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Energy harvesting technologies in highway systems: a review

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ABSTRACT

Energy harvesting technology research has progressed significantly in recent years due to the increasing demand for alternative energy sources. One of the most promising methods of supplying renewable energy has been successfully put on the road, known as energy harvesting technology. There are four energy harvesting technologies on the roadway: solar, piezoelectric, thermoelectric, and geothermal. This paper discusses the development of energy harvesting technology on roadway other than geothermal, examines the basic principles of energy harvesting technology on the roadway, and provides an analysis and comparison of these technologies. Energy harvesting technology from energy conversion factors, weaknesses, and advantages that are most likely to be applied on the roadway is piezoelectric.

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1. INTRODUCTION

Green and clean renewable energy sources are one of the determining factors for sustainable development. Fossil energy sources such as oil, coal, and natural gas. currently still dominates as the most common source of electrical energy in the world. Energy harvesting techniques are promising techniques that can be used to obtain renewable energy, as an effort to ensure sustainable development. Energy harvesting technology works by capturing energy that available in the surrounding environment and then converting it into electrical energy that can be utilized. The most common sources of energy to harvest are solar, wind, thermal, magnetic, mechanical and radio frequency [1]–[7]. Along with the rapid development of technology, many researchers have developed techniques and devices that can harvest ambient energy and convert it into electricity. Commonly used energy harvesting devices are piezoelectric [8]–[16], thermoelectric generator (TEG) [17]–[22], photovoltaic [23]–[26], and geothermal.

The most potential energy harvesting systems to use on highways based on the source divided into two categories including solar energy used is heat and light radiation while kinetic energy is vibration [27], [28]. This paper focus on energy harvesting systems that commonly applied on highways. Energy harvesting is all about capturing, transforming and storing it in the form of electrical energy that can be utilized any time. Energy harvesting technologies discussed regarding photovoltaic, piezoelectric and thermoelectric systems. Photovoltaic is the most famous transducer for converting solar radiation into electricity; piezoelectric convert mechanical vibrations into electricity; The thermoelectric generator produces an electricity when there is a temperature difference on each side.

This research aims to examine the various energy harvesting technologies used on highways (photovoltaic, piezoelectric and thermoelectric). Each technology is thoroughly examined, including the operating principles and key findings from previous literature studies. The literature evaluation focused on a number of crucial energy harvesting system characteristics, including energy conversion parameters. The energy conversion factor, advantages, and disadvantages of various energy harvesting technologies are compared. Discuss the benefits and drawbacks of each identified technology and recommendations for future research

2. AN OVERVIEW OF ENERGY HARVESTING SYSTEMS ON HIGHWAY

Highways are one of the most important civil infrastructures for getting from one place to another. Traditionally, roads are seen as structural platforms for transporting traffic loads. The common energy harvesting transducer used on highways are photovoltaic, piezoelectric, thermoelectric, and geothermal, as shown in Figure 1. The road surface that is continuously passed by vehicles causes mechanical vibrations, while exposure to solar radiation causes an increase in temperature on the road surface. Mechanical energy in the form of vibrations can be harvested and converted into electrical energy with the help of a piezoelectric, while the heat energy generated by solar radiation can be harvested using a thermoelectric generator [29], [30]. On the other hand, exposure to solar radiation can also be captured and converted into electrical energy with the help of photovoltaic modules. In this manner, all of the potential energy that is lost on the roadway can be captured and transformed into electrical energy for use in a variety of applications. Figure 2 depicts examples of various energy harvesting technologies that could be used on highways.

