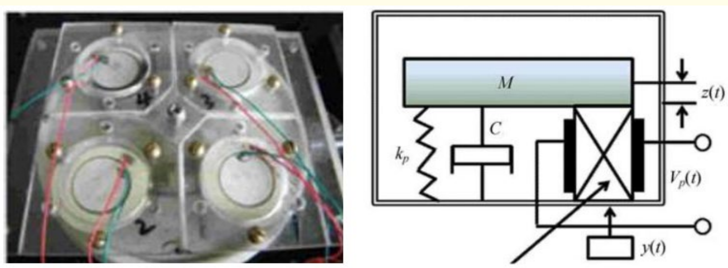

Figure 16: The circular piezoelectric membrane.

Wang et al. designed a circular piezoelectric diaphragm with 4 piezoelectric plates in parallel, covering a frequency range from 110 to 260 Hz, as shown in the figure below. A maximum power of 21.4 mW was generated when excited at 150 Hz with an optimum load resistance of 11 kΩ. This is a potential design for realizing a wide-bandwidth piezoelectric recuperator to match the frequency band of rail vibration. In addition, there are also applications for PE-VEH mounted on other non-vehicle scenarios, such as railway bridges and sleepers. Cahill et al. explored the possibility of recovering train-induced vibration energy in bridges by attaching piezoelectric patches to the underside of the bridges. In simulations, PZT and PVDF materials generated a maximum average power of 588 μW and 307.1 μW respectively under conditions where two high-speed trains were moving in opposite directions at a speed of 120 km/h. Despite a lower power generation capacity, PVDF is considered a better choice for long- term operation due to its higher mechanical strength and excellent flexibility [7].

It should be noted that the above examples are based on laboratory or field studies and tests, and actual power output may vary depending on many factors such as vehicle speed, energy recovery system characteristics, environmental conditions, etc. What's more, the use of piezoelectric energy vehicles (PE-VEH) is still limited, and further research and development efforts are needed to optimize design, improve performance and assess their applicability in real-life scenarios.

Conclusion

The exploration and integration of ambient energy recovery technologies is paving the way for innovative solutions to meet the growing energy needs of modern transportation systems. By harnessing sources such as solar, thermal, wind, hydraulic and piezoelectric energy, it is possible to develop more autonomous, sustainable and environmentally-friendly infrastructures and vehicles.

These technological advances not only offer an alternative to fossil fuels, but also improve energy efficiency and reduce the carbon footprint of the rail and road sectors. However, challenges remain, particularly in terms of performance, cost and adaptability to real-world environments.

Increased collaboration between researchers, industry and policy-makers is essential to optimize these systems and promote their widespread adoption. In the long term, these technologies could transform the way energy is produced, stored and used, contributing to a more sustainable and resilient energy future for the transport sector.

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