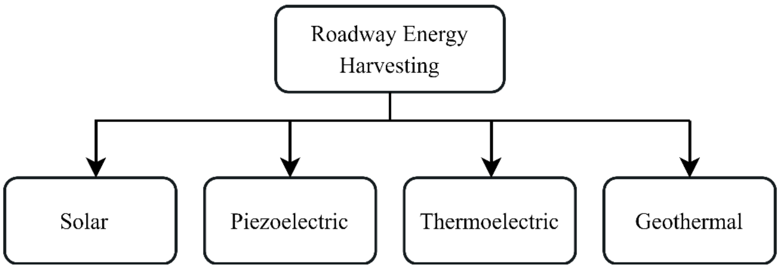

Figure 1. Roadway energy harvesting categories

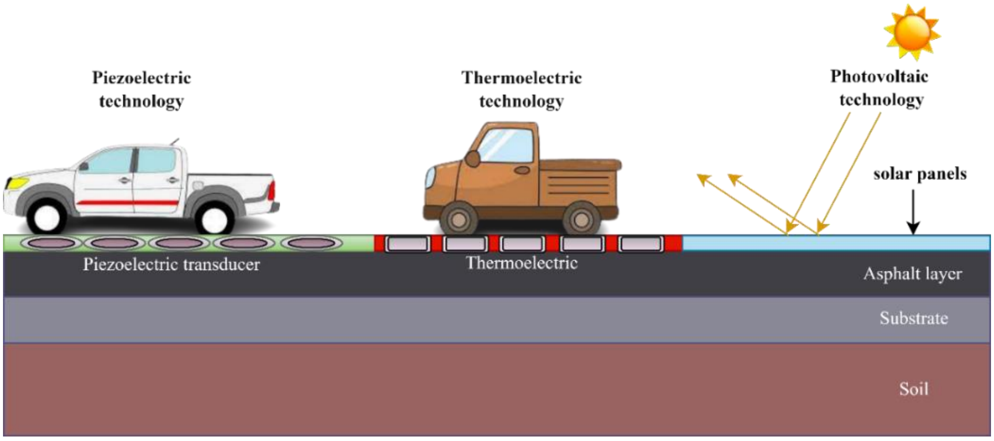

Figure 2. Source of energy harvesting

An energy harvesting system basically has three main components, namely: a power plant, a power converter, and an energy storage element. After converting the surrounding energy into electrical energy, a power converter circuit is used to adjust the system voltage level to a voltage level that suits the load or battery. Supercapacitors or rechargeable batteries can store the accumulated energy. The amount of power produced varies greatly, depending on environmental conditions and the type of energy harvester system used. Most of the energy can be directly used as a source of electricity and connected to the grid. On the other hand, In the winter, heated road surfaces can be created using the electrical energy produced, or for lighting and any traffic equipment.

3. ENERGY HARVESTING FOR HIGHWAY APPLICATION

3.1. Solar energy harvesting

In general, a photovoltaic (PV) cell that uses sun energy to generate electricity. Solar cells basically consist of N-type and P-type semiconductors. The semiconductor material in the solar cell will be forced to flow in a certain direction when sunlight strikes it. The P-type semiconductor will typically attract positively charged electrons, whereas the N-type semiconductor will typically attract negatively charged electrons. Figure 3 illustrates the fundamental workings of a solar cell. When it is connected to a load, the flow of moving electrons generates an electrical current.

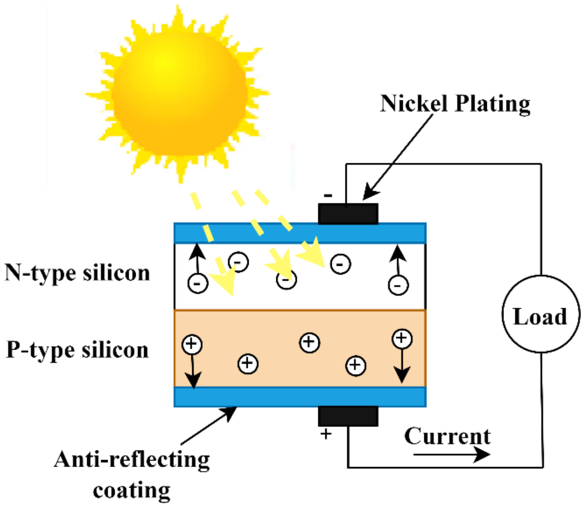

Figure 3. Working principle of photovoltaic solar cell

Several studies have looked into the use of PV cells on highways to harvest solar energy. Research on solar panels for highway such as [31], where solar panel technology is installed on the surface layer to replace asphalt, as well as revealing that solar panels have a high-power density.

Solar PV cell technology [32], [33] is also carried out on the road, specifically by applying protective coatings to solar panels made of transparent resin concrete. The amount of resin and the type of glass aggregate gradation have a significant impact on the optical and mechanical properties. Nonetheless, the results show that it had no effect on the volume index. When considering the material's properties and cost, the optimal resin content is 43.7%. In terms of high-temperature resistance, temperature cracking resistance, and slip resistance, the solar pavement performed exceptionally well. The solar highway module produces approximately 0.152kWh/m2 of power per day.

3.2. Piezoelectric

The fundamental part of piezoelectric materials is piezoelectricity. In general, piezoelectricity is divided into two types, namely; the conversion of mechanical vibrations into electrical energy is referred as direct piezoelectricity, while the conversion of electrical energy into mechanical vibrations is referred as reverse piezoelectricity. The Quartz watch is one of the most well-known applications of piezoelectric materials. Piezoelectric materials can be natural or synthetic, and when stressed, they conduct an electrical charge. As shown in (2), the constitutional law of Piezoelectric raw materials are useful for measuring the magnitude of the output voltage based on the resulting strain [33]–[35].

$$\begin{bmatrix} \varepsilon \\ D \end{bmatrix} = \begin{bmatrix} S^E & d^t \\ d & \varepsilon^\sigma \end{bmatrix} \begin{bmatrix} \sigma \\ E \end{bmatrix} \tag{1}$$

The strain vector (m/m) is written with the symbol ε in (1), and the electrical energy transfer vector (C/m^2) is written with the symbol D, the dipole displacement produces an electric field and S^E is the matrix constant in an electric field (m^2/N). The polarizability of dielectric material is indicated by constant voltage on the constant electrical permittivity matrix (F/m) at constant stress, where is d (m/V). The applied electric field vector E is (V/m), and the stress vector σ is (N/m^2). Figure 4 depicts the direct piezoelectric conversion in the context of a highway application.

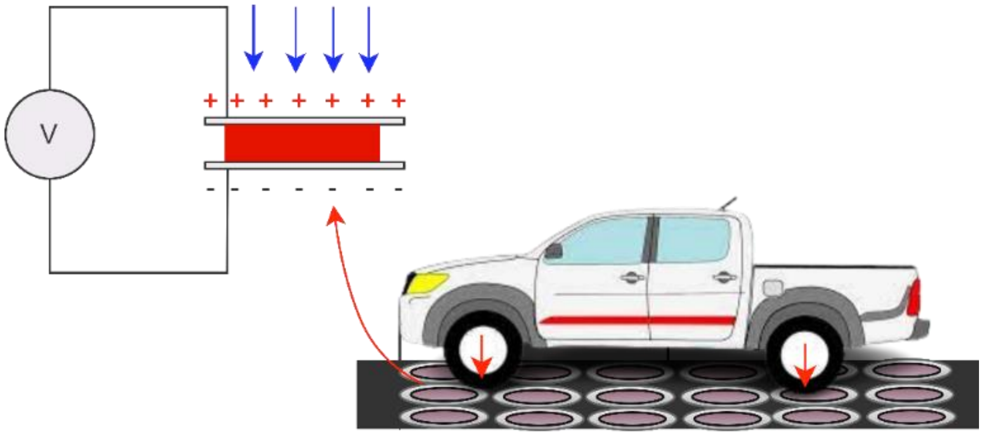

Figure 4. Direct piezoelectric harvester application in a road

The piezoelectric charge constant (d) and permittivity are these materials' primary characteristics (ε). The former refers to the polarization produced under unit mechanical stress, whereas the latter refers to charge polarization under pressure per unit electric field. The figure of merit (FOM) is a metric used to evaluate and improve the performance of these materials. Depending on their use and loading circumstances, piezoelectric materials can have a variety of FOM. The parameters used for the evaluation of materials with mechanical energy equivalents are the electromechanical factors applied to the energy harvesting:

$$FOM = k^2 = \frac{d^2E}{\varepsilon} = \frac{Stored\ Electrical\ Energy}{Input\ Mechanical\ Energy} \quad (2)$$

For the materials subjected to equivalent mechanical stress, another measure of merit is established:

$$FOM = \frac{d^2}{\varepsilon} \quad (3)$$

where E denotes Young's modulus, ε denotes dielectric permittivity, and d denotes the piezoelectric charge constant. PZT (lead zirconate titanate), PZN-PT (lead zinc niobate-lead titanate), and PMN PT are high-performance synthetic piezoelectric materials used for energy harvesting functions (lead magnesium niobate-lead titanate). Common piezoelectric harvesters include cantilever beams, disks, cylinders, and stacks.

Ambient factors influence piezoelectric harvesters' output in addition to the qualities of the materials, such as temperature and loading. If the stresses being applied align with the direction of polarization, their output will increase. In addition to temperature, loading frequency substantially impacts output, and the temperature at which a material stops becoming piezoelectric is known as the Curie point.

Piezoelectric energy harvesting technology is a reliable and long-lasting solution for generating on-road power. An innovative piezoelectric energy harvesting system for highways achieves an energy density of up to 15.37 J/m/(m.pass.lane) based on open-circuit voltage measurements in road tests [33]. was carried out using the mobile load system model (MMLS3), with a 40 kΩ resistor, has an instantaneous power of up to 200 mW. The number of harvesters connected in parallel has a linear effect on performance. The calculated power densities with this impedance reach 8.9 W/m2, indicating that flexible energy collectors based on piezoelectric polymers can offer energy densities comparable to those based on piezoelectric ceramics. As a wireless monitoring system with an average power of 3.106mW, piezoelectric energy harvesting can serve as an energy source for many small and microelectronics embedded in sidewalks or installed in other facilities near sidewalks [12], [36].

3.3. Thermoelectric generator (TEG)

Thermal gradients between pavement layers can occur when roadways are exposed to solar radiation. TEG technology can harvest energy generated by temperature differences based on the Seebeck effect. Temperature differences at the ends of the TEG device, one hot and one cold, cause voltage production [37]–[39]. Figure 5 depicts the TEG principle. When there is a temperature difference on each surface, charge carriers will move from the hot surface to the cold surface of the TEG module. The TEG module itself consists of two materials, namely type N and type P parallel, as in semiconductor materials. It is important to note that electrons in N-type semiconductors have a negative charge. Because the holes in a P-type semiconductor are positively charged, electric current flows in opposite directions between these two parallels. When connected to an external circuit on the cold side, energy can thus be harvested and used. The most significant barrier to TEG use on highways is its inefficiency [40], [41]. As shown in (4)-(6), the parameter indicators used to evaluate the technical performance of the TEG module in this paper are: loaded output power, open circuit voltage, and loaded current.

$$P_o = \frac{V_o^2}{R_L} \tag{4}$$

$$I = \frac{P_o}{V_o} \tag{5}$$

and

$$V_o = \frac{V_{oc}}{2} \tag{6}$$

Where: P_o represents loaded output power in watts, V_o represents loaded output voltage in volts, R_L represents load resistance in ohms, I represent load current in amperes, and V_{oc} represents open circuit voltage in volts.

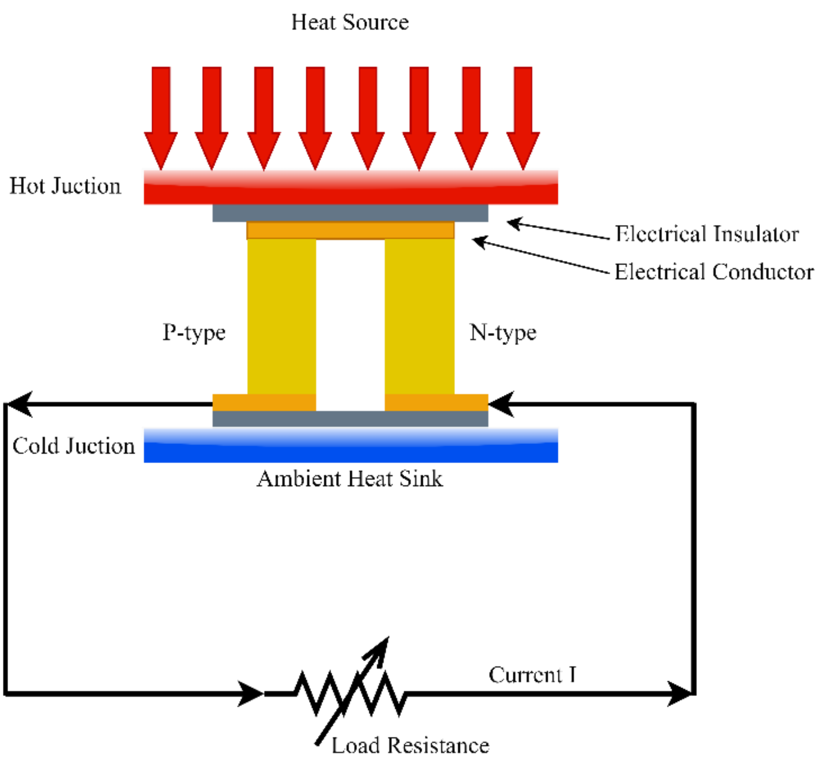

Figure 5. Principle of thermoelectric generator

Study in [42] yielded an average power of 29 mW for South Texas (i.e., moderate) conditions, which appears to be a promising stand-alone power source for roadside wireless sensors and short-range communications. Researcher [20] generates about 0.4 V for an asphalt slab (size 300 mm × 300 mm) if the temperature difference between the road surface and the outside air is 15 °C in winter. In summer, the output voltage is about 0.6-0.7V, and the temperature difference is 25-30 °C. This means that about 160 kWh of energy can be generated in 8 hours on a road 1 km long and 10 m wide. The electricity generated by [43] all highways is 55 GWh per day with the proposed PP-TEG system. In contrast, the electricity covered by the PZT circuit (PZT system) only generates 4.04 MWh of electricity per day [31].

4. ENERGY HARVESTING COMPARISON AND DISCUSSION

One of the differences in energy harvesting technology on the highway is the output power. The output power generated is sufficient for powering street lights, installation and wireless connection. However, its application still has limitations because it has to pay attention to traffic flow and maintenance and is relatively new.

One method of highway energy harvesting is piezoelectric. The energy conversion in a piezoelectric depends on the vibration frequency and vibration acceleration. Placement is piezoelectric easier because it can be directly placed on the road pavement system. The installation system is equipped with a protective system. Piezoelectric is not affected by the weather. Even though the power is low, it can be used as a sensor or system that requires low power.

For energy harvesting on the roads, thermoelectric and photovoltaic technologies can be applied. These technologies in their work systems depend on weather and climatic conditions. The energy conversion factor in thermoelectric is the spatial temperature gradient, while photovoltaic depends on light intensity, temperature, and materials used. They produce less power than electromagnetic systems, on the whole. Both are less expensive than piezoelectric energy harvesters, simple to install, and incorporate into line structures. Yet like the piezoelectric harvester, this harvester has a low output power, making it more suited for low-power gadgets and sensors. Street PV placement, unlike rooftop systems, street solar panels cannot be tilted to reach the best angle of the solar panels, which means an energy loss of 20% or more. They will also encounter shadows of passing vehicles, surrounding buildings and vegetation, and debris such as dust and leaves. Even a little shading greatly impacts the solar panel manufacturing process. Because they are installed on the street, the panels cannot be cooled by circulating air. This will reduce the efficiency of the solar panel, which will decrease when the panel temperature exceeds the optimal level. Table 1 describes the positive and negative characteristics of each of the technologies studied.

Table 1. Comparison of advantages and disadvantages of harvesting technologies

Technologies	Energy conversion factors	Advantages	Disadvantages	Ref
Photovoltaic	Light intensity; Temperature gradient; Material properties;	Predictable; Scalable; Average power output;	Dependent on the weather Fragile and not suitable with roads mechanically High cost Can't handle traffic loads Low solar power production	[4], [7], [12], [13]
Piezoelectric	Vibration frequency; Vibration acceleration;	High voltage output; High power density; Good mechanical properties; Easy installation; Performance not dependent on weather;	AC only; Not receptive at low frequencies; Minimal power output; Expensive maintenance and fabrication	[2], [14]–[17]
Thermoelectric	Spatial temperature gradient;	Long life due to stationary parts; High reliability; Easy installation;	Low conversion efficiency; Expensive maintenance and fabrication; Output power depends on weather conditions.	[17], [20], [37], [41]–[43], [44]–[48]

5. CONCLUSION

This paper summarises the available energy harvesting technologies from roadways. The harvesting technology of piezoelectric, thermoelectric, and solar panels has been briefly discussed. One easy-to-apply roadway energy harvesting system is piezoelectric. It is easier to place because it can be directly applied to the road pavement. Piezoelectricity is not affected by the weather. Therefore, for future research, it is suggested to improve this system in terms of efficiency and maintainability as well as energy storage to develop a more sustainable infrastructure.

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